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Escaping Lock-in: The Scope for a Transition Towards Sustainable Growth?

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SUMMARY

In this paper we develop a simple endogenous growth model with two competing production technologies and learning spillover effects between firms that use the same technology. Investments are directed to the technology with highest current and expected returns. Since current investments increase future returns through learning, the economy will usually lock in, that is specialise in one of the two technologies. In case the economy has selected a relative polluting technology, sustainable growth requires a transition towards the clean technology. We analyse the scope for (environmental) policies that induce such a transition.

Keywords: Endogenous growth, lock-in, transition, convergent expectations

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CONTENTS

1. Introduction

Many are concerned that a continuously growing world economy is at odds with the inherently limited supply of natural resources as well as with the solution of environmental problems caused by increasing levels of various emissions. Matching exponential output growth with limited resource inputs and limited absorption capacities of ecosystems will require production to become less dependent upon the use of natural resources and less polluting per unit of output. This makes it clear why the direction of technological change, towards 'clean' or resource extensive technologies, is an essential parameter determining the feasibility of sustainable development. Searching the literature for a model to study the issue, we find two classes of models looking into the sources of technological progress, the neo-classical endogenous growth models, and the so-called evolutionary growth models.

Neo-classical growth theory has its roots in the 1950s when Solow (1956) and Swan (1956) developed their theoretical framework for understanding world-wide growth of output. Still, in the Solow-Swan model, technological progress is exogenous; long-run growth comes like 'manna from heaven'.[1] The model offers no clue as to the sources of economic growth and the bias of technological change in the long run. In the 1980s, the growth model was further developed leading to the so-called new or endogenous growth theory emerging in the early 1990s (e.g. Romer, 1990, Rebelo, 1991).[2] This new growth theory explicitly describes two sources of technological change, non-intentional learning and intentional research and development. An important contribution of new growth theory is that it enables the study of policies that enhance or direct learning and research, and it enables the analysis of welfare implications of different directions and levels of economic growth.

In the late 1990s, the new growth theory was linked to the issue of sustainable development. In several articles, implications of environmental policies on economic growth were studied. Also, the more fundamental question was raised whether sustained economic growth is compatible with the conservation of the environment (Bovenberg and Smulders 1995, Smulders 1995, and Hofkes 1996). The conclusion emerged that sustainable development and economic growth can go

[1] The Solow-Swan model can explain the stylised facts on growth as listed by Kaldor (1961), but it has heavily been criticised for its prediction of convergence between rich and poor countries. There is now a broad literature on absolute and conditional convergence; we leave the subject aside, however.
[2] See [Jones and Manuelli 1997] for an overview of endogenous growth models.

together if there is a steady flow of technological innovations that increase the efficiency of resource use (Aghion and Howitt 1998, Ch. 5). Yet, the typical endogenous growth model has an important omission. It does not diversify between 'clean' and 'dirty' technologies, while this distinction is believed to be the key to the understanding of sustainable economic development. The concerns about climate change are a case in point. There is increasing support for the idea that, if substantial carbon dioxide emission reductions are aimed for, a technological transition away from hydrocarbon based energy sources towards non-carbon energy sources will be needed. However, the common endogenous growth models with natural resources treat sustainable development as a uniform decrease of the environmental intensity of production, without distinguishing 'clean' from 'dirty' production technologies.

At the same time, the focus on technological diversity is one of the major elements in the class of evolutionary models (e.g. Nelson and Winter, 1982), which has its roots in the Schumpetarian tradition. Evolutionary models typically describe a divers set of technologies,[3] a diversification mechanism broadening the set, such as the arrival of random innovations, and a selection mechanism for the reproduction of specific technologies. Jointly, the continuous diversification and selection mechanisms cause a drift in the characteristics of the current technology set. Those technologies that are most successful given the economic environment, the institutions, and policy regulations, are the fittest and will be reproduced.

Within the context of evolutionary models, technological regimes, technological transitions, and technological lock-ins play a central role (see e.g. Dosi, 1982, Nelson and Winter, 1982, Arthur, 1989). Following Street and Miles (1996), a technological regime refers to "the whole complex of scientific knowledge, engineering practices, process technologies, infrastructure, product characteristics, skills and procedures which make up the totality of a technology." In the context of this paper, where we abstract from a detailed analysis of most of these elements, we will use the term technology cluster instead of the term technological regime. Many spillover effects exist between technologies within the same cluster, resulting in increasing returns to scale. Between technology clusters, fewer spillover effects exist. Once a specific cluster has gained a relative advantage over a competing technology clusters (that is a cluster of technologies that can be used to produce a substitute good), the scale effects will enhance its dominance. The economy

[3] This technological variety may be embodied in firms, sectors or countries. For example, in (Nelson and Winter, 1982), the set consists of firms that possess different capabilities, procedures, and decision rules.

will specialise in technologies typical for that cluster, instead of following a uniform growth path over all technologies within different clusters. This phenomenon of specialisation in a cluster is known as a lock-in.

For many environmental problems, the solution may require a technological transition away from a technological regime that is emission intensive or heavily rests upon the exploitation of specific natural resources, towards technological regimes that are less emission intensive or less dependent on resource exploitation. In this paper, we study policies that can unlock the economy from an emission or resource intensive technology cluster, and that set in motion a transition towards a cluster of environmentally more friendly technologies.

We develop an endogenous growth model based on the Romer (1986) AK model in which investments in the capital stock increase labor productivity. We extend the basic one-sector model, and describe two competing sectors, representing clusters of technologies that have strong internal spillover effects. The problem of lock-in is described as the existence of, and the ambiguity in the selection out of, multiple locally stable equilibria. A technological transition corresponds to the selection of a locally stable equilibrium different from the present one. This paper studies the mechanisms of, and policy initiatives necessary to set in motion, such a transition.[4,5]

In the literature, there are two opposing streams considering history and expectations, respectively, as the factors that determine the selection of one specific equilibrium, out of a set of multiple locally stable equilibria (see Krugman, 1991). The first stream, which believes that the historical path of development is essential, is represented both in the mainstream economic literature (e.g. Ethier, 1982, Krugman, 1981, 1987) and in the evolutionary economics literature (Arthur, 1986). The second stream holds the view that the expected economic development is the key determinant of choice of equilibrium (e.g. Chen and Shimomura 1998). In this view, self-fulfilling prophecies play an important role, and accordingly, a major responsibility of the public

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[4] Tahvonen and Salo (2001) also describe an endogenous growth economy with a transition from non-fossil-fuel energy technologies to fossil-fuel energy technologies, and backwards. Different from our analysis, in their paper, the transition is set in motion by the different characteristics of both energy technologies, that is the increasing costs of the non-fossil-fuel technology, and the depletion of fossil fuels, respectively. In Tahvonen and Salo there is no ambiguity in the selection of the inter-temporal equilibrium.

[5] The recent literature also suggests that niche markets can be essential for the locking out of an economy, securing a minimal market size for infant technologies (Cowan and Hulten, 1996, Islas, 1997). In this paper, we abstract from this phenomenon.

agency is to create convergent expectations as to the future direction of economic development. In our model, both history and expectations play a role.

As regards the interplay between present policies, history, and expectations, our paper fits in a broader literature on environmental policies and the selection of socially preferred equilibrium allocations out of a multiple set of possible equilibria. Recent papers such as Mäler (2000) and Kremer and Marcom (2000) study policies that would bring back an economic and environmental system locked in an inferior steady state to an environmentally superior steady state. Similar to these two papers, in our paper, we study the scope for government intervention that aims at the selection of an environmentally preferred dynamic equilibrium. In another way, abstracting from the environmental concerns, our analysis is also related to the endogenous growth literature that studies multiple balanced growth paths. Recent examples of endogenous growth models that contain multiple equilibria include Chen and Shimomura (1998) and Zhang (1998). In Chen and Shimomura (1998), only self-fulfilling expectations matter in selecting the equilibrium. There is no path dependency. Zhang (1998) asks for public intervention to ensure the economy selects the preferred equilibrium. In his model, like in ours, history and expectations play an important role.

The paper is organised as follows. In section 2 the set-up of our basic model, without an environmental externality, will be discussed. In section 3, we will analyse equilibrium path solutions of this basic model. In section 4, we study the consequences of an environmental constraint for economic growth and analyse the scope for environmental policies. Section 5 concludes.

2. Model set up

We consider a so-called AK model with endogenous growth in the tradition of the Romer (1986) model.[6] Our model adds to the literature as we consider two sectors for production of the single man-made good, instead of one, studying the effects of the non-convexity in the production set on optimal investments, the selection of one sector for specialisation, and the possibility for a transition when environmental constraints lock the economy in an inferior steady state.

An infinitely-lived consumer maximizes intertemporal welfare, as given by

[6] A good reading of the model can be found in Barro and Sala-i-Martin [1995, Ch. 4]

$$\max w = \int_0^{\infty} e^{-\rho t}\,\mathrm{U}(C_t)\,\mathrm{d}t\,, \tag{1}$$

where C_t is the consumption of a single consumer good in period t. We assume that the utility function U(.) has constant elasticity of intertemporal substitution $\gamma > 0$, so that the interest rate r evolves according to

$$r = \rho + \gamma \hat{C}\,, \tag{2}$$

where the hat denotes the relative growth rate, i.e. $\hat{C} = \dot{C} / C$.

The production side of the economy is described by two sectors. Each sector, i=1,2, represents a different cluster of technologies that is available for the production of the consumer good. Both technologies are characterized by a Cobb-Douglas production function:

$$Y_i = \eta_i K_i^{\alpha} (H_i L_i)^{1-\alpha}\,, \tag{3}$$

where η_i is a constant overall productivity coefficient, K_i is the capital stock, H_i is the human knowledge productivity factor, and L_i denotes the employed labor force. The capital stock depreciates with rate δ, while gross investments I_i are added to the stock:

$$\dot{K}_i = I_i - \delta K_i\,. \tag{4}$$

Capital has a spill over to labor productivity. Part of this spillover, ζ, is sector-specific, and the remainder is non-sector-specific:

$$H_i = \zeta K_i + (1-\zeta)(K_1+K_2) = K_i + (1-\zeta)K_{-i}, \tag{5}$$

for $0<\zeta<1$, where we use subscript "$-i$" when referring to the other sector. If in both sectors the capital stock increases by factor 2, then in both sectors labor productivity increases by the same factor (5), and in both sectors output increases by factor 2 (3). Thus, the overall production frontier of the economy has constant returns to scale in the capital stock as in the Romer (1986) growth model, thereby permitting a sustained growth path.

Consumption plus investments are constrained by gross production:

$$C + I_1 + I_2 = Y_1 + Y_2\,. \tag{6}$$

Finally, labor supply, $\overline{\mathrm{L}}$, which is assumed to be constant and inelastic, matches labor demand:

$$L_1 + L_2 = \overline{L}. \tag{7}$$

Without loss of generality, we assume that labor units are chosen such that $\overline{L}$=1. We can thus describe the labor allocation by the variable l_1=L_1, which denotes the share of labor used in the first sector.

3. Optimal paths

The Hamiltonian for the welfare maximization program reads:

$$\begin{aligned}\mathbf{H} = \;& \chi\,\mathrm{U}(C) - (C + I_1 + I_1 - Y_1 - Y_2) \\ & - p_1(Y_1 - \eta_1 K_1^{\alpha}(H_1 L_1)^{1-\alpha}) - p_2(Y_2 - \eta_2 K_2^{\alpha}(H_2 L_2)^{1-\alpha}) \\ & - \psi_1(\delta K_1 - I_1) - \psi_2(\delta K_2 - I_2) \\ & - \lambda_1(H_1 - K_1 - (1-\zeta)K_2) - \lambda_2(H_2 - K_2 - (1-\zeta)K_1) \\ & - w(L_1 + L_1 - \overline{L}) \\ & + \mu_1 I_1 + \mu_2 I_2\end{aligned} \tag{8}$$

where we normalised prices for the consumer good, that is, we have a shadow price equal to unity for the commodity balance (6). The first order conditions are not altered by the normalisation, except for the shadow price dynamics ψ_i associated with the state variables. The dynamics for the shadow prices ψ for the stock K are now given by $\dot{\psi}_i = r\psi_i - \partial\mathbf{H}/\partial K_i$, with the real interest rate r replacing the pure time preference rate ρ that is applied in the common present value Hamiltonian. Furthermore, we notice that we add the Lagrangean terms $\mu_1 I_1$ and $\mu_2 I_2$ to account for the non-negative investments constraints, $I_i \geq 0$, which can be binding along an optimal path.

The first order conditions for Y_1 and Y_2 ($\mathbf{H}_{Y_i} = 0$) set the prices for both output goods equal to unity:

$$p_1 = p_2 = 1. \tag{9}$$

Labor is allocated so as to maximize its productivity, and its distribution over both sectors immediately adjusts to the current capital and human knowledge stock distribution. Labor productivity (the wage) is denoted by w. Now, for both sectors the wage should equal marginal labor productivity in the specific sector, w_i, given by:

$$w_i = (1-\alpha)\eta_i K_i^{\alpha} H_i^{1-\alpha} L_i^{-\alpha}, \tag{10}$$

for i=1,2, and along an optimal path, we have w=w_1=w_2. For given capital stock K_i and human knowledge H_i, the labor market equilibrium is found by setting $w_1 = w_2$, which gives:

$$l_1 = \frac{\eta_1^{1/\alpha} K_1 H_1^{(1-\alpha)/\alpha}}{\eta_1^{1/\alpha} K_1 H_1^{(1-\alpha)/\alpha} + \eta_2^{1/\alpha} K_2 H_2^{(1-\alpha)/\alpha}} = 1/(1 + \frac{\eta_2^{1/\alpha} K_2 H_2^{(1-\alpha)/\alpha}}{\eta_1^{1/\alpha} K_1 H_1^{(1-\alpha)/\alpha}}) . \tag{11}$$

The equation shows that a higher capital stock K_i, which in turn implies a higher human knowledge productivity factor H_i, increases the labor share l_i employed in sector i (keeping the capital stock in the other sector constant). We notice that the labor allocation is homogeneous of degree zero in K, since H_i is also linearly homogeneous in the vector K. That is, l_1 only depends on the relative shares of capital in both sectors. For convenience, we define the level of the capital stock in first sector as a share of the total capital stock,

$$k_1 \equiv K_1/(K_1+K_2). \tag{12}$$

Now, (11) can be written in reduced form as

$$l_1 = \mathrm{F}(k_1 \,;\, \alpha, \zeta, \eta_1, \eta_2), \tag{13}$$

for continuous F(.):(0,1)→(0,1). Notice that F(0;.)=0 and F(1;.)=1; if all capital is allocated to the first sector, then all labor is allocated to the first sector as well, and if all capital is allocated to the second sector, then labor is allocated thereto as well.

After investments, there is no capital mobility between the two sectors. Capital formation follows from past and present investment decisions. First order conditions for investments I_i give the equality ψ_i+μ_i=1, which says that the capital stock prices ψ_i equals unity unless investments are zero: $\psi_i \leq 1$ with equality if I_i>0. Using the complementarity sign, ⊥, we write:

$$\psi_i \leq 1 \quad \perp \quad I_i \geq 0. \tag{14}$$

for i = 1,2. In less technical terms, the inequality states that investments take place only when the aggregated and discounted future returns on capital, reflected in the price of capital, ψ_i,

$$\psi_i(t) = \int_t^\infty e^{-\int_t^s r(\tau)+\delta \, \mathrm{d}\tau} q_i(s) \, \mathrm{d}s \,, \tag{15}$$

are sufficient to balance the costs of investments, i.e. ψ_i=1, where q_i is the immediate capital return for sector *i*. Equation (15) is a rewriting of the standard dynamic equation for the stock price dynamics, based on the derivative of the Hamiltonian for the capital stock K_i,:

$$\dot{\psi}_i = r\psi_i - \partial\mathbf{H}/\partial K_i = (r+\delta)\psi_i - q_i\,. \tag{16}$$

The value of the immediate capital returns q_i is given by:

$$q_i = \alpha\eta_i K_i^{\alpha-1}(H_i L_i)^{1-\alpha} + \lambda_i + (1-\zeta)\lambda_{-i}\,. \tag{17}$$

After substitution of

$$\lambda_i = (1-\alpha)\eta_i K_i^{\alpha} H_i^{-\alpha} L_i^{1-\alpha}\,, \tag{18}$$

which follows from the first order condition for the labor productivity stock H_i, we arrive at

$$q_i = \alpha\eta_i K_i^{\alpha-1}(H_i L_i)^{1-\alpha} + (1-\alpha)\eta_i K_i^{\alpha} H_i^{-\alpha} L_i^{1-\alpha} + (1-\zeta)(1-\alpha)\eta_{-i} K_{-i}^{\alpha} H_{-i}^{-\alpha} L_{-i}^{1-\alpha}\,. \tag{19}$$

On the right hand side, we find the direct contribution of capital to production as in (3), the indirect contribution through the increase in human knowledge in the own sector, H_i, as represented in (5), and the indirect contribution through the increase in human knowledge in the other sector H_{-i}. Similar to the labor allocation l_1, the returns on capital q_i are homogeneous of degree zero in the total capital stock; q_i is a function of the relative capital stock, which we can write in reduced form as

$$q_1 = \mathrm{G}(k_1\,;\alpha, \zeta, \eta_1, \eta_2)\text{ , and } q_2 = \mathrm{G}(1-k_1\,;\alpha, \zeta, \eta_2, \eta_1), \tag{20}$$

for continuous $\mathrm{G}_i(.)$:(0,1)→(0,∞). For the capital stock share converging to zero, $k_1 \to 0$, we have:

$$\mathrm{G}(0;\alpha,\zeta,\eta_1,\eta_2) = \alpha\eta_1^{1/\alpha}\eta_2^{(1-\alpha)/\alpha}(1-\zeta)^{(1-\alpha)/\alpha} + (1-\zeta)(1-\alpha)\eta_2\,. \tag{21}$$

And for $k_1 \to 1$, we have:

$$\mathrm{G}(1;\alpha,\zeta,\eta_1,\eta_2) = \eta_1\,. \tag{22}$$

A graphical representation of the possible capital returns q_1 and q_2 as a function of k_1 is given in Figure 1.

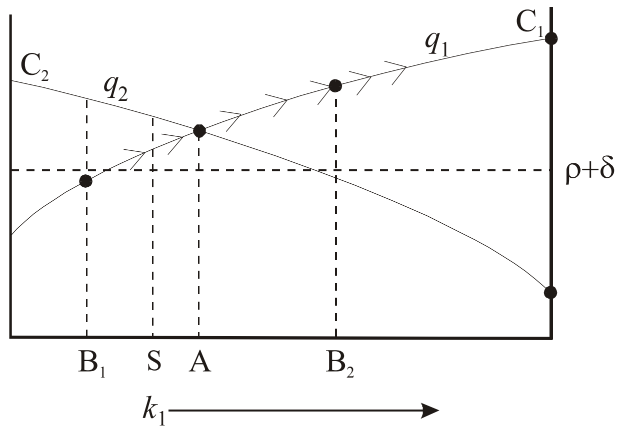

Figure 1. Returns on capital as a function of the capital share k_1

To ensure that a sustained growth path is feasible and optimal, we assume that for all possible initial values of k_1, one of the two sectors has capital returns exceeding the capital depreciation rate δ plus the pure time preference ρ:

$$\min_{k_1}(\max\{G(k_1;\alpha,\zeta,\eta_1,\eta_2),G(1-k_1;\alpha,\zeta,\eta_2,\eta_1)\})>\rho+\delta \tag{23}$$

Under this assumption, there is always one sector for which capital returns can support sustained economic growth, and investments are always positive in at least one sector.

Investments will take place in the sector with the highest present and future returns, captured in the capital price ψ_i (15). The full dynamic analysis of investments is somewhat complicated, and as a starting point, we assume that the initial state of the economy is such that, at t=0, capital returns in the first sector are equal to capital returns in the second sector, $q_1(0)= q_2(0)$, for the optimal labor share l_1 given by (11). That is, the economy starts at point A in Figure 1. Furthermore, we assume that the economy selects the first sector to invest in, $I_1>0$, $I_2=0$, and we ask ourselves whether this selection is consistent with an optimal path. Capital in both sectors depreciates, but only in the first sector the depreciation is counterbalanced by investments, so that the capital stock and the human productivity factor of the first sector increase relative to the levels in the second sector, and consequently, the capital productivity in the first sector relative to the capital productivity in the second sector increases as well, $\partial/\partial t(q_1/q_2)>0$. Once the economy selects the first sector for investments, the returns to capital in the first sector increase relative to the returns to capital in the second sector, and the selection becomes self-enforcing. Investments in the second sector remain zero, and the economy fully specializes. A lock-in occurs. Figure 1 shows the selection of the first sector; the initial situation for t=0 is represented by point A, the arrows towards C show the increase in the relative capital stock k_1 as the economy specialises. The economy converges to a steady state C with k_1=1, l_1=1, $r = \eta_1 - \delta$, $g = (\eta_1 - \delta)/\gamma$, ψ_1=1, and ψ_2<1, where g is the common growth rate for output, investments, and consumption.

In short, if $q_1(0)= q_2(0)$, then the choice to invest only in the first sector is consistent with the first order optimality conditions. Obviously, if the economy were initially, at period t=0, in another state to the right of A in Figure 1, with $q_1(0) > q_2(0)$, the same investments decisions could be rationalised and the economy would still converge to a full specialisation in the first sector.

However, though this may not be obvious, even if initial capital returns in the first sector are below capital returns in the first sector, $q_1(0) < q_2(0)$, a path can exist that satisfies the first order conditions for optimality and in which the economy selects the first sector for specialisation. More precisely, there is an interval of initial states $k_1 \in (B_1, B_2)$ such that for any initial state within this interval, there exists both a path with full specialization in the first and a path with full specialization in the second sector, both paths being consistent with the first order optimality conditions. Krugman (1991) refers to this interval as the 'overlap'.[7] This finding, of two different paths that select different steady states to which they converge, is a well-known phenomenon in the literature. An early analysis is by Skiba (1978), who analysed optimal investments under a convex-concave production function and who proved the existence of two stable steady states and one unstable steady state in-between. In our economy, we have a similar situation, as A represents an unstable steady state (balanced growth path), while C_1 and C_2 represent two stable steady states (balanced growth paths). The unstable balanced growth path A is straightforwardly constructed by taking the relative capital stocks for which q=$q_1(0)$=$q_2(0)$, and choosing investments as

$$I_i = ((q - \rho)/\gamma + (1 - 1/\gamma)\delta)K_i. \tag{24}$$

The resulting path has growth rate $g=(q-\rho-\delta)/\gamma>0$ (23). For any initial capital state near the unstable steady state, Skiba showed two paths exist that satisfy the first order conditions, converging to either one of the two stable steady states. Moreover, he made clear that there is a unique initial state S (known as the Skiba point) near the unstable steady state A that marks the boundary between optimal paths converging to one and to the other stable steady state. Regarding the stability and optimality properties, the situation in our economy is not different. From a

[7] There is no simple analytical formula that determines the levels of B_1 and B_2.

welfare point of view, there is a level S for the relative capital stock k_1 to the right of which it is optimal to specialize in the first sector, and to the left of which it is optimal to specialize in the second sector. In the recent growth literature, Benhabib and Perli (1994), Chen and Shimomura (1998), and Ladrón-de-Guevara *et al*. (1999) discuss similar dynamic patterns in relation to the existence of multiple equilibrium paths.

Yet, in our economy, the precise analysis of dynamics is somewhat more complex as suggested above, since we have two state variables K_1 and K_2, and two associated co-state variables ψ_1 and ψ_2. To study in more detail the selection mechanisms in our economy, we will construct a phase diagram in state-co-state space. A complete phase diagram for (K_1,K_2,ψ_1,ψ_2) would require an analysis in four dimensions. Fortunately, the analysis of the four-dimensional state-co-state space (K_1,K_2,ψ_1,ψ_2) can be reduced to the two-dimensional state-co-state space (k_1,φ), since, as we have seen above, the labor allocation and capital returns only depend on the relative capital share k_1, and either one of the two capital prices ψ_1 and ψ_2 has value unity, so that

$$\varphi \equiv (1 + \psi_1 - \psi_2)/2 \tag{25}$$

defines a one-to-one mapping of the feasible equilibrium values for $(\psi_1,\psi_2)\in[0,1]^2$ on $\varphi\in[0,1]$. The following figure pictures the mapping.

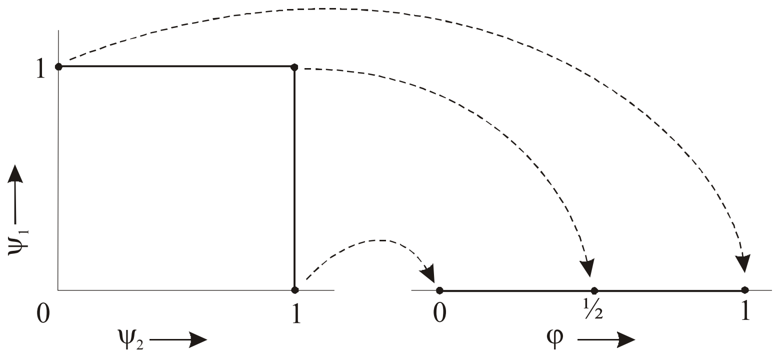

Figure 2. Mapping of $(\psi_1,\psi_2)\in[0,1]^2$ *on* $\varphi\in[0,1]$ *as in* (25).

The value φ=0 stands for the situation in which ψ_1=0 and ψ_2=1, only capital for the second sector has a positive value. If $0<\varphi<1/2$, then $0<\psi_1<1$ and ψ_2=1; the capital stock in the first sector has a positive value, but its value is so low that no investments take place, I_1=0 (14). The value φ=1/2 stands for the situation in which $\psi_1=\psi_2=1$. It is possible that both sectors have positive investments levels $I_1>0$ and $I_2>0$. If $1/2<\varphi<1$, then ψ_1=1 and $0<\psi_2<1$; the capital stock in the second sector has a positive value, but its value is so low that no investments take place, I_2=0 (14).

Finally, φ=1 stands for the situation in which ψ_1=1 and ψ_2=0, only capital for the first sector has a positive value.

Now, we are in the position to study the dynamics in (k_1,φ) space (Figure 3). We follow the common procedure; we first consider the dynamics of k_1, and then we consider the dynamics of φ in (k_1,φ)-space.

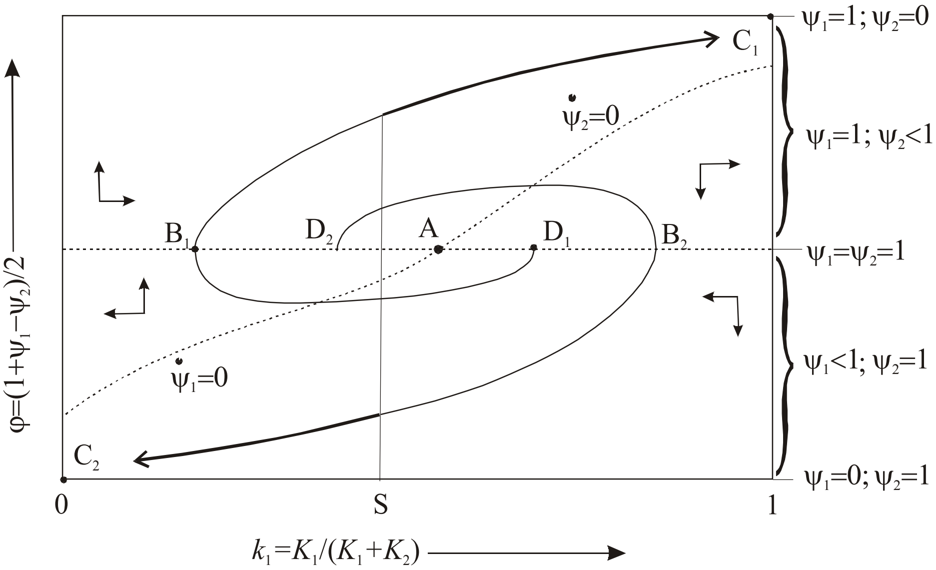

Figure 3. Phase diagram for the capital stock and capital prices

For 0≤φ<1/2, we have 0≤ψ_1<1 and ψ_2=1, and in turn I_1=0 and I_2>0 (14). Since both capital stocks have the same depreciation rate δ, investments in the second sector ensure that the share of the second capital stock in the total capital stock will increase, $\dot{k}_1 < 0$. In analogy, for 1/2<φ≤1, we have ψ_1=1 and 0≤ψ_2<1, and in turn I_1>0 and I_2=0 (14), and the share of the first capital stock in the total capital stock will increase, $\dot{k}_1$>0. Thus, below the line φ=1/2, or $\psi_1 = \psi_2 = 1$, paths are directed to the left, and above the line, paths are directed to the right:

$$\psi_1 < 1; \psi_2 = 1 \Rightarrow \dot{k}_1 < 0 \text{, and } \psi_1 = 1; \psi_2 < 1 \Rightarrow \dot{k}_1 > 0 . \qquad (26)$$

The direction of movement for φ is determined by the relative returns on capital q_i when comparing both sectors (16). For 0≤φ<½, (0≤ψ_1<1, ψ_2=1) we can immediately deduce $\dot{\psi}_2 = 0$ and thereby, $\dot{\varphi} = 0$ is equivalent to $\dot{\psi}_1 = 0$. Substituting $\dot{\psi}_1 = 0$ and $\dot{\psi}_2 = 0$ in (16), we get

$$q_1 = (r + \delta)\psi_1 \text{, and} \qquad (27)$$

$$q_2 = (r + \delta)\psi_2 = r + \delta , \qquad (28)$$

which, in turn, gives

$$\dot{\varphi} = 0\,;\, \varphi \leq ½ \;\Leftrightarrow\; \psi_1 = q_1/q_2\,;\, \psi_2=1, \tag{29}$$

where we can rewrite the right-hand-side in terms of φ as follows: $\varphi = (q_1/2q_2)$. Equivalently, we have

$$\dot{\varphi} = 0\,;\, ½ \leq \varphi \;\Leftrightarrow\; \psi_1=1;\, \psi_2 = q_2/q_1. \tag{30}$$

or in terms of φ: $\varphi=1-(q_2/2q_1)$. Now, on the basis of the capital returns drawn in Figure 1, we can draw the line $\dot{\varphi} = 0$ in Figure 3 as a function of the capital share in the first sector k_1. The line runs from just above the left-lower corner upwards to the point A, where $q_1=q_2$, $\psi_1=\psi_2=1$, and $\varphi=½$, further upwards to just below the right upper corner.

The dynamics in state-co-state of paths satisfying the first order conditions are drawn in the figure. When a path satisfying the first order conditions crosses the line $\dot{\varphi} = 0$, its motion is horizontal, and when it crosses the line $\varphi=½$, its motion is vertical. At first instance, it may seem that the phase diagram does not exclude paths that hit the right or left axis, $k_1=0$ or $k_1=1$, before moving to the corner. However, we can argue that such paths do not exist. If the economy fully specialises in, say, the second sector, and no investments take place in the first sector, then the capital stock level will decrease exponentially due to depreciation, but will remain positive. This rules out paths that touch the boundaries $k_1=0$ or $k_1=1$, before converging to the corner. Similarly, we can exclude paths that hit the lower and upper boundaries set by $\varphi=0$ and $\varphi=1$. Unless the capital stock in sector i is zero, its value will be strictly positive, and no path will hit the top or floor of the diagram. Accordingly, optimal paths in the lower part of the diagram (below $\dot{\varphi} = 0$ and below $\varphi=½$), must converge to the left-lower corner or leave the area by crossing the line $\dot{\varphi} = 0$. Similarly, optimal paths in the upper part of the diagram (above $\dot{\varphi} = 0$ and above $\varphi=½$) must converge to the right-upper corner or leave the area by crossing the line $\dot{\varphi} = 0$.[8]

To conclude this section, we comment on the policies required to ensure the decentralised economy selects an optimal path. If, within each sector, the firms are small, they will neglect the spillover effects of their investments on the productivity in other firms, and investments in the

[8] We also notice that the phase diagram does not rule out spiral paths around the unstable steady state A. However, these paths are not relevant, since a cycling between the two sectors will cause welfare losses as it does not fully profit from the increasing returns to scale. The optimal path must select immediately one sector for specialisation.

competitive equilibrium will fall short of the social optimum. It is therefore necessary for the social planner to have instruments available such as subsidies that internalise the investment spillovers. Similar to the one-sector AK-model, in our economy, the social planner needs to ensure that the level of investments match their social optimum. In the model with two sectors, however, the social planner also needs to guide the economy with respect to the distribution of investments over both sectors, that is the social planner has to determine the direction of economic growth and it has to ensure that the individual firms select the proper sector (technology) to invest in.

For all initial states between B_1 and B_2, there are two paths that satisfy the first order optimality conditions, one converging to C_1, and the other converging to C_2, respectively. For given initial state, the market is indeterminate as to the direction of economic growth. Yet the Skiba point S marks a unique state to the left of which it is optimal to select the second sector, and to the right of which it is optimal to select the first sector for specialisation. The social planner has to ensure that the economy selects the proper path for its development (Bold in Figure 3). As Krugman (1991) has pointed out, when an ambiguity persists for the path the economy will follow, the planner should create convergent expectations around aggregate investments in specific technologies. The social planner has to communicate that she will support the preferred investment path, and that, if necessary, she will take measures to lock out the other possible future investment path (similar to the policy in Kremer and Marcom 2000). Now we are ready to continue with the second step of our analysis, i.e. to introduce, next to the investment externality and the 'choice of technology' externality, a third, environmental, externality in our model.

4. Environmental constraints and a transition policy

Environmental concerns may arise if the economy has specialized in a sector (technology) that turns out to be polluting or relative resource intensive. We can think of the fossil fuel technologies that are associated with greenhouse gas emissions. So-called backstop technologies with zero emissions may provide an alternative for the energy supply, but these alternative technologies have lower immediate capital returns and will need substantial initial investments to become competitive. While a technology transition may be beneficial from an environmental point of view, in an economic sense, the past selection of the fossil-fuel technologies can be irreversible; the economy is locked in.

In our model, let us assume that the economy has specialized in the first sector and has reached the balanced growth path C_1. Growth has continued for some time, but at some time, detrimental effects of resource use, necessary for the production in the first sector, become significant. We can think of resources becoming scarce, manifested through increasing resource extraction costs, or, alternatively, we can think of resource use causing pollution that decreases the amenity values of the environment. Furthermore, let us assume that the second sector provides an alternative for a 'green' growth path, in the sense that resource use will pose no significant limit to its expansion. Thus, if the economy succeeds in making a successful transition, the economy could continue on an undisturbed sustained growth path.

In the formal terms of our economy, let us assume that resource use is strictly linked to output of sector 1, $R=Y_1$,[9] and in turn, that per period resource use adds negatively to the utility function, so that (1) becomes:

$$\max w = \int_0^\infty e^{-\rho t}\, \mathrm{U}(C_t - \nu R_t)\, \mathrm{d}t\,, \tag{31}$$

where, for convenience, we assumed that the resource externality can linearly be expressed in consumer good units.

While the economy grows and maintains its selection of the first sector, the environmental externality will receive a (Pigouvian) shadow price, internalised through a tax τ levied on the output of the first sector. In the Hamiltonian (8), we replace utility $\chi\mathrm{U}(C)$ by $\chi\mathrm{U}(C-\nu R)$, and we add the term $\tau(Y_1-R)$, so that we have

$$\begin{aligned}
\mathbf{H} = \quad & \chi\,\mathrm{U}(C-\nu R) - (C + I_1 + I_1 - Y_1 - Y_2) \\
& - p_1(Y_1 - \eta_1 K_1^{\alpha}(H_1 L_1)^{1-\alpha}) - p_2(Y_2 - \eta_2 K_2^{\alpha}(H_2 L_2)^{1-\alpha}) \\
& - \psi_1(\delta K_1 - I_1) - \psi_2(\delta K_2 - I_2) \\
& - \lambda_1(H_1 - K_1 - (1-\zeta)K_2) - \lambda_2(H_2 - K_2 - (1-\zeta)K_1) \\
& - w(L_1 + L_1 - \overline{L}) \\
& + \mu_1 I_1 + \mu_2 I_2 \\
& - \tau(Y_1 - R)
\end{aligned} \tag{32}$$

[9] In fact we assume that the production function in sector 1 has a Leontief specification with respect to resource use.

It follows immediately from the first order conditions for R and C that $\tau=\nu\chi U'(.)=\nu$. Taking the first order conditions for Y_1, we find that the net output price for goods produced in the first sector is reduced by factor $(1-\tau)$. In turn, labor productivity and capital returns in the first sector decrease and net capital investments decrease.

The question addressed in this section is: which policy is required to set in motion the transition towards the 'clean' sector (technology). We take as a starting point the situation where the environmental externality is fully internalised; the environment has received its price.

We can distinguish three possibilities. First, immediate capital returns in the second sector exceed immediate capital returns in the first sector and a transition begins without the need for any further policy (Figure 4). Second, it is possible that the immediate capital returns in the first sector decrease, but still exceed the capital returns in the second sector. Nonetheless, a transition becomes attainable (Figure 5), but it needs additional policy measures to be set in motion. The third possibility is that, though the capital productivity in the second sector improves relative to the capital productivity in the first sector, this does not warrant a transition. We now elaborate on the first two cases.

Given output taxes τ for the first sector, returns to labor decrease by factor $(1-\tau)$ and the labor distribution (11) changes into:

$$l_1 = 1/(1+\frac{\eta_2^{1/\alpha} K_2 H_2^{(1-\alpha)/\alpha}}{(1-\tau)\eta_1^{1/\alpha} K_1 H_1^{(1-\alpha)/\alpha}}) . \qquad (33)$$

Similarly, the capital returns for the capital stock in the first sector q_1 decrease by factor $(1-\tau)$ inasmuch as the direct and indirect contribution to the output of the first sector is concerned (19):

$$\begin{aligned} q_i &= (1-\tau)\alpha\eta_i K_i^{\alpha-1}(H_i L_i)^{1-\alpha} + ((1-\tau)1-\alpha)\eta_i K_i^{\alpha} H_i^{-\alpha} L_i^{1-\alpha} \\ &+ (1-\zeta)(1-\alpha)\eta_{-i} K_{-i}^{\alpha} H_{-i}^{-\alpha} L_{-i}^{1-\alpha} \end{aligned} . \qquad (34)$$

We notice that since the Pigouvian tax decreases capital returns in the first sector, which is dominant, it also decreases the growth rate of the economy. In reduced form, we may write

$$q_1 = \widetilde{G}(k_1 ; \alpha, \zeta, \eta_1, \eta_2, \tau, 0) \text{, and } q_2 = \widetilde{G}(1-k_1 ; \alpha, \zeta, \eta_2, \eta_1, 0, \tau), \qquad (35)$$

where, we added tax parameters for both sectors to the function G(.). Under full specialization, $k_1=1$, the capital returns become

$$q_1 = \widetilde{G}(1\,; \alpha, \zeta, \eta_1, \eta_2, \tau, 0) = (1-\tau)\eta_1, \text{ and} \tag{36}$$

$$q_2 = G(0; \alpha, \zeta, \eta_2, \eta_1, 0, \tau) = \alpha\eta_2^{1/\alpha}\eta_1^{(1-\alpha)/\alpha}(1-\zeta)^{(1-\alpha)/\alpha} + (1-\tau)(1-\zeta)(1-\alpha)\eta_1. \tag{37}$$

While the output tax for the first sector decreases the returns on labor and capital within this sector, it relatively raises the returns on labor and capital in the second sector. When the Pigouvian tax increases from zero to a positive value, the unstable steady state A in Figure 1 for which $q_1 = q_2$, the Skiba point S, and the transition points B_1 and B_2 shift to the right. If taxes are such that the immediate capital returns in the first sector drop below the immediate returns in the second sector, $q_1 < q_2$, it becomes optimal for every single firm to shift investments to the second sector, and the transition takes off. (Figure 4). In this case, it suffices for the social planner to give the environment its price, since the Pigouvian tax ensures that the optimal path, which defines a transition, is the only path consistent with first the order conditions.

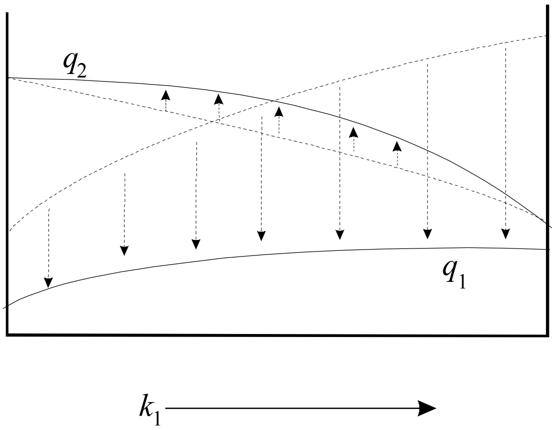

Figure 4. Capital returns lowered by a resource tax τ; *induced transition*

In the second case, the Pigouvian tax is insufficient to raise the returns to capital in the second sector above the returns in the first sector (Figure 5), given the historic full specialization in the first sector. Yet, a transition towards the second sector may be optimal when taking into account future capital returns. Under these circumstances, the social planner has to lock out the economy and to guide it to ensure that it selects the second sector for investments, as for the individual firm, continued investments in the first sector is still a consistent strategy. The transition is also consistent with the first order conditions, but its initiation requires that the individual agents believe it will take place. Public intervention is required to initiate the transition, for example by eliminating the current balanced growth path, as in Kremer and Marcom (2000). An effective policy would be if the planner announces a future environmental levy above the Pigouvian level in case the transition does not take place. The announcement will force all individual firms to move their investments to the second sector, forming a coherent strategy. Notably, the threat of increased environmental levies need not be implemented, as the mere announcement suffices to enforce the transition to be set in motion. Finally, it should be noted that in this case a pure environmental policy, which fully internalises the environmental externality, does not suffice to reach the welfare optimum. In fact we are back in the basic model where next to an internalization of the investment externality the government has to guide the economy to select the optimal technology.

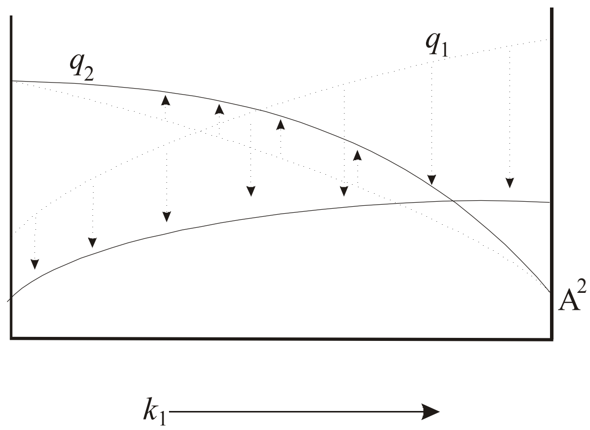

Figure 5. Capital returns lowered by a resource tax τ; *no induced transition*

For small environmental externalities, we end up in the third case, in which the resource externality is insufficient to justify a transition towards the alternative technology. The net present value of the transition costs exceeds the net present value of environmental damages, and there is no need for the government to guide the economy starting a transition. Still the intervention of the government is needed to internalize he capital spill-overs as well as the environmental externalities as such.

5. Conclusion

In this paper we have constructed a model that combines elements of endogenous growth theory with the concept of lock-in that has its roots in the evolutionary economics literature. We described an endogenous growth model with two sectors (technologies) that both have strong internal spillovers. In this economy, there exist multiple growth paths satisfying the first order conditions. More specifically, the economy can choose to specialize in either one of the two sectors. Current investments determine the relative growth of both sectors, and thereby the selection of the growth path, and in turn, current investments are determined by the immediate and expected capital returns in both sectors. Since future capital returns are positively related to present investments, there is a positive feedback, and the selection of one or another sector (technology) for investments is ambiguous, but once the selection is made, it is self-enhancing.

Both history and expectations play a role in the selection of equilibrium. In case immediate capital productivity does not differ too much between the two sectors, the economy can specialize in either of the sectors. It is well possible that the economy specializes in the sector that has the lowest immediate capital returns. To ensure the selection of the socially optimal path, the social planner has to create coherent expectations about the direction of economic growth, as already pointed out by Krugman (1991).

If the economy has specialized in a sector heavily resting on resource use, or causing environmental pollution, this may constrain future growth in case of a limited resource supply or a limited pollution absorption capacity. If immediate capital returns do not differ too much between the 'clean' and 'dirty' sector, the announcement of environmental policies supporting a transition to the 'clean' sector suffices to set in motion the transition, without the need for actual environmental regulations to take place. In case of a substantial advantage of the 'dirty' sector, in terms of immediate capital returns, a transition may need the support of environmental levies or subsidies. In all cases there is a role for the government as to ensure the internalization of the investment spill-overs as well as of the environmental externalities.

The implication of our analysis for environmental policy is twofold. First, it makes clear that the impact of environmental levies and subsidies on economic production is not restricted to marginal changes in production inputs and outputs. Environmental regulations may bring about the development of specific technologies that cause a substantial shift in the production input-output matrix. Second, the analysis stresses the importance of a clear and reliable policy regarding the future direction of economic growth. The government can guide technology dynamics by demonstrating that continued pollution would be responded to by stringent environmental policies. The certainty of a 'green' future stimulates individuals to search for technological innovation in this direction, thereby reducing the need for actual stringent environmental regulations. When applied to the issue of climate change, it follows that a clear policy statement on aimed future emission reductions will lessen the need for high-level carbon dioxide taxes needed to bring these reductions about.

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