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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 stocks. Switching from dirty to clean innovation leads to ongoing reductions in the relative costs of producing clean investment goods, making them ever cheaper to purchase and so encouraging clean investment. At the same time, falling replacement costs imply falling asset values. Consequently, continuing innovation in capital-embodied clean technologies also generates obsolescence costs, which are borne by users of clean capital. The negative effect of obsolescence costs on demand for clean investment and consequently on the speed of transition to clean growth has been neglected in the literature on directed technical change.

We show theoretically and using numerical simulations that optimal policies differ in our model of embodied technological change, relative to an otherwise comparable model of disembodied technological change. With embodied technologies: (i) optimal emissions taxes start higher and rise faster; (ii) much higher clean research and development subsidies are required to effect the switch to clean innovation; and (iii) climate damages under optimal policies are greater. We suggest that more attention should be paid to the role of obsolescence costs in modelling transitional effects of climate policies.

1. Introduction

The Copenhagen Accord (UNFCCC, 2009) expresses broad international consensus that actions should be taken to keep global warming below 2 °C. Doing so will require rapid and extensive development of and investment in carbon-free technologies over the next several decades (Edenhofer et al., 2010; Luderer et al., 2012).[1] In this context, two questions of current interest are: (i) what policies are required to incentivise firms to redirect innovation from emission-intensive ('dirty') to emission-free ('clean') products and industries?; and (ii) how quickly can emissions be reduced, given such a redirection of technical change? In this paper we examine how embodiment of clean and dirty technologies in long-lived capital stocks affects the answers to these two questions.

The nature of energy and other emissions-intensive sectors suggests that many of the relevant technologies are embodied in long-lived capital stocks. Studying changes in energy intensity over four decades in the United States, Sue Wing (2008, p47) attributes the majority of energy intensity reduction within industries to capital-embodied technological change. More direct evidence can be found in bottom-up studies of particular energy-intensive technologies or 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. It is therefore important to understand the implications of technological embodiment for the transition from dirty to clean growth.

Innovations in capital-embodied technologies make new vintages of capital equipment cheaper to purchase and/or more productive. Firms wishing to adopt new capital-embodied technologies must make corresponding investments. Boucekkine et al. (2005), refer to the consequent productivity growth as the 'modernization effect' of embodied technological change. They contrast this with the

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[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 9.5 GtC while cumulative emissions from all sources had reached 555 GtC (IPCC, 2013: p10).

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'obsolescence effect' of embodied technological change. With ongoing innovation in capital-embodied technologies, users of capital make current investments with the expectation that they will be able to purchase an effective unit of capital more cheaply in the future. Falling (quality-adjusted) prices of investment goods reduce the value of capital assets already held and so add to the users' costs of capital. Other things being equal, a higher user cost of capital lowers capital demand, and consequently also investment demands.

To analyse the obsolescence and modernization effects of capital-embodied technological progress on the transition from dirty to clean growth, we develop a model that incorporates investment-specific technical change à la Krusell (1998) within the Directed Technological Change (DTC) framework proposed by Acemoglu et al. (2012); henceforth, AABH. As in AABH, a final good is produced from clean and dirty intermediates and emissions are proportional to dirty sector output. Intermediates are produced using labour and a continuum of sector-specific machines. Research and development (R&D) reduces monopolistic firms' costs of producing machines. The key difference in our model is that machines depreciate slowly, whereas in AABH they are fully depreciated each period. Firms in our model therefore increase their existing stocks of machines by making new investments.

We first examine how obsolescence costs alter the path of the transition from dirty to clean growth. Commencing clean innovation generates obsolescence costs for users of clean capital, while ceasing dirty innovation eliminates obsolescence costs previously borne by users of dirty capital. These changes in obsolescence costs depress clean investment demand and boost dirty investment demand. In the short run, dirty output may even increase as a consequence. In the long run, the modernisation effect dominates and the economy follows a clean growth path. Nevertheless, obsolescence effects create a permanent lag in the accumulation of capital embodying clean technologies, relative to the accumulation of clean technological knowledge itself.

We also show, theoretically and using numerical simulations, that optimal policies differ in our model of embodied technological change, relative to an otherwise comparable model of disembodied technological change. With embodied technologies: (i) optimal emissions taxes start higher and rise faster; (ii) much higher clean research and development subsidies are required to effect the switch to clean innovation; and (iii) climate damages under optimal policies are greater.

The paper is structured as follows. In Section 2, we review related empirical and theoretical literature. In Section 3, we describe our model of the economy and of the environment. In Section 4, we analyse responses to R&D policies and show how obsolescence effects may temporarily dominate modernization effects as innovation switches from dirty to clean technologies. Optimal policies are analysed in Section 5. In Section 6, we describe our numerical calibration of the model and present results of optimal policy simulations. These simulations are also run using a model in which technologies are disembodied but that is comparable in all other respects. In this way we can quantify the implications of technological embodiment. In the final section, we present our conclusions and make suggestions for future research.

2. Related literature

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 that model, a 'planned obsolescence effect' results from firms' optimal allocation of resources between investment and R&D. In the decentralized economy, obsolescence costs depress investment and R&D, and growth is lower than is socially optimal. In a similar framework, focussing on development, Boucekkine et al. (2005) emphasize the modernization effect of investment in new capital, demand for which incentivises R&D.

Our focus on capital-embodied technological change is motivated by a number of empirical studies in the literature on climate mitigation that emphasize the slow rate at which energy-intensive capital turns over. Lecocq and Shalizi (2014, p197) estimate that 40% of global emissions originate from the energy, transportation and housing sectors: these sectors depend heavily on long-lived capital stocks. Considering only direct energy and process emissions, Davis et al. (2010) estimate that existing capital assets will generate cumulative additional CO_2 emissions of 136 GtC over their lifetimes.[3] These and other similar studies are concerned with accounting for existing stocks of dirty capital and projecting required rates of clean investment. The one empirical study of which we are aware that is specifically concerned with obsolescence effects in the energy sector is Gibbons (1984). He finds evidence of obsolescence effects in the fact that average lifetimes of fixed U.S. manufacturing assets fell sharply following the 1973 Arab oil embargo.

As in the model of AABH, described in the previous section, most theoretical models of DTC and the environment abstract from interactions between processes of innovation and capital accumulation: technologies in these models are disembodied. For example, in Smulders and de Nooij (2003), technology augments either labour or energy inputs in an aggregate production function. van Zon and Yetkiner (2003) develop a model in which R&D increases both the number of capital varieties and their embodied energy efficiency. However, they assume a fixed ratio between the rates of these two types of technical change. Schwoon and Tol (2006) consider the implications of real adjustment costs in the accumulation of mitigation knowledge; whether by means of R&D investments or learning-by-doing. While their mechanism introduces inertia into the knowledge accumulation process, there is no interaction with the accumulation of physical capital, as in our model.

Accumulation of clean and dirty capital in a two-sector AK growth model is studied in van Zon and David (2013) and van Zon (2016). Growth is the direct result of accumulating capital in three phases: (1) accumulation of and production using dirty capital; (2) accumulation of clean capital and production using both clean and the remaining dirty capital; and (3) accumulation of and production using only clean capital (with any remaining dirty capital scrapped). In an extension of their basic model, van Zon and David (2013) allow also for endogenous R&D on the clean technology.[4] However, they treat R&D as increasing returns to new and existing clean capital alike. This does not generate the type of obsolescence costs with which we are concerned here.

Pottier et al. (2014) test several key assumptions in AABH of which they are highly critical. One of their arguments is that embodiment of relevant technologies in long-lived capital stocks is important to the effective elasticity of substitution between clean and dirty goods. We address this issue by modelling such technological embodiment explicitly. We also agree with these authors that the climate system is modelled in AABH in a way that significantly overestimates the available carbon budget. We address this by employing the same two-stock model of carbon accumulation as in Pottier et al. (2014) in the theoretical part of our paper. For numerical simulations, we employ the climate component of the established DICE integrated assessment model (Nordhaus and Sztorc, 2013).

Mattauch et al. (2015) replace R&D in the AABH framework with a learning-by-doing specification in which cumulative clean production generates spillovers that increase productivity in the clean sector. Their contribution is complementary to ours in considering the importance of learning effects, as well as the role that public investments in infrastructure may play in making clean technologies

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

[3] See note 1 regarding the available carbon budget.

[4] To avoid explosive clean growth, R&D decrease with distance to an exogenous clean technology frontier.