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Phasing out a polluting input in a growth model with directed technological change[☆]

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ABSTRACT

This paper explores the potential conflict between economic growth and the environment, and the optimal long-run environmental policy. It formulates a growth model with directed technological change and focuses on the case with low elasticity of substitution between clean and dirty inputs in production. New technology is substituted for the polluting input, which results in a gradual decline in pollution along the optimal long-run growth path. In contrast to some recent work, the era of pollution and environmental policy is here not just a transitory phase in economic development. This result means that the government's continuous efforts to reconcile economic growth and the environment will always be needed. The socially optimal policy includes a perpetual subsidy to 'green' research. The tax rate of pollution is monotonously increasing, while the pollution tax payments constitute a constant share of income. These policies result in a quite modest growth drag.

1. Introduction

Economic growth is potentially harmful for the environment.[1] This possible conflict can however be mitigated by technological change, for example in the process where clean production inputs are substituted for polluting inputs. Innovations with such capacities are not least important in the transformation of the energy system, where fossil fuels are gradually replaced by renewable sources of energy, such as solar and wind power.[2] To analyze various issues related to these aspects of economic development, endogenous growth models have been presented where innovative efforts can be directed to make production cleaner.[3] Such models are in particular useful for analyses of the optimal long-run environmental policy.

In a very influential article Acemoglu et al. (2012) (hereafter: AABH) use such a model to analyze the problem of climate change. Focusing on the case with a high elasticity of substitution between clean and polluting inputs in production, they show that a sustainable long-run growth can be obtained by merely a temporary policy that promotes 'clean' innovations. After this transitory period the clean input/technology will be superior, since it has become more competitive due to learning effects. This means that the era of pollution and environmental policy becomes just a limited episode in economic development.[4] The policy recommendations from this analysis put a remarkably strong emphasis on subsidies to research in clean technologies, while the Pigouvian tax on pollution is quite moderate. The motivation for this is that the effects of the positive knowledge externalities in 'clean' research are so strong that it is not worth disturbing present production by a high pollution tax. These findings are closely linked to the assumption of a high elasticity of substitution.

This paper adds to the insights in AABH by exploring the case with low substitution possibilities in a somewhat different model. This generates a quite different growth path and very different policy

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[1] A higher material throughput tends to result in more emissions of wastes that are directly unhealthy and also damaging to ecosystems upon which we rely. The environmental history of the 20th century, boldly summarized in Table 12.1 of McNeill (2001), indeed shows many disturbing trends, for example in terms of lost species and increasing pollution. See also Rockström et al. (2009) for warnings that the trend starting with the Industrial Revolution may be leading to serious environmental instability.

[2] See Yergin (2011) and Stern (2003) for broad expositions of recent developments in renewable-energy technologies.

[3] This literature builds on Acemoglu (1998) and Acemoglu (2002). An early application to environmental issues is Grimaud and Rouge (2008). Another early article that considers both ordinary and environmentally-oriented research is Hart (2004). Smulders and Nooij (2003) uses directed technological change to analyze the problem of energy conservation.

[4] A subsequent paper, Acemoglu et al. (2016), even assumes an infinite elasticity of substitution in a model with more detailed descriptions of innovations, employment and production. An earlier paper in the same spirit is Tahvonen and Salo (2001), but their production structure is simpler and technological progress comes from a simple learning-by-doing effect.

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implications. The case with low substitution possibilities is interesting in the light of the meta analysis in Stern (2012), which provides empirical support for the assumption of a low elasticity of substitution between different types of energy. The first important respect in which the model differs from AABH is that I here make a clear distinction between the 'energy' inputs and the technology components that are complementary to them.[5] This explicit modeling of the saving of some of the polluting input by technological change is necessary to make feasible the phasing out of a polluting input in the case of complementarity. By contrast, AABH put all this together in a composite input, which makes it impossible to substitute technology for dirty energy.[6] Second, the disutility of pollution is in AABH derived from the polluting input *and* the machines that are used together with it. Here I make the more natural assumption that the disutility stems solely from the dirty input.

A result of these modifications is that the efforts to reduce the use of the polluting input go on forever here. In AABH, the green technology comes out as the winner once and for all, after an intense initial effort to make it competitive. Thereby the conflict between growth and the environment is forever eliminated in the baseline case of their model.[7] The assumptions chosen here imply that it will always be costly to keep pollution low and that the government's continuous efforts to reconcile economic growth and the environment will always be needed. Behind this choice is the notion that it will always be possible to produce at lower costs by being more careless with the wastes of production.

An other notable difference in the results, compared to AABH, is that the optimal growth path has a considerably different character. Here the polluting input will be used all along the long-run growth path, although in a gradually decreasing quantity. The decline in the use of the dirty input is possible because of the growth in the technology factor that is complementary to it, which makes the use of the dirty input more effective. The intense research that makes this possible has an opportunity cost in terms of slower growth in a second technology factor, with the consequence that income growth is reduced. This is an instance of the tradeoff between growth and the environment that is so prevalent in models of this kind. An expression is derived for the magnitude of the reduction in the growth rate that the optimal policy to phase out pollution causes. Some simple calculations indicate that this long-run growth drag may be quite modest or at least acceptable in the light of the improved environment: it is estimated that between 10% and 30% of the long-run growth rate is lost when the optimal environmental policy is implemented.

There are also considerable differences in the policy implications between this paper and AABH. First, the optimal pollution tax rate is more prominent here. It is monotonously increasing over time but the pollution tax payments will constitute a constant share of GDP on the long-run growth path, due to the downward trend in the quantity of pollution. Secondly, the optimal policy package includes a perpetual subsidy to clean research, in a range that is estimated to run from 15% to 30% of the cost. This contrasts with the result in AABH, where the corresponding subsidy declines to zero in finite time.

Economists have examined the relation between growth and pollution at least since the start of the limits-to-growth debate that followed the publication of Meadows et al. (1972). Two early articles that analyze the dampers that the optimal management of pollution puts on growth are Keeler et al. (1972) and Brock (1977). Since these models lack endogenous technological change it is not possible to analyze how different policy instruments can be used to stimulate research and development. For examples of early endogenous growth models with pollution, see Bovenberg and Smulders (1995) and Stokey (1998).[8] An analysis of environmental problems in a growth model with creative destruction is found in Aghion and Howitt (1998). Grimaud (1999) describes a policy that makes the decentralized market economy follow the socially optimal growth path in this model. Reviews of this large literature are found in Brock and Taylor (2005), Xepapadeas (2005) and more recently in Smulders et al. (2014).

In addition to the papers cited above, the analysis in Golosov et al. (2014) of how an optimal tax on greenhouse gases should be designed is very interesting in this context. That paper follows the real-business-cycle literature more than the growth literature, thus excluding endogenous technological change. It includes, however, a quite detailed description of the carbon cycle. The model is used to simulate different possible development paths for the economy and for the climate. A similar analysis is performed by van der Ploeg et al. (2014), with more general assumptions about for instance the utility function and the costs of extracting oil. Gerlagh et al. (2014) study the optimal time path of an economic policy that is intended to support the development of clean energy. In addition to the policy instruments that have been mentioned above, they also use the patent life length. In a very interesting article Jones (2016) develops a growth model where some technologies are beneficial while others are harmful and even life-threatening. This leads to a tradeoff between safety and consumption growth, which may result in a consumption growth that is much lower than what is feasible.

Finally, the optimal solution to the model involves a kind of transition between two energy regimes. This puts an element of non-balanced growth into the model. Therefore the analysis is also based on the works by Kongsamut et al. (2001) and Acemoglu and Guerrieri (2008), where growth is balanced only asymptotically.

This paper proceeds as follows. The model is presented in Section 2. Section 3 derives and analyzes the conditions for social optimum. In Section 4 the decentralized solution is derived and Section 5 develops the policies required to attain social optimum in a decentralized economy. Section 6 extends the model to stock pollution and Section 7 concludes the paper. Some derivations are put into Appendix A, while some longer (and standard) derivations are found online in Appendixes B and C.

2. The model

The production structure of the model is very similar to that in Acemoglu (2002), and it will therefore be presented quite briefly. There are three types of firms, producing: (1) final output; (2) intermediate inputs; and (3) machines that are combined with 'energy' to produce the intermediate inputs. In addition, there are also innovating firms.

Final output is produced by a large number of firms in a competitive environment. They all use labor, L, and two composite inputs, Y_D and Y_Z. The representative production function is

$$Y(t) = AL^{1-\alpha}\left[\gamma_D Y_D(t)^{\frac{\varepsilon-1}{\varepsilon}} + \gamma_Z Y_Z(t)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\alpha\varepsilon}{\varepsilon-1}}. \quad (1)$$

It is assumed that $0 < \alpha < 1$, $0 < \gamma_D < 1$, $0 < \gamma_Z < 1$, $\gamma_D + \gamma_Z = 1$, and $0 < \varepsilon < \infty$. This is a constant-returns-to-scale function in L, Y_D and Y_Z. All technological change takes place in Y_D and Y_Z, but since the overall

[5] Although the inputs will be called (clean and dirty) energy the pollutants in this paper may be other substances than greenhouse gases, such as sulphur dioxide, tropospheric ozone and particles, which means that the environmental problem addressed here is not necessarily climate change. The model can thus be used to analyze the relationship between economic growth and pollution in general.

[6] This choice between various ways of modeling the source of pollution in the model echoes a long-standing theme in the literature. For example, in Michel and Rotillon (1995) pollution is proportional to final output, while it is proportional to a polluting input in Schou (2000).

[7] AABH have a middle case called 'weak substitutes', which means that the elasticity of substitution is higher than 1 but not sufficiently high. It has properties that are partially similar to what is found here, but even in this case clean innovations will become dominant in finite time so that subsidies to research are no longer needed. The tax on GHG emissions is not temporary. They do not analyze what time paths pollution and the tax take in this case.

[8] For a recent elaboration on Stokey (1998), see Aznar-Marquez and Ruiz-Tamarit (2016).