NOTA DI LAVORO
73.2014

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Climate Change and Sustainable Development
Series Editor: Carlo Carraro

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Summary

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Keywords: Climate Change Mitigation, Directed Technical Change, Capital-Embodiment, Investment-Specific Technological Change, Obsolescence

JEL Classification: O33, O44, Q54, Q55, Q58

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Directed Technical Change with Capital-Embodied Technologies: Implications for Climate Policy

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Abstract

We develop a theoretical model of directed technical change in which clean (zero emissions) and dirty (emissions-intensive) technologies are embodied in long-lived capital. We show how obsolescence costs generated by technological embodiment create inertia in a transition to clean growth. Optimal policies involve higher and longer-lasting clean R&D subsidies than when technologies are disembodied. From a low level, emissions taxes are initially increased rapidly, so they are higher in the long run. There is more warming. Introducing spillovers from an exogenous technological frontier representing non-energy-intensive technologies reduces mitigation costs. Optimal taxes and subsidies are lower and there is less warming.

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INTRODUCTION

The Copenhagen Accord (UNFCCC 2009) expresses a broad international consensus that actions should be taken to keep global warming below 2°C. Achieving this will require rapid and extensive development of and investment in carbon-free technologies over the next few decades (Edenhofer et al. 2010; Luderer et al. 2012).[1] In this paper, we develop a theoretical model of directed technical change (DTC) and the environment in which technologies are embodied in capital goods. An important implication of capital-embodiment is that technical progress generates obsolescence costs, adding to the user cost of capital. That is, developing new capital goods that are cheaper or more productive shortens the economic lifetime of old ones. In this paper, we show theoretically and with illustrative numerical simulations that obsolescence costs may generate significant inertia in transitions from dirty to clean growth. One consequence is that emissions taxes should start lower but rise faster than often suggested.

Formal analysis of technological embodiment in investment goods in the macroeconomic growth literature dates back to Solow (1960). Empirically, Greenwood, *et al.* (1997) estimate that over 60% of US post-war productivity growth is attributable to embodied technical progress. A fully endogenous macroeconomic growth model with investment-specific R&D is first developed in Krusell (1998).[2] In this model, a 'planned obsolescence effect' results from firms' optimal allocation of resources between investment and R&D. In the decentralised economy, obsolescence costs depress investment and R&D and growth is lower than socially optimal. However, in the context of development, Boucekkine *et al.* (2005) emphasise the 'modernisation' of capital through investment, which increases R&D incentives.

Energy-intensive technologies tend also to be capital-intensive, therefore we might expect embodiment of energy technologies to be particularly important. This hypothesis is supported by bottom-up studies of particular energy-intensive technologies or

[1] The fifth Intergovernmental Panel on Climate Change (IPCC) assessment concludes that a >66% chance of not exceeding 2°C warming requires cumulative anthropogenic carbon dioxide (CO_2) emissions to remain below 1000 gigatonnes of carbon (GtC); perhaps below 790 GtC after allowing for non-CO_2 forcings (IPCC 2013: p25). In 2011, annual emissions from fossil fuel combustion and cement production were 9.5GtC while cumulative emissions from all sources had reached 555 GtC (IPCC 2013: p10).

[2] Another early contribution is Hsieh (2001).

industries, such as Sterner (1990) on the Mexican cement industry and Worrell and Biermans (2005) on the electric arc furnace in the US steel industry. More broadly, Sue Wing (2008) estimates that embodied technical progress accounted for three quarters of a 32% reduction in intra-industry energy intensity in the United States from 1980 to 2000 attributable to either embodied or disembodied technical progress.[3] Technological embodiment also relates to broader concepts of 'technological lock-in' that involve complementarities between up-stream, down-stream and end-use energy technologies, infrastructure and urban form (Grubb 1997; Unruh & Einstein 2000).

Many empirical studies in the literature on climate mitigation emphasise the slow rate at which much energy-intensive capital turns over. Shalizi and Lecocq (2009) estimate that long-lived capital stocks directly influence 50% of global emissions. Considering just direct energy and process emissions, Davis *et al.* (2010) estimate that existing capital assets will generate cumulative additional CO_2 emissions of 136GtC over their lifetimes.[4] However, these and other studies focus only on the role of clean technical progress in reducing the cost of clean investments, i.e. modernisation effects. Obsolescence effects of embodied technological change have rarely been studied in the context of energy technologies. An exception is Gibbons (1984), who finds that average lifetimes of fixed U.S. manufacturing assets fell sharply following the 1973 Arab oil embargo.[5]

Most theoretical models of DTC and the environment abstract from processes of capital accumulation. For example, in Smulders and de Nooij (2003), technology augments either labour or energy inputs in an aggregate production function. In Acemoglu *et al.* (2012) – henceforth AABH – technology augments labour in either clean or dirty sectors. van Zon and Yetkiner (2003) develop a model in which R&D increases both the number and capital-embodied energy efficiency of varieties of capital. However,

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[3] Note that these estimates are not entirely comparable with those of Greenwood *et al.* The aim of Sue Wing's study is to decompose and explain changes in U.S. energy intensity. However, even in energy-intensive industries, profit-driven innovations need not be energy-saving. Indeed, Sue-Wing also finds that between 1958 and 1980, embodied technological change was associated with a 6.9% increase in U.S. energy intensity and disembodied technological change with a 0.4% decrease.

[4] Cf. note 1.

[5] Gibbons notes that the fall exceeded effects attributable to the ensuing recession.

they consider only a fixed relationship between energy-using and energy-saving change. Schwoon and Tol (2006) make a contribution close in spirit to our own. However, the source of inertia is not capital-embodiment of technologies but assumed capital adjustment costs. Moreover, their model lacks a micro-founded specification of R&D. Finally, our contribution relates to van Zon and David (2013), who develop a model with DTC in which clean and dirty outputs are given by AK production functions. In those models, dirty capital may be underutilised, whereas in our model, the entire capital stock may be utilised more or less intensively. While van Zon and David emphasize capital accumulation, they specify technical change is as being capital augmenting, thus obsolescence costs do not arise in their model.

Our model introduces investment-specific technical change à la Krusell (1998) into the framework proposed in AABH. As in AABH, a final good is produced from clean and dirty intermediates and emissions are proportional to dirty sector ouput. Intermediates are produced using labour and a continuum of sector-specific machines. The key difference in our model is that machines depreciate slowly. Monopolistic firms make investments and rent machines to producers. R&D on investment-specific technologies is conducted by firms that behave myopically because of inter-firm spillovers. In this way, we maintain the same type of intertemporal externalities in R&D as in AABH. In our numerical implementation of the model, we link emissions to global mean surface temperature using the climate sub-model from DICE (Nordhaus & Sztorc 2013) and employ a climate damage function proposed by Weitzman (2010).

We initially consider a specification in which researchers build only on technological knowledge in their own sector, as in AABH. We then go on to consider a specification in which there are technological spillovers from an exogenously defined technological frontier. This latter specification is motivated by studies using patent data that find spillovers between energy and non-energy technologies to be significant. Nemet (2012) finds that citations to non-energy technologies (notably, in the chemical, electronics and electrical sectors) add value to energy technology patents. Braun *et al.* (2010) find that external knowledge stocks contribute significantly to innovations in the wind technologies, although they find insignificant effects for solar technologies. On the other hand, intuition suggests that spillovers between clean and dirty substitute technologies may be weak. Aghion *et al.* (2013) provide direct evidence for this view, studying spillovers between ‘clean’ and ‘dirty’ and ‘neutral’ technologies in the automotive sector. We therefore omit spillovers between clean and dirty technologies from our model. There is some evidence that certain clean energy technologies generate larger spillovers than dirty ones (Dechezleprêtre, Martin, & Mohnen 2013; Nemet 2012; Noailly & Shestalova 2013). However, our model does not have a rich enough structure to investigate these types of spillovers.

Optimal environmental policies in our model involve a tax on the dirty input and a temporary subsidy to clean R&D, as in AABH. However, dynamic responses are significantly altered by the presence of obsolescence costs. Switching to clean R&D causes the user cost of clean capital to rise and that of dirty capital to fall. In the short run, dirty output may rise rather than fall because obsolescence effects dominate modernisation effects. In the long run there is clean growth as modernisation effects dominate. Nevertheless, accumulation of clean capital lags accumulation of clean technological knowledge when technologies are embodied. We show through numerical simulations that the inertia created by capital-embodiment of technologies is quantitatively significant. When technologies are embodied, optimal policies involve higher and longer-lasting clean R&D subsidies thatn when they technologies are disembodied. The dirty input tax rate rises faster from a similar initial level and is higher in the long run. There is additional warming. Introducing spillovers from an exogenous technological frontier representing non-energy-intensive technologies reduces mitigation costs, lowers the optimal tax and subsidy rates and reduces warming.

The paper is structured as follows. In the next section we describe our model of the economy and of the environment. We then describe equilibrium allocations and the structure of optimal policies, highlighting the ways in which these are affected by capital-embodiment of technologies. This is followed by a section describing a numerical implementation of the model and presenting illustrative numerical simulations of optimal policies. Simulations are presented with and without spillovers from the exogenous technological frontier. We also present simulations using an otherwise comparable model in which technologies are disembodied. Finally, we present our conclusions and make suggestions for future research.

Model

Production and consumption

We assume an infinitely-lived representative household that is composed of scientists and workers and owns firms. The household's preferences are given as

$$U = \sum_{t=0}^{\infty} \frac{u\left(C_t\right)}{\left(1+\rho\right)^t}, \tag{1}$$

where $u(C_t)$ is the instantaneous utility derived from consumption of the unique final good C_t and ρ is the pure rate of time preference. The utility function is twice-differentiable and satisfies $u'\left(C_t\right) > 0$, $u''\left(C_t\right) < 0$ and $\lim_{C_t \to 0} u'\left(C_t\right) = \infty$. Maximising (1) subject to an income constraint results in the Euler equation

$$u'\left(C_t\right) = \frac{1+i_t}{1+\rho} u'\left(C_{t+1}\right), \tag{2}$$

where i_t is the market interest rate.

As in AABH, identical and perfectly competitive firms produce a unique final good from two types of intermediate inputs, which we label 'clean' and 'dirty'. There is a constant elasticity of substitution ε between clean and dirty inputs. Thus, firms in the final sector have a unit cost function

$$\left(p_{c,t}^{1-\varepsilon} + \left(1+\tau_t\right)^{1-\varepsilon} p_{d,t}^{1-\varepsilon}\right) = 1, \tag{3}$$

where $p_{c,t}$ and $p_{d,t}$ are the prices of the clean and dirty goods respectively relative to the price of the final good, which we take as a numeraire for each period. Prices are defined in this way throughout. An *ad valorem* tax τ_t may be levied on dirty inputs.

Aggregate output Y_t of the final sector is

$$Y_t = \left[Y_{c,t}^{(\varepsilon-1)/\varepsilon} + Y_{d,t}^{(\varepsilon-1)/\varepsilon}\right]^{\varepsilon/(\varepsilon-1)}, \tag{4}$$

where $Y_{c,t}$ and $Y_{c,t}$ are aggregate clean and dirty inputs respectively. As in AABH, we assume that the empirically relevant case is that in which these inputs are gross substitutes ($\varepsilon > 1$). From firms' first order conditions, ratios of clean and dirty outputs and prices satisfy:

$$\hat{Y}_t = \left(1+\tau_t\right)^{\varepsilon} \hat{p}_t^{-\varepsilon}. \tag{5}$$

where here and below, for any pair of prices or quantities $x_{c,t}$ and $x_{d,t}$, we denote their ratio by $\hat{x}_t \equiv x_{c,t} / x_{d,t}$.

Within the clean or dirty sectors, goods are produced by identical, perfectly competitive firms. Firms combine labour with a continuum of sector-specific 'machines'. Labour is homogenous and perfectly mobile between sectors. The key difference between our model and AABH is that we model machines as slowly-depreciating capital goods embodying clean or dirty technologies. Aggregate outputs of the clean and dirty sectors $j \in \{c, d\}$ are

$$Y_{j,t} = \Phi_t L_{j,t}^{1-\alpha} \int_0^1 k_{j,i,t}^{\alpha} di \,, \tag{6}$$

where Φ_t is environmental quality, $L_{j,t}$ is labour input and $k_{j,i,t}$ is quality-adjusted stock of the (j,i)th machine. Capital stocks accumulate as

$$k_{j,i,t} = A_{j,i,t} z_{j,i,t} + \left(1 - \delta\right) k_{j,i,t-1} \,, \tag{7}$$

where $z_{j,i,t} \geq 0$ is the amount of the final good used for investment, $A_{j,i,t}$ is the level of investment-specific technology and δ is the physical depreciation rate. As in Krusell (1998), we assume that long-lived monopolistic firms make investments and rent their capital to producers. [6] We assume that investment firms take technologies as exogenous.

Clean and dirty firms earn zero profits, so we have:

$$p_{j,t} \Phi_t L_{j,t}^{1-\alpha} \int_0^1 k_{j,i,t}^{\alpha} di - \left(1 - \varsigma\right) \int_0^1 r_{j,i,t} k_{j,i,t} di - w_t L_{j,t} = 0 \,, \tag{8}$$

where $r_{j,i,t}$ is the rental price of the (j,i)th machine and w_t is the common wage rate. An *ad valorem* capital rental subsidy ς will correct a monopoly distortion in capital rental markets. From (8), the first order conditions with respect to labour and to capital are:

$$L_{j,t} = \left(1 - \alpha\right) p_{j,t} Y_{j,t} / w_t \quad \text{and} \tag{9}$$

$$k_{j,i,t} = L_{j,t} \left(\frac{\alpha p_{j,t} \Omega_{j,t}}{\left(1 - \varsigma\right) r_{j,t}} \right)^{\frac{1}{1-\alpha}} . \tag{10}$$

[6] Given our assumptions, this separation of production and investment is not economically significant, but simplifies the mathematics. It is possible, if tedious, to obtain the same results with producers making investments directly.

Given current and future technology, investment firms maximise their present value, subject to (10), (7) and non-negativity of investment. The Lagrangian for this problem is

$$\mathcal{L} = \sum_{t=0}^{\infty} p_t \left\{ r\left(k_{j,i,t}\right) k_{j,i,t} - z_{j,i,t} + \lambda_{j,i,t} \left[A_{j,i,t} z_{j,i,t} + \left(1-\delta\right) k_{j,i,t-1} - k_{j,i,t} \right] + \mu_{j,i,t} z_{j,i,t} \right\}, \quad (11)$$

where p_t is the Arrow-Debrue price of consumption in period t, $\lambda_{j,i,t} > 0$ is the current shadow price of capital and $\mu_{j,i,t} \geq 0$ the current shadow value of the non-negativity constraint. We derive $r\left(k_{j,i,t}\right)$, the capital rental rate as a function of capital, from (10).

From the Kuhn-Tucker conditions for (11) we obtain (noting $i_t \equiv p_t / p_{t+1} - 1$)

$$\lambda_{j,i,t} + \mu_{j,i,t} = A_{j,i,t}^{-1}, \quad (12)$$

$$z_{j,i,t} \mu_{j,i,t} = 0, \text{ and} \quad (13)$$

$$\alpha r_{j,i,t} = \lambda_{j,i,t} - \left(\frac{1-\delta}{1+i_t} \right) \lambda_{j,i,t+1}. \quad (14)$$

Thus, investment firms set a mark-up of $1/\alpha$ over their cost of capital. The value of an additional unit of capital $\lambda_{j,t}$ is less than the investment cost only if there is zero investment. When $z_{j,i,t} > 0$ and $z_{j,i,t+1} > 0$, equations (12) to (14) reduce to

$$r_{j,i,t} = \frac{1}{\alpha} \left[\frac{1}{A_{j,i,t}} - \left(\frac{1-\delta}{1+i_t} \right) \left(\frac{1}{A_{j,i,t+1}} \right) \right]. \quad (15)$$

Equation (15) shows how technological progress in either sector adds to the user cost of capital in that sector.

Finally, we have market clearing conditions for labour and for the final good:

$$L_{c,t} + L_{d,t} \leq 1 \text{ and} \quad (16)$$

$$C_t = Y_t - \int_0^1 z_{c,i,t} di - \int_0^1 z_{d,i,t} di. \quad (17)$$

Research and development

R&D firms each work on one, or a small number of clean and/or dirty technologies and are granted single-period patents for these technologies. At the beginning of each period, firms hire scientists at a competitive market wage to improve their technologies. The supply of scientists is normalised to one:

$$s_{c,t} + s_{d,t} \leq 1. \quad (18)$$

Technical progress is a deterministic function of the number of scientists working on a technology $s_{j,i,t}$ and their productivity η_j:

$$A_{j,i,t} = \left(1 + \eta_j s_{j,i,t}\right) A_{j,t-1}. \tag{19}$$

We assume that within each sector, there are complete spillovers between technologies after one period, such that scientists build on the previous average technology of that sector $A_{j,t-1} \equiv \int_0^1 A_{j,i,t-1} di$. These spillovers play two roles. Firstly, they create the same sort of intertemporal externality in R&D as exists in AABH. If R&D firms can build on the average technology and their decisions have negligible impact on the sector average, they will behave myopically. Secondly, complete spill-overs ensure that technologies are symmetric within each sector. With identical knowledge production functions and identical starting points, firms will allocate the same number of scientists to every line within a sector. Thus for variables take the same value for every i so we hence forth drop this subscript.

Free entry into the investment sector ensures that investments will be made using the latest technology and that monopoly profits earned in the investment sector are ultimately captured by scientists. In period t, the present value of an investment $z_{j,t}$ and hence the value of an innovation is given by

$$\sum_{s=t}^{\infty} \left(\frac{r_{s,t}}{\prod_{s'=t}^{s-1} \left(1 + i_{s'}\right)} \right) A_{j,t} z_{j,t} - z_{j,t} \tag{20}$$

which, using (12) and (14), simplifies to

$$\left(\frac{1-\alpha}{\alpha} \right) z_{j,t}. \tag{21}$$

Although R&D firms are myopic, they do consider how their decisions affect current level of investment and hence the value of their innovations. They choose $s_{j,t}$ to maximise

$$\Pi\left(z\left(a\left(s_{j,t}\right)\right)\right) \equiv \eta_j \left(\frac{1-\alpha}{\alpha} \right) \frac{k_{j,t}\left(A\left(s_{j,t}\right)\right) + \left(1-\delta\right) k_{j,t-1}}{A\left(s_{j,i,t}\right)} - \left(1 - \xi_{j,t}\right) w_{S,t} s_{j,t} \tag{22}$$

subject to $0 \le s_{j,t} \le 1$, where we used the capital equation of motion (7) in (21) and subtracted the cost of hiring $s_{j,t}$ scientists at the competitive wage $w_{S,t}$. Scientists' wages in the clean sector may be subsidised at the rate $\xi_{c,t}$. The first order condition is

$$\frac{\partial \Pi_{j,t}}{\partial s_{j,t}} = \eta_j \left(\frac{1-\alpha}{\alpha}\right) \frac{A'\left(s_{j,t}\right)}{A_{j,t}} \left[k'\left(A_{j,t}\right) - \frac{z_{j,t}}{A_{j,t}}\right] - \left(1-\xi_{j,t}\right) w_{S,t} = 0 \tag{23}$$

whenever $s_{j,t} > 0$. This shows that on the one hand, better technology increases demand for capital embodying that technology. On the other, fewer units of raw investment are needed per unit of effective capital. The following conditions must hold in equilibrium:

$$\frac{\partial \Pi_{j,t}}{\partial s_{j,t}} \leq 0 \quad \textit{and} \quad 0 \leq s_{j,t} \leq 1 \quad \textit{and} \quad s_{j,t} \frac{\partial \Pi_{j,t}}{\partial s_{j,t}} = 0\,. \tag{24}$$

INTERSECTORAL SPILLOVERS IN R&D

To study spillovers between non-energy-intensive and energy/energy-intensive technologies, we would ideally add a third sector to the framework, as in Hémous (2013). As this would complicate the model considerably, we take a simpler approach of introducing spillovers from an exogenous technology frontier that we define as $A_{ex,t} \equiv \left(1+\eta_{ex}\right)^t$ where η_{ex} is the rate of exogenous technical progress. In doing so, we abstract from spillovers from energy to non-energy technologies, crowding out between energy and non-energy technologies, and from wider general equilibrium interactions. Nevertheless, since energy-intensive sectors account for a minority of economic activity and R&D and since there is evidence that clean energy R&D tends to crowd our dirty energy rather than non-energy R&D (Popp & Newell 2012), this specification may still give meaningful insights.

We model spillovers from the exogenous frontier as a function of distance to the frontier $D_{j,t-1} \equiv A_{ex,t-1} / A_{j,t-1}$ so that there is an 'advantage of backwardness' (Gerschenkron 1952). Spillovers increase the productivity of R&D and (19) becomes

$$A_{j,t} = \left[1 + \eta_j s_{j,t} \left(1 + \phi\left(1 - D_{j,t-1}^{-1}\right)\right)\right] A_{j,t-1}\,, \tag{25}$$

where the parameter ϕ gives the maximum spillover strength. If we had started from the commonly used Cobb-Douglas specification of internal and external knowledge stocks, we would have $\phi D_{j,t-1}^{\beta}$ rather than $\phi\left(1 - D_{j,t-1}^{-1}\right)$ in (25). We use the latter functional form to give a reasonable approximation of the former for modest distances from the frontier while ensuring that spillovers do not grow without bound. This is in the spirit of models in which the value of spillovers depends on both distance and absorptive capacity.

The implication of (25) for the (very) long run costs of climate policies is dramatic: they approach zero. From this perspective, we can consider our alternative specifications as representing polar views, with reality lying somewhere in between them. Using equation (19), the long run costs are proportional to the initial clean technology gap. The more backward the clean sector, the longer it takes to reach the initial level of dirty technology. Using equation (25), the clean technology eventually approach the productivity level defined by the exogenous technology frontier, at least in the simplest case in which $\eta_c = \eta_d = \eta_{ex}$.

Climate dynamics and damages

Theoretical model

In the theoretical part of the paper, we model environmental quality as

$$\Phi_t = \Phi_{t-1} + \Delta\Psi_{t-1} - \left(1-\Theta\right)\chi Y_{d,t}, \tag{26}$$

$$\Psi_t = \left(1-\Delta\right)\Psi_{t-1} + \Theta\chi Y_{d,t}, \tag{27}$$

where χ is the emissions intensity of the dirty input and environmental quality Φ_t is reduced in proportion to the atmospheric carbon concentration. The latter is modelled as the sum of three parts: (i) a stock corresponding to the pre-industrial concentration of approximately 280 ppm CO_2; (ii) a stock Ψ_t formed by a fraction Θ of carbon emissions E_t that are slowly degradable at rate Δ and (iii) a stock formed by a fraction $1-\Theta$ of carbon emissions that remain permanently in the atmosphere. This two-stock model is based on Hourcade *et al.* (2011) and is in accordance with Archer's (2005, pC09S05) conclusion: 'A better approximation of the lifetime of fossil fuel CO_2 for public discussion might be "300 years, plus 25% that lasts forever"'. The above specification allows us to derive relatively simple expression for the optimal dirty input tax.

Numerical model

In the numerical implementation of our model, we replace (26) and (27) with a more sophisticated representation of carbon and temperature dynamics from Nordhaus' DICE model (Nordhaus & Sztorc 2013). This climate sub-model has five state variables: atmospheric and ocean temperatures and atmospheric, shallow and deep ocean carbon concentrations. Its parameters are calibrated by Nordhaus and Sztorc to emulate the responses to radiative forcing of large-scale carbon cycle and atmosphere-ocean general circulation models. Concentrations of other greenhouse gases are not modelled in DICE. Instead, the associated radiative forcing is imposed exogenously. For simplicity, we ignore these forcing components.

We use a damage function relating aggregate damages to the global mean atmospheric temperature increase. What is referred to by the IPCC as 'dangerous anthropogenic interference with the climate system' concerns many different types of impacts that occur on many different timescales and have different likelihoods (to our current scientific knowledge) under different conditions (Smith et al. 2009). In our opinion, the damage function proposed in Weitzman (2010) is consistent with this understanding. See also Hansen *et al.* (2013) on the long-term consequences of a nominal 2°C target.

Below about 3°C of warming, the damages given by Weitzman's function are very similar to those given by the damage function in DICE or by the damage function used in AABH, which is proposed in Golosov *et al.* (2011). However, above 3°C of warming, Weitzman's damage function gives more rapidly increasing damages (reaching 9% at +4°C, 25% at +5°C and 50% at +6°C). Damages given by the other two functions increase much more slowly; except that in AABH, damages start to rise extremely fast just below +6°C, at which point there is a 'climate disaster' involving total losses. We apply damages to output of the clean and dirty sectors rather than to consumption, as in AABH. This is more consistent with the empirical literature on which estimates of aggregate damage functions draw (e.g. Tol 2009).

Finally, we model emissions as

$$E_t = \chi L_{d,t}^{1-\alpha} \int_0^1 k_{d,i,t}^{\alpha} di = \left(\chi / \Phi_t\right) Y_{d,t} . \tag{28}$$

That is, we link emissions to inputs of the dirty sector rather than to dirty inputs to the final sector as we did in (26) and (27). This creates a positive feedback in which damages increase the emissions intensity of the dirty sector. For example, higher ambient temperatures will reduce the thermal efficiency of coal-fired electricity generating units and therefore will increase CO_2 emissions per unit of electricity sent out. These feedbacks only become important if damages are allowed to become relatively large.

Allocations and optimal policies

Equilibrium allocations and reduced forms

Taking ratios of equations (5), (6), (9) and (10), together with (5) and sequentially eliminating $\hat{k}_t$, $\hat{L}_t$ and $\hat{p}_t$, we obtain labour, capital and output ratios as functions of only the capital rental rate ratio and the dirty tax rate:

$$\hat{L}_t = \frac{\left(1+\tau_t\right)^{\varepsilon}}{\hat{r}_t^{\alpha(\varepsilon-1)}}. \tag{29}$$

$$\hat{k}_t = \frac{\left(1+\tau_t\right)^{\varepsilon}}{\hat{r}_t^{1+\alpha(\varepsilon-1)}}. \tag{30}$$

$$\hat{Y}_t = \frac{\left(1+\tau_t\right)^{\varepsilon}}{\hat{r}_t^{\alpha\varepsilon}}. \tag{31}$$

Equations (29) and (30) can be solved for the shares of clean or dirty labour and of clean or dirty capital respectively. We can thus determine the levels of clean, dirty and aggregate output as a function of the (fixed) aggregate labour supply, the aggregate stock of clean and dirty effective capital and clean and dirty capital rental rates. Defining

$$\Psi_t \equiv \frac{\left[r_{c,t}^{\alpha(\varepsilon-1)} + \left(1+\tau_t\right)^{\varepsilon-1} r_{d,t}^{\alpha(\varepsilon-1)}\right]^{\frac{\varepsilon}{\varepsilon-1}}}{\left(r_{c,t}^{1+\alpha(\varepsilon-1)} + \left(1+\tau_t\right)^{\varepsilon} r_{d,t}^{1+\alpha(\varepsilon-1)}\right)^{\alpha}\left(r_{c,t}^{\alpha(\varepsilon-1)} + \left(1+\tau_t\right)^{\varepsilon} r_{d,t}^{\alpha(\varepsilon-1)}\right)^{(1-\alpha)}},$$

which is a measure of static efficiency, we have

$$Y_t = \Phi_t \Psi_t \left(k_{c,t} + k_{d,t}\right)^{\alpha}, \tag{32}$$

$$Y_{c,t} = \left[\frac{r_{d,t}^{\alpha(\varepsilon-1)}\left(1-\tau_t\right)^{\varepsilon-1}}{r_{c,t}^{\alpha(\varepsilon-1)} + \left(1+\tau_t\right)^{\varepsilon-1} r_{d,t}^{\alpha(\varepsilon-1)}}\right]^{\frac{\varepsilon}{\varepsilon-1}} \Phi_t \Psi_t \left(k_{c,t} + k_{d,t}\right)^{\alpha}, \tag{33}$$

$$Y_{c,t} = \left[\frac{r_{c,t}^{\alpha(\varepsilon-1)}}{r_{c,t}^{\alpha(\varepsilon-1)} + \left(1+\tau_t\right)^{\varepsilon-1} r_{d,t}^{\alpha(\varepsilon-1)}}\right]^{\frac{\varepsilon}{\varepsilon-1}} \Phi_t \Psi_t \left(k_{c,t} + k_{d,t}\right)^{\alpha}, \text{ and} \tag{34}$$

Note that for $\tau_t = 0$, Ψ_t has a maximum value of $2^{1/(\varepsilon-1)}$ when $r_{c,t}$=$r_{d,t}$ and a minimum value of 1 as either $\hat{r}_t \to 0$ or $\hat{r}_t \to \infty$ (i.e. as the technology gap between the sectors becomes very large).

Solving the representative household's problem subject to the ratio of clean to dirty capital (30) chosen by producers, we obtain a version of the Euler equation that can be rearranged to determine the socially optimal level of aggregate effective capital:[7]

$$k_{c,t} + k_{d,t} = \left\{ \frac{\alpha \Phi_t \Psi_t}{\frac{\kappa_{c,t}}{A_{c,t}}\left[1 - \frac{(1-\delta)}{(1+\rho)}\frac{U'(C_{t+1})}{U'(C_t)}\frac{A_{c,t}}{A_{c,t+1}}\right] + \frac{\kappa_{d,t}}{A_{d,t}}\left[1 - \frac{(1-\delta)}{(1+\rho)}\frac{U'(C_{t+1})}{U'(C_t)}\frac{A_{d,t}}{A_{d,t+1}}\right]} \right\}^{\frac{1}{1-\alpha}}, \quad (35)$$

where $\kappa_{j,t}$ is the share of effective capital in sector j, determined using (30). Linearly approximating terms in the denominator and denoting the rate of growth of any variable X by $g_{X,t} \equiv X_{t+1}/X_t - 1$, we obtain

$$k_{c,t} + k_{d,t} = \left\{ \frac{\alpha \Phi_t \Psi_t}{\frac{\kappa_{c,t}}{A_{c,t}}\left[\delta + \rho + g_{A,c,t} + g_{U,t}\right] + \frac{\kappa_{d,t}}{A_{d,t}}\left[\delta + \rho + g_{A,d,t} + g_{U,t}\right]} \right\}^{\frac{1}{1-\alpha}}. \quad (36)$$

Assuming that climate policies induce a switch to clean growth, environmental quality eventually recovers to a new equilibrium value that depends on the stock of permanent emissions. The asymptotic equilibrium level of the normalised stock of effective capital is then:

$$\lim_{t\to\infty}\left(\frac{k_{c,t} + k_{d,t}}{A_{c,t}^{1-\alpha}}\right) \approx \left(\frac{\alpha \lim_{t\to\infty}(\Phi_t)}{\delta + \rho + \eta_c + g_{U,t}}\right)^{\frac{1}{1-\alpha}} \quad (37)$$

The asymptotic growth rate of consumption is $\lim_{t\to\infty} g_{C,t} = \alpha/(1-\alpha)\eta_c$. Given any specific utility function of the form assumed, the growth rate of utility follows.

Short run response to climate policy

From (15) we derive an expression for the ratio of capital rents under the simplifying assumptions of investment in both sectors at times t and t+1:

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[7] Note that obtaining this result in the fully decentralised equilibrium requires an capital rents to be subsidised optimally at the rate $\varsigma_t = \varsigma = \alpha$.

$$\hat{r}_t = \hat{A}_{t-1}^{-1}\left(\frac{1+\eta_c s_{c,t}}{1+\eta_d s_{d,t}}\right)^{-1}\frac{\left[\left(1+i_t\right)-\left(1-\delta\right)/\left(1+\eta_c s_{c,t+1}\right)\right]}{\left[\left(1+i_t\right)-\left(1-\delta\right)/\left(1+\eta_d s_{d,t+1}\right)\right]}. \tag{38}$$

Combining (38) with (31), we can analyse the short-run effects of climate policies on the output ratio.

Consider the unanticipated introduction a clean R&D subsidy in period t that is sufficient to ensure only clean R&D in period t. In period t-1, all R&D is dirty and the same allocation is expected to apply in period t. Using the fact that $\hat{A}_{t-2} = \left(1+\eta_d\right)\hat{A}_{t-1}$, we have

$$\hat{Y}_{t-1}\left[s_{d,t-1}=1,\, E\left(s_{d,t}\right)=1\right] = \left\{\hat{A}_{t-1}\left[\frac{\left(1+i_{t-1}\right)-\left(1-\delta\right)/\left(1+\eta_d\right)}{\left(1+i_{t-1}\right)-\left(1-\delta\right)}\right]\right\}^{\alpha\varepsilon} \quad \text{and} \tag{39}$$

$$\hat{Y}_{t}\left[s_{c,t}=1,\, E\left(s_{c,t+1}\right)=1\right] = \left\{\hat{A}_{t-1}\left(1+\eta_c\right)\left[\frac{\left(1+i_{t}\right)-\left(1-\delta\right)}{\left(1+i_{t}\right)-\left(1-\delta\right)/\left(1+\eta_c\right)}\right]\right\}^{\alpha\varepsilon}. \tag{40}$$

Notice that in equation (39), the square-bracketed term exceeds one. In equation (40) it is not only smaller than one, but for reasonable parameters, smaller than $\left(1+\eta_c\right)^{-1}$. This is explained by the simultaneous disappearance in (40) in of an obsolescence effect in the dirty sector and the appearance of such an effect in the clean sector. This causes a sudden rise in the cost of clean capital relative to dirty capital. This implies that output gets dirtier in the short run ($\hat{Y}_t < \hat{Y}_{t-1}$) following the switch to clean R&D. Obsolescence effects dominate modernisation effects.

In the long run, the modernisation effect will dominate. However, while capital and output ratios become cleaner, they will lag the technology ratio relative to their responses in a model in which technologies are disembodied. Embodiment thus creates inertia in the transition to clean growth.

Optimal policies

The socially optimal allocation maximises the intertemporal utility of the representative household (1), subject to the constraints (2), (3), (4), (5), (6), (7), (9), (10), (12), (13), (14), (16), (17), (18), (23), (24) and (25) (with $\phi > 0$ if there are spillovers from the exogenous technological frontier or $\phi = 0$ otherwise), (26) and (27). We assume that tax revenues are returned lump sum to the household and that subsidies can be financed by lump sum taxes on the household as needed.

From the first order conditions of the social planner's problem with respect to clean and dirty inputs, we have

$$\tilde{p}_{c,t} = \left(Y_t / Y_{c,t}\right)^{\varepsilon} u'\left(C_t\right) \text{ and} \tag{41}$$

$$\tilde{p}_{d,t} + \left(1-\Theta\right)\chi\nu_{\Phi,t} + \Theta\chi\left(\nu_{\Phi,t} - \nu_{\Psi,t}\right) = \left(Y_t / Y_{c,t}\right)^{\varepsilon} u'\left(C_t\right). \tag{42}$$

The Lagrange multipliers $\tilde{p}_{c,t}$ and $\tilde{p}_{d,t}$ are the current social values of clean and dirty goods respectively, while the multipliers $\nu_{\Phi,t}$ and $\nu_{\Psi,t}$ correspond to the constraints (26) and (27) respectively.

We see from equation (42) that the optimal carbon tax has two components, the first relating to permanent fraction of emissions and the second to the degradable fraction. From the first order conditions with respect to environmental quality and the degradable carbon stock, we obtain:

$$\nu_{\Phi,t} = \frac{\nu_{\Phi,t+1}}{1+\rho} + \frac{\tilde{p}_{c,t} Y_{c,t} + \tilde{p}_{d,t} Y_{d,t}}{\Phi_t} = \sum_{s=t}^{\infty} \frac{\tilde{p}_{c,s} Y_{c,s} + \tilde{p}_{d,s} Y_{d,s}}{\left(1+\rho\right)^{s-t} \Phi_s} \tag{43}$$

$$\nu_{\Psi,t} = \frac{1-\Delta}{1+\rho}\nu_{\Psi,t+1} + \frac{\Delta}{1+\rho}\nu_{\Phi,t} = \frac{\Delta}{1+\rho}\sum_{s=t}^{\infty}\left(\frac{1-\Delta}{1+\rho}\right)^{s-t}\nu_{\Phi,s} \tag{44}$$

Improving environmental quality increases clean and dirty productivity. Thus the current value of the environment is equal to the discounted value of these current and future outputs. The marginal social cost of degradable emissions is lower than that of permanent emissions. Equation (44) shows that the marginal social cost is reduced by $\nu_{\Psi,t}$, the present value of future removals associated with an initial emission of degradable carbon.

From firms' first order conditions for technology, we have

$$\upsilon_{j,t} = \frac{1}{1+\rho}\upsilon_{j,t+1}\left[1 + \eta_j s_{j,t+1}\left(1 + \phi\frac{D_{j,t-1} - 1}{D_{j,t-1}^2}\right)\right] + \frac{u'\left(C_t\right)}{A_{j,t}} z_{j,t}\,. \tag{45}$$

As in AABH (eq A.13), the shadow value of a technological improvement in the current period is equal to the shadow value of an improvement in the next period multiplied by that improvement, plus the marginal contribution to the current period's utility. For simplicity, consider the case with $\phi = 0$. Then from (45), we obtain

$$v_{j,t} = \frac{1}{A_{j,t}} \sum_{s=t}^{\infty} \frac{u'\left(C_s\right) z_{j,s}}{\left(1+\rho\right)^{s-t} A_{j,t}}. \qquad (46)$$

The social planner will allocate scientists to the sector in which the value of innovation $v_{j,t}\eta_j A_{j,t-1}$ is highest; thus to the clean sector when

$$\frac{\eta_c}{\left(1+\eta_c s_{c,t}\right)} \sum_{s=t}^{\infty} \frac{u'\left(C_s\right) z_{c,s}}{\left(1+\rho\right)^{s-t} A_{c,t}} > \frac{\eta_d}{\left(1+\eta_d s_{d,t}\right)} \sum_{s=t}^{\infty} \frac{u'\left(C_s\right) z_{d,s}}{\left(1+\rho\right)^{s-t} A_{d,t}}. \qquad (47)$$

Since R&D firms do not internalise the future value of their innovations, attaining the social optimum may require a subsidy to R&D. No subsidy will be needed in the case that it is socially optimal for all scientists to be allocated to one sector and private incentives are strong enough to achieve this allocation, because the supply of scientists is fixed. The case that interests us is where it is socially but not privately optimal to allocate all scientists to clean R&D. From (23) and (25), the subsidy $\xi_{c,t}$ must satisfy

$$\xi_{c,t} > 1 - \frac{\hat{\eta}^2}{\left(1+\eta_{c,t}\right)} \left(1 + \phi \frac{D_{c,t-1} - 1}{D_{c,t-1}^2}\right) \left(k'\left(A_{c,t}\right) - \frac{z_{c,t}}{A_{c,t}}\right) \left(1 + \phi \frac{D_{d,t-1} - 1}{D_{d,t-1}^2}\right)^{-1} \left(k'\left(A_{d,t}\right) - \frac{z_{d,t}}{A_{d,t}}\right)^{-1} \qquad (48)$$

to have $s_{c,t} = 1$.

From this expression, we see that the required clean R&D subsidy is lowered if the productivity of clean R&D is raised relative to that of dirty R&D. Intersectoral spillovers modelled according to (25) increase the productivity of R&D as a function of distance from the exogenous frontier. This has important implications for a transition to clean technology. Initially, while clean technologies are more backward spillovers will be larger in the clean sector. Not only will clean technology progress faster than without spillovers, but the switch to clean R&D can be achieved with a smaller clean R&D subsidy. As clean technologies draw ahead, dirty technologies will be advantaged by stronger spillovers. Here, our assumption that the 'advantage of backwardness' is bounded is important. It implies that any possible advantage of the dirty sector will be temporary.

NUMERICAL ILLUSTRATION

To assess the quantitative significance of technological embodiment, we present the results of simulations using a numerical implementation of our model. In the first part of this section, we describe calibration of the model. In the second part, we present the results of first-best policy simulations. Results are presented for versions with and without spillovers from the exogenous technological frontier. To distinguish the particular effects of technological embodiment, we compare these results with those from simulations of a comparable model in which technologies are disembodied, as in AABH.

CALIBRATION

We assume an elasticity of substitution $\varepsilon = 3$ between clean and dirty inputs in the final sector, as in AABH. In the clean and dirty sectors, we take capital shares to be $\alpha = 0.5$ and physical depreciation rates to be δ=0.05.[8] The capital shares represent a compromise between a plausible economy-wide (typically α=1/3 is assumed) and higher values characterising most energy and energy-intensive production.[9] Conveniently, with $\alpha = 0.5$ we have $\alpha = 1 - \alpha$ and therefore the same relationship between output and productivity gaps with embodied technical change as with disembodied change. We therefore choose the same values $\eta_c = \eta_d = 0.02$ as in AABH and this gives the same asymptotic growth rate of g=2%. Given these parameters, we calibrate the initial clean technology level such that the initial clean output share is 25%. This value gives qualitatively plausible responses and is probably conservative because it implies that 45 years are required for the clean sector to attain the initial productivity of the dirty sector when it does not benefit from spillovers from the exogenous technological frontier.

We characterise instantaneous utility as

$$u\left(C_t\right) \equiv \frac{C_t^{1-\sigma} - 1}{1 - \sigma} \tag{49}$$

where $\sigma > 0$ is the intertemporal elasticity of substitution. We assume an intertermporal elasticity of substitution of $\sigma = 1.5$. This is close to the value of 1.4 assumed in DICE

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[8] In the numerical model we use time-steps of five years and convert annual values to five-yearly values.

[9] As with the difficulties noted in the context of intersectoral technology spillovers, this tension could be resolved by introducing a third sector representing non-energy-intensive production.

2013 but significantly lower than the value of 2 assumed in AABH. We assume a pure rate of time preference of 1.25% per annum. The long run interest rate ($i = \rho + \theta g$) is therefore 4.25%, the same value as in DICE.

Initial capital stocks are calibrated so that in the absence of climate damages or climate policies (but with subsidies to correct the monopoly distortions in capital rental markets) the economy is on a smooth transition to asymptotic specialisation in dirty production. We will refer to this path below as the 'baseline'. However, it must be recognised that because it assumes away damages for climate change, it not actually a feasible path for the economy. The procedure used to calibrate initial technology, capital levels and the dirty sector emissions intensity is detailed in appendix 1.

To isolate the effects of technological embodiment, we compare our results with those from a comparable model with disembodied technologies. This latter model is as in AABH, except for the different parameterisation and different specification of the climate subsystem and impacts. The baselines of the two models are not identical because of the models' different dynamic responses on the transition path. However, levels of output and emissions are similar even after two centuries. Significant differences in optimal policies and economic outcomes are therefore attributable to the embodiment or disembodiment of technologies.

In the version of the model with spillovers from an exogenous technological frontier, we choose $\phi = 1/2$. With this choice, the strength of spillovers is close to that which would be obtained from a Cobb-Douglas specification with an exponent of $\beta = 1/3$ for the external knowledge stock. This latter value is based loosely on Braun *et al.* (2010), who find that that for wind technology innovations, the coefficient on the (domestic) wind technology knowledge stock is 2-3 times as large as that on the (domestic) stock of 'related' technological knowledge. The initial rate of progress of clean technologies rises from 2% p.a. to 2.6% p.a..

First best policies

In all three cases, climate policies induce immediate specialisation in clean R&D. With disembodied technologies (dotted curves labelled 'DISEMB'), dirty taxes rise at a roughly constant rate that only slows significantly towards the end of the second century (Figure 1). With embodied technologies but without spillovers (solid curves labelled

'EMB'), the initial rate of dirty tax is similar (1.36% vs. 1.32%)[10] but the rates increases almost three times as fast. The rate of increase is declining though, so that after around six decades, rates in the two models move roughly in parallel: those in the model with embodied technologies are ~0.9% higher. When spillovers from the exogenous technological frontier are modelled (dashed curves labelled 'EMB & EX SPILL'), the dirty tax is initially set slightly lower (1.20%) and again rises fast over several decades. In the longer term, dirty taxes rise faster with spillovers than without. From the latter part of the second century, the model with spillovers from the exogenous technological frontier gives the highest dirty tax rates.

Clean R&D subsidies start higher and fall more slowly when technologies are embodied than when they are disembodied (Figure 2). When spillovers from the exogenous technological frontier are modelled, subsidies can be slightly lower and are phased out sooner. Such spillovers initially increase the productivity of clean R&D relative to dirty R&D, both lowering the necessary R&D subsidy (see equation (48)) and permitting faster progress of clean technologies. However, once clean technologies overtake dirty technologies, the advantage in R&D productivity switches to the dirty sector. R&D subsidies nevertheless remain lower than in the case without spillovers, implying that increased demand for clean investment outweighs this advantage. That is, the modernisation effect dominates the obsolescence effect. After 65 years, R&D subsidies are no longer needed.

[10] In the model with embodied technologies, an initial *ad valorem* tax of 1.36% on the dirty sector implies a carbon tax of around US$24/t CO_2, given global emissions of 37Gt CO_2 and dirty output accounting for 80% of a gross world production of US$80b.

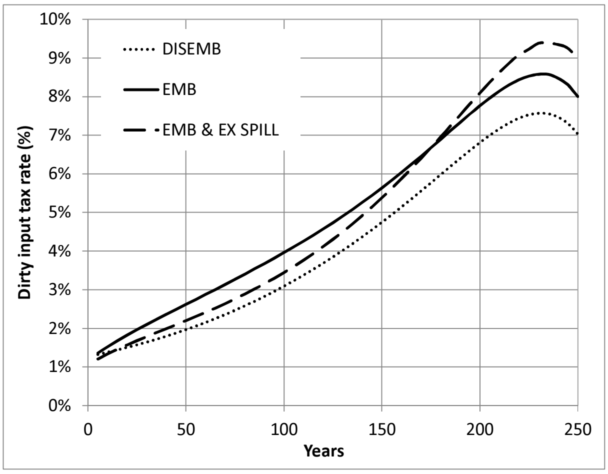

Figure 1 – Dirty input tax rates

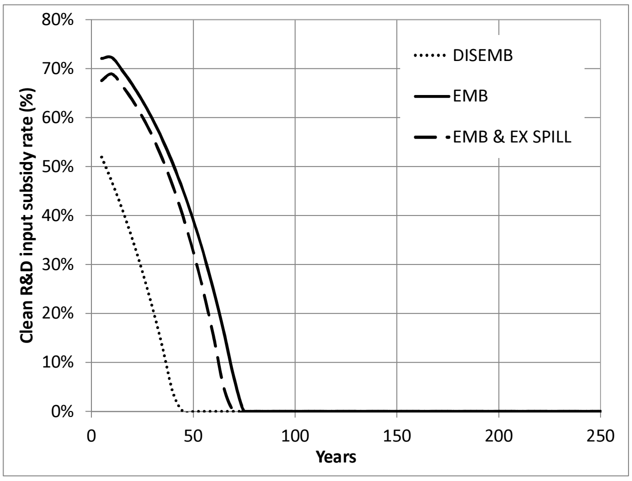

Figure 2 – Clean R&D subsidies

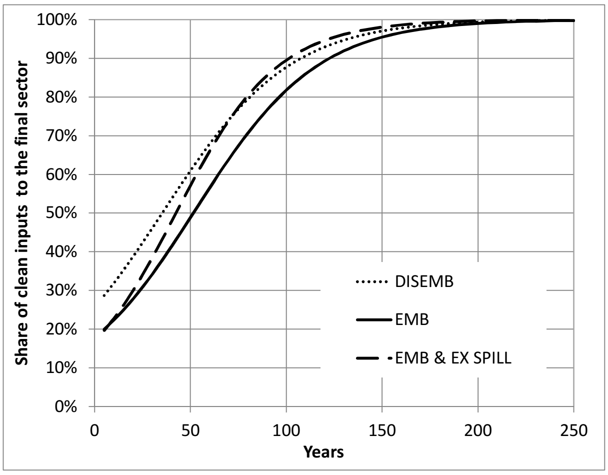

Figure 3 – Clean input share

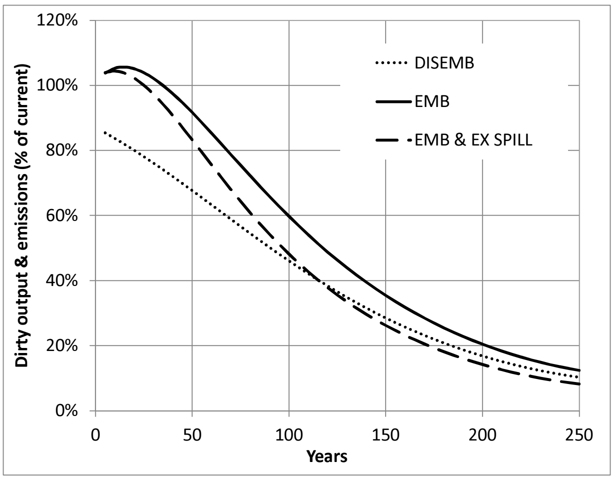

Figure 4 – Dirty output & CO_2 emissions

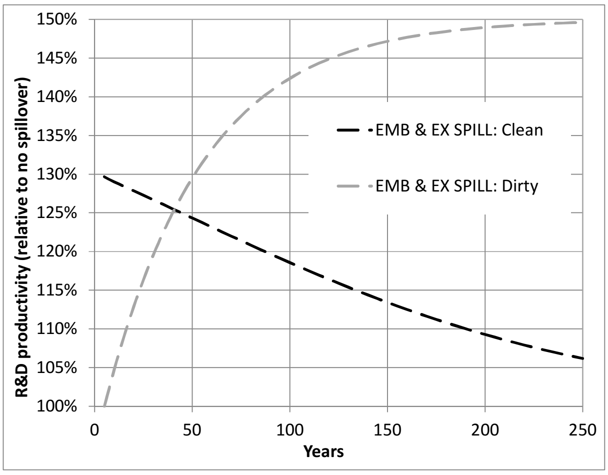

Figure 5 - R&D relative productivity with spillovers

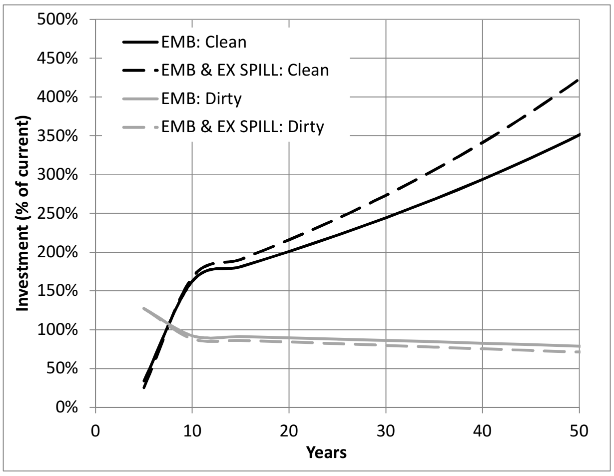

Figure 6 – Clean and dirty investment

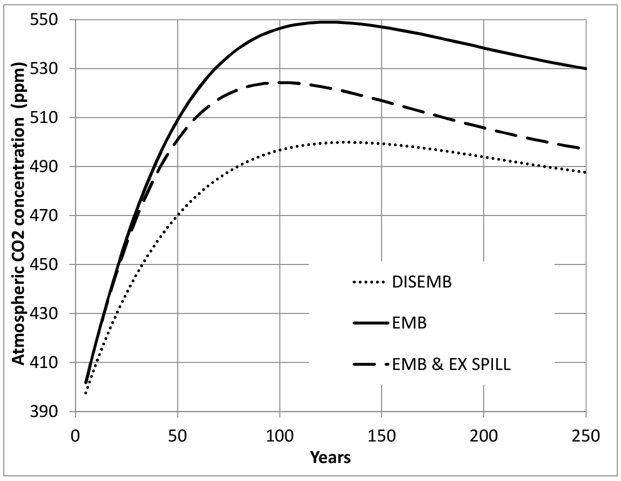

Figure 7 – Atmospheric CO_2 concentration

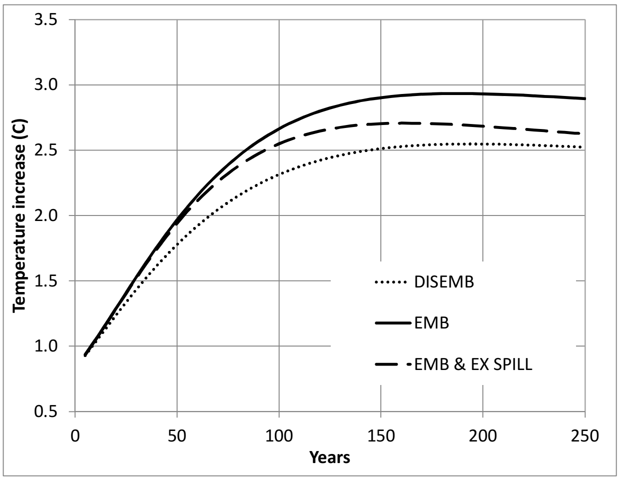

Figure 8 – Atmospheric temperature increase

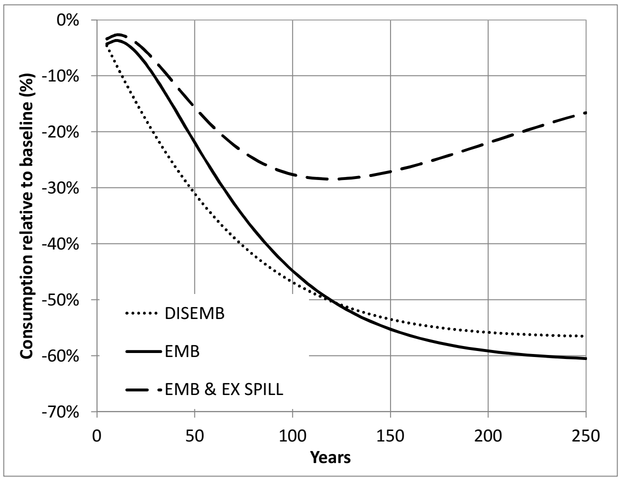

Figure 9 – Consumption relative to baseline

Figure 3 shows clean inputs as a share of final sector inputs while Figure 4 shows dirty output relative to its pre-initial level. With embodied technologies, the immediate response is a reduction in the share and even the absolute level of clean output (recall that the pre-initial share is 25%). This is in contrast to the case of disembodied technologies, where there is an immediate increase in the share and level of clean output. These results accord with our theoretical analysis of a switch from dirty to clean R&D (see equations (39) and (40)). Initially, the switch of obsolescence costs from the dirty to the clean sector causes the optimal stock of dirty capital to rise and that of clean capital to fall, despite the improvement in clean technology. Even in the long run, the clean to dirty output ratio lags the clean to dirty technology ratio, as seen in equation (38). This inertia in the accumulation of clean capital can also explain the fact that R&D subsidies must be higher with technological embodiment, as observed above.

When spillovers from the exogenous technological frontier are introduced, the share of clean output rises much faster. The level of dirty output falls faster too. Figure 5 shows R&D productivity with spillovers relative to productivity without spillovers. Productivities are equal when clean and dirty technologies are neck and neck. In the clean sector, spillover strength slowly decline towards zero as the productivity of clean technologies approach productivities defined by the exogenous frontier asymptotically. This convergence is very slow because spillovers are relatively weak with our choice of $\phi = 0.5$. In the dirty sector, spillovers approach their maximum strength asymptotically.

Figure 6 shows clean and dirty investment over the first five decades relative to pre-initial levels in the two specifications of the model with embodied technologies. Dirty investment initially rises while clean investment initially falls dramatically. These results make the obsolescence effects even clearer than do the changes in output. When obsolescence effects switch from the dirty to the clean sector, there is sudden increase in the optimal stock of dirty relative to clean capital. This explains the very high dirty investment and very low clean investment in the first period. Spillovers have little influence on these initial responses. Over time though, the faster improvements of clean technologies result in higher levels of investment.

Figure 7 shows atmospheric CO_2 concentration [11] while Figure 8 shows temperature rises above a pre-industrial average in the three models. In the model with disembodied technologies, the maximum temperature rise is 2.5°C. This temperature is reached after almost two centuries, although most of the increase occurs over the first century, during which time atmospheric CO_2 concentrations are also rising. With technological embodiment, the maximum temperature rise is 2.9°C. This higher maximum reflects the higher economic costs of mitigation resulting from embodiment. With spillovers from the exogenous technological frontier, the maximum temperature rise is 2.7°C and occurs three decades earlier. This reflects the fact that mitigation costs are initially high, due to embodiment, but lower in the long term, due to more rapid clean progress and accumulation of clean capital. Recall that in this specification,

[11] We convert GtC in the numerical model to concentrations in ppm using a factor of 2.13 GtC per 1ppm, given by the Carbon Dioxide Information Analysis Center (CDIAC): http://cdiac.ornl.gov/pns/convert.html#3.

mitigation costs eventually approach zero as clean technologies approach the exogenous technological frontier.

Figure 9 shows consumption relative to the baseline path. The slower switch from clean to dirty production that occurs with embodiment has one advantage: considerably less foregone consumption over almost a century. Over the third and fourth decades, losses relative to the baseline are 10% less with embodiment than without. In the very long run though, costs to consumption are greater with embodiment. This is firstly because damages are higher and secondly because higher dirty taxes are required. Furthermore, the dirty output share is also slightly higher due to the inertia caused by clean sector obsolescence costs. Spillovers from the exogenous frontier further reduce consumption losses over the first century. After 120 years, relative consumption losses are decreasing.

Conclusions and recommendations

We have presented an analytically tractable model of DTC and the environment, in which clean and dirty technologies are embodied in capital stocks. We have characterised the decentralised equilibrium and the structure of socially optimal policies. With the embodiment of technologies in capital, technological progress in the clean or dirty sector generates obsolensce costs, which add to the user cost of capital in that sector. Climate policies induce a switch from dirty to clean R&D. The disappearence of obsolescence costs from the dirty sector and their appearance in the clean sector causes dirty output to rise and clean output to fall in the short run. The modernisation effect of clean technical progress dominates in the long run, but obsolescence costs cause the accumulation of clean capital to lag the accumulation of clean technological knowledge.

Optimal policies consist of (i) a capital rental subsidy that corrects for monopoly distortions (ii) taxes on the dirty input that corrects for the costs of climate change and (iii) subsidies for clean R&D that correct for intertemporal and (if present) intersectoral technology spillovers. This basic structure of climate policies is independent of the nature of technologies. However, the high initial mitigation costs and ongoing inertia that result from capital-embodiment have significant quantitative effects. Clean R&D subsidies must be higher and maintained longer. Emissions taxes must be higher in the long term. However, these higher tax rates should be reached from a relatively low initial level that is increased more rapidly than usually suggested (i.e. initially increasing at well above the interest rate). This argument for setting relatively low taxes initially is similar to that of Schwoon and Tol (2006), who motivate it as a result of capital adjustment costs.

Including spillovers from an exogenous technological frontier in our model with embodied technologies reduces mitigation costs in the medium and long term. In our numerical simulations, clean R&D subsidies are slightly lower and as are (at least, for the better part of two centuries) dirty input taxes. The device of the exogenous technological frontier is more consistent with evidence on the sources of spillovers and the sources of R&D in energy technologies than an alternative specification of direct spillovers between clean and dirty technologies. Nevertheless in reality, some crowding out of non-energy R&D by clean R&D could weaken the benefits of spillovers to clean energy R&D unless it were offset by relatively large spillovers from clean energy R&D. The existence of limited direct spillovers between clean and dirty technologies would be beneficial initially, but damaging later once clean technologies overtook dirty technologies. This would imply higher and protracted use of clean R&D subsidies in the medium term.

The model we have presented is highly stylised and could be usefully be extended in several ways. Most importantly, a third, non-energy-intensive sector could be modelled explicitly. [12] This would allow a more comprehensive investigation of intersectoral spillovers and crowding out. It would also be easier to determine appropriate parameter values of such a model. Ideally, parameters should be directly estimated, as in Dechezleprêtre *et al.* (2013). While we obtain clearer theoretical results by assuming a fixed supply of R&D (as in AABH), it would be more realistic to endogenise the supply of R&D (Hourcade et al. 2011). With this modification, interactions between the processes of capital and accumulation could be more fully examined. Finally, sector-specific investment taxes and/or subsidies could easily be

[12] This approach is taken by Hemous (2013), who extends the AABH model of disembodied directed technical change to three sectors and two regions linked by international trade.

introduced into the model. This would enable investigation of clean investment subsidies (widely used in practice) as a second-best instrument of climate policy.

Acknowledgements

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA grant agreement n° 328454.

Appendix 1 – Calibration procedure

Given any technology levels and interest rates, the values of all other variables in the model can be calculated sequentially. We know that in the absence of climate damages, there will be only dirty R&D. Therefore, our approach is therefore to guess a sequence of interest rates and initialise other variables consistent with these rates. However, these initial values will not satisfy the Euler equation. We therefore solve the model numerically to determine the baseline equilibrium.

To calibrate the initial levels of clean technology and of clean and dirty capital, we need the initial value of the interest rate. We estimate an approximate initial interest rate in three steps:

1. Assume that the interest rate is constant at its asymptotic value and calculate the values implied for the other model variables. The order of calculation is: initial capital rents, the initial level of clean technology, then the complete time series for clean technology, capital prices, capital rents, labour allocations, clean and dirty goods prices, capital stock levels, clean and dirty output, final output, investment and consumption.
2. From the path of consumption derived in the first step, use the Euler equation to calculate the implied interest rates.
3. Using the initial interest rate from step 2, recalculate the initial levels of clean technology and of clean and dirty capital. These and the initial technology levels are then fixed to solve the baseline.

From the baseline scenario, we calibrate the dirty sector emissions intensity to match global emissions of 9.7Gt CO_2 p.a. in the first period.[13] Parameters and initial conditions of the climate sub-model are exactly as in DICE 2013.

Acknowledgments

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2013) under REA grant agreement no. 328454.

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