Induced Technological Change under Technology Competition

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NOTA DI LAVORO 5.2003

JANUARY 2003

KNOW – Knowledge, Technology, Human Capital

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Summary

We develop a partial one-sector model with capital, natural resources, and labor as production factors, and endogenous technological change through research. Production exhibits increasing returns to scale. We compare the response of output and resource use to a change in resource prices with and without induced technological change (ITC). It is shown that induced technological change is insignificant in reducing resource use when there is one representative technology and output demand is inelastic to prices. In contrast, substantial gains from ITC appear when we allow for two competing technologies that can be employed for production, while these technologies are good substitutes. Also, in case of two technologies, conditions are specified under which multiple balanced growth paths exist, and it is shown that because of ITC, a temporary resource tax can lock out the economy from a resource intensive path and lock in to a resource extensive path.

Keywords: Induced technological change, environmental taxes, partial equilibrium

JEL: H23, O31, O41, Q42, Q43

The author is grateful to David Popp, Chris Green, and Sjak Smulders for their suggestions and comments on an earlier draft. The usual disclaimer applies. The research has been funded by the Dutch National Science Foundation (NWO) under contract nr. 016.005.040.

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Induced technological change under technology competition[1]

1. Introduction

It has become increasingly clear that environmental taxes and regulation not only reduce pollution by shifting behavior away from polluting activities, but also encourage the development of new technologies that make pollution control less costly in the long run (Popp 2002). Understanding the response of technology to economic incentives – dubbed induced innovation or induced technological change (ITC) – will prove crucial for designing appropriate environmental policies.[2] This paper studies the contribution of ITC to pollution reduction and it specifically addresses the issue in the context of multiple competing technologies that are good substitutes for producing the same good. The analysis extends the literature that has mainly studied ITC in the context of one representative aggregate technology.

Since Grossman and Krueger (1993), the effect of environmental taxes and regulation on pollution is commonly decomposed in a scale effect, a composition effect, and a factor substitution effect, where the latter effect is often referred to as the technology effect.[3] The scale effect signifies the increase or decrease in aggregate output and pollution, all other things equal. The composition effect records the shift away from polluting activities. The factor substitution effect measures the implication on pollution of the substitution of less polluting production factors for more polluting production factors. A similar breakdown into a composition and factor substitution effect can be made for ITC. First, when multiple technologies are available that can be employed for the production of a good, each technology with a different resource use and pollution profile, then environmental taxes will induce a change in technological composition, that is a shift towards technologies that are less polluting. Second, treating technology as a production factor, ITC stands for a substitution of technology for other production factors. Most of the

[1] The author acknowledges financial support by the Netherlands Organisation for Scientific Research (NWO) under contract number 016.005.040.

[2] For an extensive literature overview of policy instruments in relation to ITC, see Jaffe *et al*. (2002).

[3] The reason for our change in labeling is that, in this paper, we want to separate factor substitution from a technology effect.

literature on ITC is based on the concept of a representative technology and focuses on ITC as enhanced factor substitution (e.g. Newell, Jaffe and Stavins 1999, Goulder and Matthai 2000).

ITC is receiving much attention, for example in the climate change related literature where its potential contribution to policies aiming at greenhouse gas emission reductions is subject of a yet undecided debate. A few studies try to estimate empirically the impact of enhanced factor substitution through ITC relative to the direct factor substitution effects (Goulder and Schneider 1999, Nordhaus 2002). They conclude that, though ITC is not negligible, its contribution to emission abatement is small when compared to the contribution of direct factor substitution. Nordhaus' (2002) conclusion is, however, based on an assumed representative technology, and it neglects induced changes in the technological composition as a channel through which ITC operates. The reduction of resource use will not only require the substitution of knowledge for a resource, it will also require the substitution of 'clean' technologies for 'dirty' technologies. Goulder and Schneider model two energy sources but treat these as complements (elasticity of substitution below unity), so that substitution and competition between energy sources is limited. Technology competition is of specific interest for climate change in relation to energy use and supply. In the long term, energy savings will be insufficient for substantial abatement levels of carbon dioxide emissions, since energy is an essential production factor. Instead, if a substantial emission abatement strategy is aimed for, a shift away from fossil-fuel based energy sources towards carbon-free energy sources will have to carry such a strategy (Chakravorty *et al*. 1997). For this reason, we have to take into account the effect of ITC on the relative contribution of various technologies used for production (Weyant and Olavson 1999).

The effect of ITC on the technological composition has fundamentally different features when compared to the enhanced factor substitution effect of ITC. Even though ITC amplifies factor substitution, factor substitution remains a continuous process. For multiple technologies, we can expect discontinuous responses to environmental taxes, since under endogenous innovation, production exhibits increasing returns to scale, and profit maximization or cost minimization implies a non-continuous adjustment of production to price changes. Specifically, in this paper, we make a case for the existence of so-called bifurcation equilibria. An environmental tax can, when it passes a certain threshold, cause a trade in places between a currently dominant and polluting technology, and a currently minor but non-polluting technology. An analysis based on a representative technology cannot represent this behavior.[4]

In this paper, we develop a one-sector two-technology model with endogenous R&D in the tradition of the endogenous growth models with natural resources that have been specified to study growth and sustainability (Gradus and Smulders 1993; Bovenberg and Smulders 1995; den Butter and Hofkes 1995; Bovenberg and Smulders 1996; Smulders 1999). Section 2 describes the basic features of the model for one sector and one technology. Section 3 studies the dynamic paths and steady states, and it examines the returns to scale. An important finding of this section is that returns to scale increase when output levels increase. A matured technology has higher increasing returns vis-à-vis an infant technology. ITC enters the analysis in Section 4, where the model is used to examine the effect of ITC on the elasticity of output and resource use, with respect to resource prices. Section 5 extends the model to take account of two competing technologies. That is, two different technologies are considered that can be used to produce goods that are good substitutes. In this setting, increasing returns to scale typically produce a one-takes-all allocation, that is a corner solution where one technology dominates and the other technology disappears. In contrast, the increasingness of returns we have found in Section 4 permits the existence of multiple interior solutions. We specify explicit conditions for existence of stable and unstable equilibria. Section 6 examines the effect of ITC on the elasticity of output and resource use, with respect to resource prices, in the two-technology model. ITC is shown to act as a strong multiplier for the elasticities. This section also shows that a resource tax can, through ITC, lock out production from a locally stable steady state in which a resource intensive technology dominates, to an alternative stable steady state in which a resource extensive technology dominates. Finally, Section 7 discusses the implications of our analysis for climate change policies.

2. Model set up for one technology

This section presents the basic elements of our model for production and innovation, describing one sector and one technology. We distinguish between 'research firms' that produce innovations and producers of the final sector good. Technology is described as an expanding library of ideas that can be used in the production process. Innovation is a cumulative process; each innovation

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[4] More in general, a representative aggregate technology does not perform well when there are increasing returns to scale at the disaggregate level (Basu and Fernald 1997).

builds on the stock of existing knowledge. Producers of the final good can make use of all past and present innovations, that is the total stock of knowledge, and pay a license fee to all research firms that have developed the innovations that are currently in use. In turn, the researchers receive the license fees from all present and future final goods producers that use their innovations. Both researchers and producers of final goods take prices as given. We do not consider product variety and price setting under monopolistic competition as in many other endogenous growth models (see Barro and Sala-i-Martin 1995 for an overview).

Demand for the sector good is assumed to show constant elasticity of substitution σ,

$$y_t = \hat{y}_t \, p_t^{-\sigma}, \tag{1}$$

for some exogenous demand variable $\hat{y}_t$, where p_t is the price of the sectoral final good. The final good is produced by firms, indexed j, according to

$$y_{j,t} = (a_{j,t})^{\eta} (k_{j,t})^{\alpha} (e_{j,t})^{\beta} (l_{j,t})^{1-\alpha-\beta}, \tag{2}$$

where $k_{j,t}$, is the capital stock, $e_{j,t}$ is resource use, and $l_{j,t}$, is labor use in efficient labor units. Human capital increasing labor productivity is not specified explicitly, as it is considered embodied in the labor good, exogenous to the individual firm. The technology variable $a_{j,t}$ denotes the number of innovations that are employed by the *j-th* firm, at date *t*.

Capital depreciates over time at rate δ, and is accumulated through investments i_t,

$$\dot{k}_{j,t} = i_{j,t} - \delta k_{j,t}. \tag{3}$$

In addition to the investment expenditures, $i_{j,t}$, resource rents $q_t e_t$, and wages, $w_t l_{j,t}$, firms have to pay a license fee for the innovations employed, denoted by θ_t, for every unit of innovation $a_{j,t}$, and for every unit of output $y_{j,t}$. At time *t*, total expenditures thus amount to $i_{j,t} + q_t e_{j,t} + w_t l_{j,t} + \theta_t a_{j,t} y_{j,t}$, while revenues amount to $p_t y_{j,t}$. The firms maximize the net present value of their cash flows:

$$\max \int_0^\infty e^{-\rho t} ((p_{j,t} - \theta_t a_{j,t}) y_{j,t} - q_t e_{j,t} - w_t l_{j,t} - i_{j,t}) \, \mathrm{d}t, \tag{4}$$

subject to (2) and (3), where ρ is the interest rate. Since expenditures on licenses are proportional to output, production has constant returns to scale, and the firms can operate in a competitive market with marginal pricing. We thus omit firms' subscripts *j*. The Hamiltonian for profit maximization reads:

$$\mathbf{H} = py - \theta ay - qe - wl - i + \lambda(a^{\eta}k^{\alpha}e^{\beta}l^{(1-\alpha-\beta)} - y) + \psi\,(i - \delta k). \tag{5}$$

For convenience, we omitted time subscripts. The first order conditions for y, a, l, e, i, and k are, respectively,

$$p = \theta a + \lambda, \tag{6}$$
$$\theta y = \eta\lambda y/a, \tag{7}$$
$$w = (1-\alpha-\beta)\lambda\, y/l\ , \tag{8}$$
$$q = \beta\,\lambda\, y/e\ , \tag{9}$$
$$1 = \psi\ , \tag{10}$$
$$\dot{\psi} = \rho\psi - \mathbf{H}_k = (\rho+\delta_k)\psi - \alpha\lambda y/k, \tag{11}$$

We can substitute equations (10) in (11) to derive a capital cost equation that shows capital costs to consist of interest and depreciation:

$$\rho + \delta_k = \alpha\lambda y/k\ . \tag{12}$$

The price of the output good, p, consists of two parts (6), the license fee θa and the immediate production costs λ. From (6) and (7), we see that innovation costs make a constant mark up η on top of the immediate production costs net of the license fee, λ,

$$p = (1+\eta)\,\lambda\ . \tag{13}$$

Furthermore, because of linear homogeneity of production y in (k,e,l), we can calculate λ, as dependent on capital costs, $\rho+\delta_k$, the resource price q, and wages, w_t,

$$\lambda = \min\,\{(\rho+\delta_k)k + qe + wl \mid 1 \leq a^{\eta}k^{\alpha}e^{\beta}l^{1-\alpha-\beta}\} = \xi\ a^{-\eta}\ , \tag{14}$$

where ξ, the production costs net of technology,

$$\xi = \alpha^{-\alpha}\,\beta^{-\beta}\,(1-\alpha-\beta)^{-(1-\alpha-\beta)}\,(\rho+\delta)^{\alpha}\,q^{\beta}\,w^{1-\alpha-\beta}\ , \tag{15}$$

is exogenous to the sector. The license fee θ is now calculated as

$$\theta = \eta\ \xi\ a^{-1-\eta}, \tag{16}$$

and output prices are given by

$$p = (1+\eta)\ \xi\ a^{-\eta}\ . \tag{17}$$

Next we turn to the supply of innovations. There are two externalities working in opposite direction. As a positive externality, knowledge about past innovations is public, that is, technology is non-rival when it is used to produce new technology. As a negative externality, research efforts r by one firm negatively affect the finding of new innovations by other firms, because of fishing out of new innovations that are attainable from the current state of technology. Research firms use the 'library' of past inventions to produce new innovations. We distinguish between the overall (non sector-specific) state of technology, denoted by upper-case A, and the sector specific technological state of the art, denoted by lower-case a. The distinction is a way of representing the finding by Jaffe (1986) that spill-over effects between 'technological neighbors' exceed spill-over effects between distant technologies. In our model, technological innovation within the sector spills over through a, whereas we abstract from spillovers between sectors. The next section studies the implications of this distinction for the returns to scale.

A research firm j can produce a number of new innovations $\mathrm{d}a_j$ according to

$$\mathrm{d}a_j = \zeta\ r^{\pi-1}\ (a+A)^{1-\pi}\ \mathrm{d}r_j. \tag{18}$$

where ζ is a scaling constant, $\mathrm{d}r_j$ denotes the research expenditures by firm i ($\mathrm{d}r_j = r_j \mathrm{d}t$, research expenditures are equal to the research flow r_j times the time interval $\mathrm{d}t$), and r denotes the overall expenditures on research by all (other) research firms. Aggregation of innovations (18) over the research firms gives

$$\dot{a} = \zeta\ r^{\pi}\ (a+A)^{1-\pi}\ . \tag{19}$$

Equilibrium on the market for innovations requires that the costs of developing a new technology, that is, the costs of an increase $\mathrm{d}a_i$, equals the revenues the research firm can obtain by selling the license fees. Costs per unit of innovation are given by (18),

$$\mathrm{d}r_j/\mathrm{d}a_j = \zeta^{-1}\ r^{1-\pi}\ (a+A)^{\pi-1}. \tag{20}$$

The revenues from an innovation are equal to the net present value of future license fees:

$$\varphi_t = \int_t^{\infty} \theta_\tau y_\tau e^{-\rho(\tau-t)}\, \mathrm{d}\tau\,, \tag{21}$$

where φ_t denotes the asset price of an innovation. In terms of a differential equation, we write

$$\dot{\varphi} = \rho\varphi - \theta y = \rho\varphi - \eta\ \xi\ y\ a^{-1-\eta}\,. \tag{22}$$

Substitution of the demand function (1) and the price-technology relation (17) gives

$$\dot{\varphi} = \rho\varphi - \eta\ (1+\eta)^{-\sigma}\ \xi^{1-\sigma}\ \hat{y}\ a^{-1-\eta+\sigma\eta}\ . \tag{23}$$

Setting costs (20) and revenues (21) equal, we obtain the overall research effort r,

$$r = (\zeta\varphi)^{1/(1-\pi)}\ (a+A), \tag{24}$$

and (19) becomes

$$\dot{a} = \zeta^{1/(1-\pi)}\ \varphi^{\pi/(1-\pi)}\ (a+A). \tag{25}$$

The two equations (23) and (25) fully describe the dynamics for technology a and its price φ. We use these in the next section to study existence, stability, and returns-to-scale properties of the steady state.

3. Steady state and returns to scale

In this section, we establish conditions for a stable balanced growth, also labeled a steady state solution, for the dynamic equations (23) and (25), and we analyze the returns to scale, that is, the decrease in production costs that occurs when the output level, y, increases. Along the balanced growth path, the rate of increase for the general purpose technology A is a constant g_A, wages increase at constant rate g_w, resource prices increase at constant rate g_q, and the exogenous demand $\hat{y}$ increases at constant rate $g_{\hat{y}}$. Furthermore, we characterize the balanced growth path by a constant ratio between the sector specific technology and the general purpose technology, a/A and denote the growth rate of both technology variables by the constant $\gamma = g_a = g_A$. It follows from the innovation dynamics (19) that research expenditures grow at the same rate, $g_r = \gamma$, and from (24) that the technology price φ is constant, $g_\varphi = 0$. In turn, the price dynamics equation (23) makes clear that the growth rates for wages, resource prices and demand $\hat{y}$ are linked such that the exogenous variable

$$\chi = \eta\ (1+\eta)^{-\sigma}\ \xi^{1-\sigma}\ \hat{y}\ A^{-1-\eta+\sigma\eta} \tag{26}$$

is a constant. We can thus express the growth rates of ξ, p, and y in terms of γ and $g_{\hat{y}}$: $g_\xi = ((1+\eta-\sigma\eta)\gamma - g_{\hat{y}})/(1-\sigma)$, $g_p = (\gamma - g_{\hat{y}})/(1-\sigma)$, $g_y = (g_{\hat{y}} - \sigma\gamma)/(1-\sigma)$. These growth rates are used in Figure 2 to normalize over time the axes. We notice that, if demand growth in proportion to technology, $g_{\hat{y}}=\gamma$, and factor costs increase by $g_{\xi}=\eta\gamma$, then prices remain constant, $g_p=0$, and output grows at the same rate as demand, $g_y=\gamma$.

First, we study the existence of a steady state and its stability through the phase diagrams for (a,φ), as in Figure 1a, b, and c. The two loci with $\dot{\varphi}=0$ and $\dot{a}=\gamma a$, are given by (23) and (25), that become in steady state:

$$\varphi = \rho^{-1}\,\chi\,(a/A)^{-1-\eta+\eta\sigma}, \text{ and} \tag{27}$$

$$a/A = \zeta^{1/(1-\pi)}\,\varphi^{\pi/(1-\pi)} \,/\, (\gamma - \zeta^{1/(1-\pi)}\,\varphi^{\pi/(1-\pi)}), \tag{28}$$

respectively. We show three figures. For $\sigma<1+1/\eta$, the $\dot{\varphi}=0$ locus is downwards sloping whereas the $\dot{a}=\gamma a$ locus is upwards sloping, as in Figure 1a. There is a unique stable steady state. For larger values of the elasticity of demand, $\sigma>1+1/\eta$, existence and stability of the steady state depends on the value of the constant χ, and for given resource price and wages this means that existence and stability depend on the market size $\hat{y}$. For $1+1/\eta<\sigma<1+1/\eta+(1-\pi)/\pi\eta$, and small $\hat{y}$, a stable steady state exists as in Figure 1b. But if the size of the market increases, the $\dot{\varphi}=0$ locus shifts upwards and the steady state vanishes, as in Figure 1c. We can extend the list of figures for higher values of σ, but we constrain ourselves to this set of figures since these will turn out to be of most interest for our further analysis. It is remarkable that an increase of $\hat{y}$ transforms Figure 1b with stable steady state into Figure 1c that has no steady state. An analysis of the returns to scale in steady state will reveal the mechanism at play, and will prove useful for the two-technology economy studied in the Section 5.

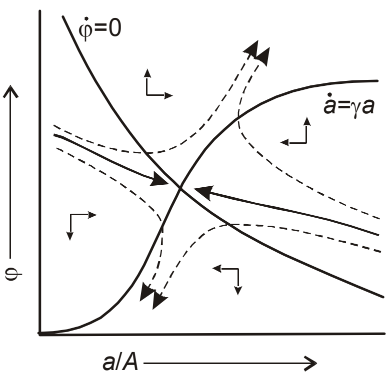

FIGURE 1a. *Phase diagram for* (a,φ); *saddle-point stability for* $0\leq\sigma<1+1/\eta$

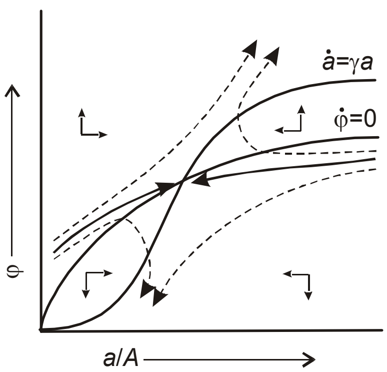

FIGURE 1b. *Phase diagram for* (a,φ); *saddle-point stability for* $1+1/\eta<\sigma<1+1/\eta+(1-\pi)/\pi\eta$,

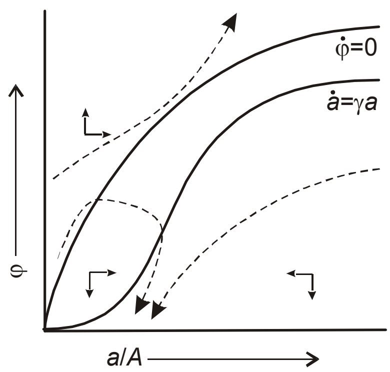

FIGURE 1c. *Phase diagram for* (a,φ); *unstable for* $1+1/\eta<\sigma<1+1/\eta+(1-\pi)/\pi\eta$,

small $\hat{y}$ large $\hat{y}$

We will measure the rate of return through the decrease in prices as a function of the output level, $\omega(y)=-(\mathrm{d}p/\mathrm{d}y)/(y/p)$.[5] For convenience, we use the symbol ε to denote relative growth rates, $\varepsilon_p=\mathrm{d}p/p$, $\varepsilon_y=\mathrm{d}y/y$, and we use double subscripts to denote elasticities, $\varepsilon_{py}=\varepsilon_p/\varepsilon_y=-\omega(y)$. Notice that we measure the scale effect with respect to actual output y; we study returns to scale in supply and abstract from the demand equation (1), and from the variable $\hat{y}$. To sketch the significance of returns to scale in production for the existence and stability of a steady state, first consider a simple economy of constant returns to scale, $\omega(y)\equiv 0$. Production prices are independent of the output level and a stable steady state exists where supply meets demand. In an economy with increasing returns to scale, i.e. $\omega>0$ and constant, a stable steady state exists as long as demand is inelastic or increasing returns are not too large, $\sigma\omega<1$. On the other hand, if demand is highly elastic, or if increasing returns to scale are sufficiently large, that is if $\sigma\omega>1$, an unstable steady state arises. As we will show, in our economy, the returns to scale vary with the output level; the condition for a stable steady state $\sigma\omega(y)<1$ can thus hold for small output levels y, while it does not hold for large output levels y.

Recall from (17) that prices p are proportional to $a^{-\eta}$, and thus

$$\omega(y) = -\varepsilon_{py} = \eta\, \varepsilon_{ay}. \tag{29}$$

Substitution of (22) with $\dot{\varphi}=0$ in (28) provides the relation between y and a:

$$a^{1+\eta+(1-\pi)/\pi}\,(a+A)^{-(1-\pi)/\pi} = \rho^{-1}\,\gamma^{-(1-\pi)/\pi}\,\zeta^{1/\pi}\,\xi\, y. \tag{30}$$

On the balanced growth path and for a given point in time, we may consider A and ξ fixed so that we can study the relation between y and a. Both sides of the equation are monotonically increasing in a and y, respectively, and if $y\to 0$, then $a\to 0$, and if $y\to\infty$, then $a\to\infty$. Thus, $\varepsilon_{ay}>0$, and production has increasing returns to scale. For low values of demand y, the sector specific technology is substantially below the general purpose technology spillover, $a\ll A$, and we have that

[5] The value of $1+\omega(y)$ is often labeled the scale factor. The value of $\omega(y)$ is also known as Verdoorn's coefficient (cf. Jefferson 1988, Harris and Lau 1998).

$$\varepsilon_{ay} = 1/(1+\eta+(1-\pi)/\pi) , \qquad (31)$$

so that (for y small),

$$\lim_{y\to 0} \omega(y) = -\varepsilon_{py} = \eta/(1+\eta+(1-\pi)/\pi) . \qquad (32)$$

For large values of demand and sector specific technology, $a>>A$, we have from (30) that

$$\varepsilon_{ay} = 1/(1+\eta) , \qquad (33)$$

so that,

$$\lim_{y\to \infty} \omega(y) = -\varepsilon_{py} = \eta/(1+\eta) . \qquad (34)$$

The economy does not only exhibit increasing returns to scale, $\omega(y)>0$, but remarkably, the returns to scale accelerate when output levels increase, $\omega'(y)>0$. This finding is consistent with the empirical literature (Caballero and Lyons 1992; Basu and Fernald 1997).[6]

The feature of $\omega(y)$ enables us to appreciate the phase diagrams of Figure 1. First, let us consider the case in which demand is relatively inelastic, $\sigma<1+1/\eta$. For all output levels, $\sigma\omega(y)<1$, and though the supply curves is downward sloping because of increasing returns to scale, still, the demand curve crosses the supply curve from above and there exists a stable steady state, as in Figure 2a. For $\sigma>1+1/\eta+(1-\pi)/\pi\eta$, not represented in Figure 1 and Figure 2, we have that $\sigma\omega(y)>1$ for all y, and supply will cross demand from above, signifying an unstable steady state. For $1+1/\eta<\sigma<1+1/\eta+(1-\pi)/\pi\eta$, we have that $\sigma\omega(0)<1<\sigma\omega(\infty)$. For low values of the size of the market, $\hat{y}$, demand crosses supply two times, and a stable and unstable steady state exists (Figure 2b). For $\hat{y}$ large, the demand curve shifts to the right and no steady state exists (Figure 2c).

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[6] Basu and Fernald (1997) find a substantial gap between the estimated rate of return on the disaggregate level and the aggregate level of production. They also show that the gap decreases if they correct their estimates for factor reallocation between sectors. From this, they conclude that the returns on aggregate level are insufficient to warrant the use of analytical models that require substantial increasing returns for providing specific results. We stress that the results of our analysis do not require substantial increasing returns. A small gap between returns to scale for low and high output levels suffices.

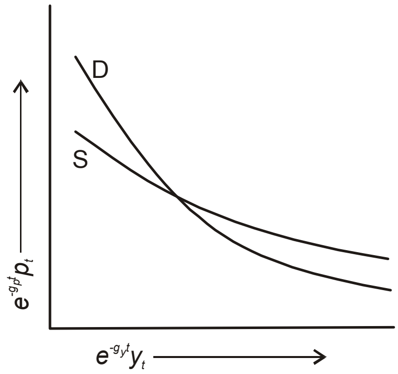

FIGURE 2a. *Demand* (D) *and Supply* (S); $0 \leq \sigma < 1+1/\eta$

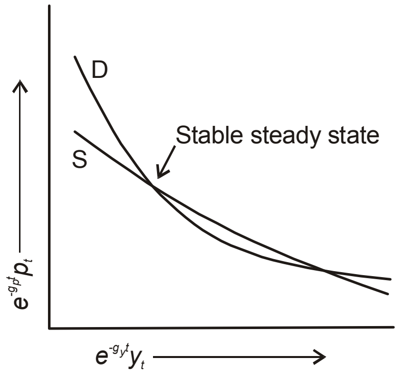

FIGURE 2b. *Demand* (D) *and Supply* (S); $1+1/\eta < \sigma < 1+1/\eta+(1-\pi)/\pi\eta$, small $\hat{y}$

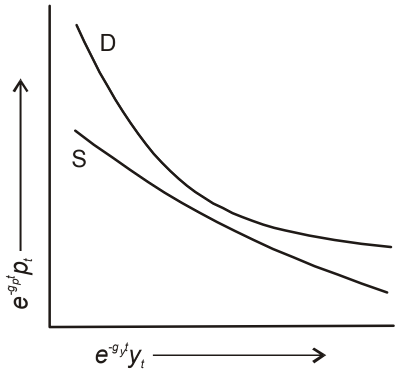

FIGURE 2c. *Demand* (D) *and Supply* (S); $1+1/\eta < \sigma < 1+1/\eta+(1-\pi)/\pi\eta$, large $\hat{y}$

4. Resource price elasticities

In this section, we study the response of output, technology, and resource use on a permanent shock in the resource price. The production factors will substitute, and technology will adapt to the change in factor prices. We can think of a resource tax that increases the resource price, and this section deals with the implications of ITC for the effectiveness of such a tax. In precise terms, we calculate the resource price elasticities for output, technology and resource use, distinguishing the direct factor substitution effect from ITC effects. More or less, in the short term, technology does not adjust and direct factor substitution is most important. In the long term, induced technological change will play a role.

An increase in the resource price q implies an increase in the unit production cost for the capital-labor-resource composite ξ by (15):

$$\varepsilon_{\xi q} = \beta. \tag{35}$$

In the short term, technology does not adjust, ε_a=0, and output prices go up by the same rate as the composite input (17):

$$\varepsilon_{pq} = \varepsilon_{\xi q} = \beta. \tag{36}$$

Consequently, output falls (1),

$$\varepsilon_{yq} = -\sigma\varepsilon_{pq} = -\beta\sigma, \tag{37}$$

and since resource expenditures have a fixed share in output value, $\beta/(1+\eta)$, resource use adjusts according to

$$\varepsilon_{eq} = \varepsilon_{yq} + \varepsilon_{pq} - 1 = -\beta\sigma-(1-\beta), \tag{38}$$

where the first part, $\varepsilon_{yq}=-\beta\sigma$, accounts for the decrease in output demand; this signifies the composition effect when seen from the overall macro-economic perspective. The second part, $\varepsilon_{pq}-1=\beta-1$, accounts for factor substitution.

In the long term, technology adjusts and changes in output prices p consist of one part reflecting the immediate production costs increase and another part reflecting the change in technology (17). Equation (36) becomes:

$$\varepsilon_{pq} = \varepsilon_{\xi q} - \eta\ \varepsilon_{aq}\ . \tag{39}$$

Technology adjusts because of two opposite forces (30). An increase in production costs ξ makes innovations more profitable, and thus, innovations increase, partly offsetting the resource tax. At the same time, a decrease in output level y decreases the value of innovations, and thus, decreases the innovation level. We have[7]

$$\varepsilon_{aq} = (\omega(y)/\eta)(\varepsilon_{yq} + \varepsilon_{\xi q}). \tag{40}$$

Substitution of (39) and (40) in (37) gives:

$$\varepsilon_{y\xi} = -\sigma(1-\omega(y))/(1-\sigma\omega(y)), \tag{41}$$

and in turn,

$$\varepsilon_{yq} = \varepsilon_{y\xi}\ \varepsilon_{\xi q} = -\beta\sigma(1-\omega(y))/(1-\sigma\omega(y)). \tag{42}$$

The short-term elasticity of output with respect to resource prices, $\varepsilon_{yq} = -\beta\sigma$ (37), is multiplied by the factor $(1-\omega(y))/(1-\sigma\omega(y))$ to reach the long-term elasticity. For inelastic demand, $\sigma<1$, an increase in innovations partly compensates for the increase in production costs ξ, $\varepsilon_{aq}>0$. After an initial fall in output, following a price increase for the resource, due to ITC in the long term,

[7] Notice that the elasticity of the left-hand-side of equation (30) with respect to a is $\omega(y)/\eta$; see also the derivation of $\omega(y)$ in (32) and (34).

production levels partly recover. For elastic demand, $\sigma>1$, the decrease in output reduces the value of innovations so much that research activities decrease, $\varepsilon_{aq}<0$, and due to ITC in the long term, production levels continue to fall. In the intermediate case, $\sigma=1$, the two forces of (40) balance and technology is unaffected by resource prices, $\varepsilon_{aq}=0$.

Under ITC, resource use adjusts according to (38), (41), and $\varepsilon_{pq}= -(1/\sigma)\varepsilon_{yq}$:

$$\varepsilon_{eq} = \varepsilon_{yq} + \varepsilon_{pq} - 1 = (1-\sigma)\beta(1-\omega(y))/(1-\sigma\omega(y)) - 1. \quad (43)$$

The short-term (38) and long-term (43) elasticity of resource use coincide for $\sigma=1$, since then, the level of technology is unaffected by resource prices. For inelastic demand, $\sigma<1$, ITC enables a recovering output level in the long term, while further reducing resource use, that is innovation is an effective substitute for the resource. For elastic demand, $\sigma>1$, ITC increases the resource intensity of production and it reduces resource use mainly through an enhanced decrease in output levels.

To assess the significance of ITC relative to factor substitution without ITC, we compare the elasticities of output and resource use with and without ITC, using some basic numbers that give an impression of climate change policy analyses insofar considering energy savings. We treat primary energy, such as oil, as the resource *e*, available at the cost of 2.5 \$/GJ (IEA/OECD, 1999, p.41), and with an average carbon content of about 0.025 gC/kJ. A carbon tax of 25 \$/tC will increase primary energy prices by 25%. Primary energy is used to produce end-use energy (e.g. heating), where primary energy sources have a cost share of say 50 per cent, $\beta=0.5$. We notice that the value of β has no bearing on the relative effect of ITC. Furthermore, we assume that energy is essential for production, and demand has a low elasticity of 0.4 (Manne *et al*. 1995). Finally, we assume moderate increasing returns for the energy sector of 20 per cent, $\omega=0.2$.[8] The calculated elasticities are reported in Table 1. The elasticity of end-use energy without ITC amounts to –0.20. The elasticity of primary energy use without ITC is –0.70. The elasticity of end-use energy with ITC is –0.17. The elasticity of primary energy use with ITC is –0.74. A carbon tax of 25 \$/tC decreases primary energy use by 16.1 %, without ITC, and by 16.9 %, with

[8] For the illustrative calculations, increasingness of $\omega(y)$ is inconsequential.

ITC.[9] In this example, the effect of ITC on primary energy use is insignificant. This confirms the result by Nordhaus (2002) who also found ITC to be less effective then direct factor substitution.

Table 1. *Calculated elasticities with respect to the resource price**

	One technology		Two technologies	
	Without ITC	With ITC	Without ITC	With ITC
Output	–0.20	–0.17	–0.28	–0.70
Resource use	–0.70	–0.74	–0.78	–1.50

* Calculations based on: β=0.5, ω=0.2, σ=0.4 (one technology, using equations (37), (38), (42), and (43)), σ=3, y_1/y_2=9 (two technologies, using equations (56), (57), (59), and (60))

Yet, if we assume that carbon-rich energy sources compete with carbon-poor or carbon-free energy sources, a different context arises, and as we will show analytically in Section 6, and as presented numerically in Table 1, the contribution of ITC increases considerably. In the context of competing technologies, demand for output produced with a specific technology is not determined by demand elasticities for total output, e.g. by energy requirements for production. Instead, demand is determined by competition between goods produced with different technologies, and we expect a higher elasticity of demand for technology specific output. Moreover, in the energy context, the competing carbon-poor or carbon-free energy sources will also benefit from increasing returns to scale through ITC when they gain market share. This brings us to the next section, where we study the joint innovation efforts for competing technologies.

5. Competing technologies

So far we did not explicitly consider competition between technologies. In this section, we extend the one-technology model assuming two competing technologies that can be used for production. Goods produced by both technologies have their own characteristics but are substitutes; we use the same elasticity of substitution σ as above, now to denote the constant elasticity of substitution between technologies. For convenience, we assume inelastic demand on the aggregate level, $\bar{y}_t$,

[9] Notice that we take the exponential function of the elasticity multiplied by the relative price increase of 25%: –0.161=1–exp(–0.7x0.25), and –0.169=1–exp(–0.74x0.25).

that grows at a constant rate γ, so that we can focus on the substitution effects between the two technologies. The technologies are denoted by g=1,2. Output aggregation satisfies

$$(y_{1,t}^{(\sigma-1)/\sigma} + y_{2,t}^{(\sigma-1)/\sigma})^{\sigma/(\sigma-1)} = \bar{y}_t \,. \tag{44}$$

We can think of various energy sources, such as oil, gas, and renewable energy systems, operating on the energy market. In a classic economy of constant returns to scale, each technology has a 'natural' share of the market, inversely proportional to the production costs associated with that technology. In an economy with increasing returns to scale, but with a constant scale factor, $1+\omega$, both technologies would share the market if both technologies are poor substitutes, or if the scale factor is not too large, $\sigma\omega<1$. On the other hand, if both technologies are good substitutes, or if there are substantial increasing returns to scale, $\sigma\omega>1$, full specialization would occur. In our economy, the returns to scale increase with the output level, and thus, it may be that $\sigma\omega(0)<1$, while $\sigma\omega(y)>1$ for larger values of output y. The increasingness of $\omega(y)$ can produce a partial pattern of specialization.

In this section, we will assume that both technologies have the same production costs net of technology, $\xi_1=\xi_2$. The states of technology a_g determine the prices p_g (17), which determine the output levels y_g (45), which drive the price dynamics for technology, $\dot{\varphi}$ (22). Simultaneously, innovation prices drive the technology dynamics (25), and this defines a four-dimensional dynamic system for $(a_1,a_2,\varphi_1,\varphi_2)$. The direct analysis thereof is beyond our capabilities. Instead, we consider steady states and we study an auxiliary mapping Λ:[0,1]$\to$[0,1] that measures the feed back of output levels on demand. To specify the mapping $\Lambda(.)$, we use the variable x_g for demand, and y_g for output levels. The economy is in equilibrium if $x_g=y_g$. For x_g and y_g, the same aggregation equation (44) applies. Furthermore, let the variable s_y be the share of technology 1 in total output, $s_y=y_1/(y_1+y_2)$, $0\leq s_y\leq 1$, and similarly, s_x is the share of technology 1 in total demand, $s_x=x_1/(x_1+x_2)$, $0\leq s_x\leq 1$. From s_y, we can derive the output levels (y_1,y_2), based on (44), and in turn the steady state technology levels (a_1,a_2) and prices (p_1,p_2), based on (30) and (17), respectively. Now, prices determine the share of the first sector in total demand, s_x, through

$$x_1/x_2 = (p_1/p_2)^{-\sigma} \,, \tag{45}$$

jointly with (44). The chain $s_y\to(y_1,y_2)\to(a_1,a_2)\to(p_1,p_2)\to s_x$ defines the mapping $\Lambda: s_y\to s_x$.

A fixed point $s_x=s_y=s^*$; $\Lambda(s^*)=s^*$ indicates a steady state solution. There are three obvious fixed points. $\Lambda(0)=0$, since for s_y=0, we have $y_1=0$ so that $a_1=0$, $p_1=\infty$, and in turn $x_1=0$. Similarly, $\Lambda(1)=1$. For s_y=½, we have $y_1=y_2$ so that $a_1=a_2$, $p_1=p_2$, and in turn $x_1=x_2$. Thus,

$\Lambda(½)=½$, as well. The slope of $\Lambda(.)$ around a fixed point tells us whether the steady state is stable, or unstable. If $\Lambda'(s^*)>1$, as in point *C* in Figure 3b and Figure 3c, then the balanced growth path *C* is unstable. An increase in the production share for technology 1, relative to the balanced growth path, will decrease production costs by so much that the increase in demand for goods produced with technology 1 exceeds the increase in production. The increase in demand further stimulates decreasing production costs, and production will converge to the stable balanced growth path *D* or *E*, for Figure 3b and Figure 3c, respectively. If $\Lambda'(s^*)<1$, as in point *C* in Figure 3a, then the balanced growth path *C* is stable. In this section, we show that Figure 3a, Figure 3b, and Figure 3c cover all possible configurations, dependent on the value of σ *vis-à-vis* the elasticity of productivity $\omega(0)$ and $\omega(½\,\bar{y})$.

On a fixed point of $\Lambda(.)$, we have $x_1=y_1$, and $x_2=y_2$, and $\Lambda'(.)>1$ is equivalent with $\mathrm{d}x_1/\mathrm{d}y_1>1$, or $\varepsilon_{x_1y_1}>1$. The elasticity of x_1 relative to y_1 we study here. From the CES aggregation (44) we have

$$\varepsilon_{y_1} = -(y_2/y_1)^{(\sigma-1)/\sigma}\,\varepsilon_{y_2}\,. \tag{46}$$

We first study the value of $\varepsilon_{x_1y_1}$ around s_y=0, that is for small values of s_y, so that $y_1<<y_2$. We can take ε_{y_2}=0 (46), and focus on output and demand changes for the first technology, ε_{y_1} and ε_{x_1}. By definition of $\omega(.)$, prices satisfy

$$\varepsilon_{p_1y_1} = -\omega(0) \tag{47}$$

whereas ε_{p_2}=0. At the same time, demand satisfies

$$\varepsilon_{x_1p_1} = -\sigma \tag{48}$$

so that

$$\varepsilon_{x_1y_1} = \varepsilon_{x_1p_1}\,\varepsilon_{p_1y_1} = \sigma\omega(0) \tag{49}$$

The slope of $\Lambda(.)$ satisfies $\Lambda'(0)>1$ if $\sigma\omega(0)>1$, as in Figure 3a and Figure 3b. In contrast, if $\sigma\rho(0)<1$, $\Lambda'(0)<1$ and demand will fall short of supply for low levels of y_1, as in Figure 3c.

Now consider the steady state with $y=y_1=y_2=(½)^{\sigma/(\sigma-1)}\,\bar{y}$, and $s_y=s_x=½$. Then, from (46), we have that $\varepsilon_{y_1y_2}=-1$, and $\varepsilon_{x_1x_2}=-1$. Analogous to the analysis for $s_y\to 0$, above, we deduct

$$\varepsilon_{p_1y_1} = -\omega(y)\ ;\ \varepsilon_{p_2y_2} = \omega(y). \tag{50}$$

At the same time, demand satisfies

$$\varepsilon_{x_1p_1} = -\tfrac{1}{2}\sigma \; ; \; \varepsilon_{x_1p_2} = \tfrac{1}{2}\sigma \; , \tag{51}$$

so that

$$\varepsilon_{x_1y_1} = \varepsilon_{x_1p_1}\,\varepsilon_{p_1y_1} + \varepsilon_{x_1p_2}\,\varepsilon_{p_2y_2}\,\varepsilon_{y_2y_1} = \sigma\omega(y) \; . \tag{52}$$

The slope of $\Lambda(.)$ satisfies $\Lambda'(\tfrac{1}{2})>1$ if $\sigma\omega((\tfrac{1}{2})^{\sigma/(\sigma-1)}\,\bar{y})>1$, as in Figure 3b and Figure 3c. In contrast, if $\sigma\omega((\tfrac{1}{2})^{\sigma/(\sigma-1)}\,\bar{y})<1$, $\Lambda'(\tfrac{1}{2})<1$ and demand will fall short of supply for decreasing levels of y_1, as in Figure 3a.

We can now distinguish three cases. First, if $\sigma\omega((\tfrac{1}{2})^{\sigma/(\sigma-1)}\,\bar{y})<1$, then also $\sigma\omega(0)<1$ and the graph of $\Lambda(.)$ will look as in Figure 3a. The goods are too poor substitutes, or even complements if $\sigma<1$, and no specialization will take place. There is one stable balanced growth path in which both technologies produce half of total output, *C*, and there are two unstable extreme balanced growth paths *A* and *E*. If $\sigma\omega(0)<1<\sigma\omega((\tfrac{1}{2})^{\sigma/(\sigma-1)}\,\bar{y})$, Figure 3b applies. The increasing returns to scale in production, jointly with the good substitutability between the two technologies, make an equal partition of production over both sectors *C* unstable. However, returns to scale are also insufficient to warrant an extreme specialization; *A* and *E* are unstable as well. There must be two symmetric stable balanced growth paths of partial specialization, *B* and *D*. If $1<\sigma\rho(0)<\sigma\rho((\tfrac{1}{2})^{\sigma/(\sigma-1)}\,\bar{y})$, then Figure 3c applies. Both goods are good substitutes and it is optimal to fully specialize using one technology only; *A* and *E* are stable, *C* is unstable.

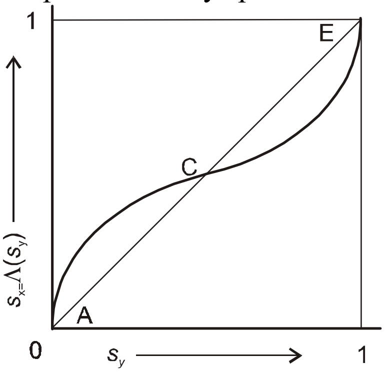

FIGURE 3a. *Mapping* $\Lambda(.)$ *for* $\sigma\omega(0)<\sigma\omega((\tfrac{1}{2})^{\sigma/(\sigma-1)}\,\bar{y})<1$

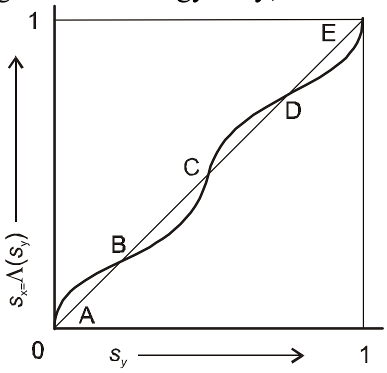

FIGURE 3b. *Mapping* $\Lambda(.)$ *for* $\sigma\omega(0)<1<\sigma\omega((\tfrac{1}{2})^{\sigma/(\sigma-1)}\,\bar{y})$

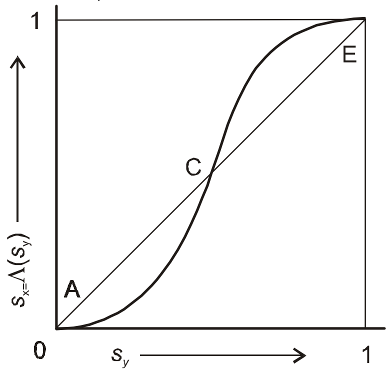

FIGURE 3c. *Mapping* $\Lambda(.)$ *for* $1<\sigma\omega(0)<\sigma\omega((\tfrac{1}{2})^{\sigma/(\sigma-1)}\,\bar{y})$

6. Resource price elasticities

In this section, we extend the analysis of Section 4, investigating the response of output, technology, and resource use on changes in the resource price for the economy with two competing technologies. We copy the structure of Section 4, comparing the response without ITC with the response with ITC. Assume that the two technologies use different resources, or use the same resource but with different share parameters β_g. An increase in the resource price will affect both technologies differently. For convenience, we assume that both technologies use different resources, and we study an increase in the resource price used by the first technology.

Without technological change, prices adjust only for goods produced with the first technology

$$\varepsilon_{p_1q_1} = \beta \ ; \ \varepsilon_{p_2q_1} = 0. \tag{53}$$

From the demand equation (45), where we use the equilibrium assumption of $x_g = y_g$, we deduce

$$(\varepsilon_{y_1} - \varepsilon_{y_2}) = -\sigma(\varepsilon_{p_1} - \varepsilon_{p_2}). \tag{54}$$

Substitution of (46) yields:

$$\varepsilon_{y_1}(1+(y_1/y_2)^{(\sigma-1)/\sigma}) = -\sigma\beta\varepsilon_{q_1}. \tag{55}$$

Rearranging terms gives for the elasticity of output:

$$\varepsilon_{y_1q_1} = -\sigma\beta/(1+(y_1/y_2)^{(\sigma-1)/\sigma}), \tag{56}$$

and (38) results in the elasticity of resource use:

$$\varepsilon_{e_1q_1} = \varepsilon_{y_1q_1} + \varepsilon_{p_1q_1} - 1 = -\sigma\beta/(1+(y_1/y_2)^{(\sigma-1)/\sigma}) - (1-\beta). \tag{57}$$

The elasticities calculated in (56) and (57) resemble the one-technology values calculated in (37) and (38), except for the correction of the fact that, when the first technology has gained a substantial share, the elasticity of demand decreases.

With ITC, technology a_g adjusts, and (53) becomes:

$$\varepsilon_{p_1q_1} = \beta - \omega(y_1)\varepsilon_{y_1q_1} \ ; \ \varepsilon_{p_2q_1} = -\omega(y_2)\varepsilon_{y_2q_1}. \tag{58}$$

After adjusting (55) and rearranging, the elasticity of output, (56) is calculated as:

$$\varepsilon_{y_1q_1} = -\sigma\beta/(1+(y_1/y_2)^{(\sigma-1)/\sigma} - \sigma\omega(y_1) - (y_1/y_2)^{(\sigma-1)/\sigma}\sigma\omega(y_2)). \tag{59}$$

The long-term resource elasticity is now calculated as:

$$\varepsilon_{e_1q_1} = (-\sigma\beta/(1+(y_1/y_2)^{(\sigma-1)/\sigma}-\sigma\omega(y_1)-(y_1/y_2)^{(\sigma-1)/\sigma}\sigma\omega(y_2))-(1-\beta))/(1-\omega(y_1)). \quad (60)$$

Comparing (57) with (59), we see that ITC increases the elasticity of output with respect to resource prices. Yet, similar to the case for the one-technology model, if both technologies are poor substitutes, or if both technologies have almost constant returns to scale, i.e. $\sigma\omega(y)<<1$ for all y, then the additional effect of ITC on resource reduction is limited. On the other hand, when both technologies are moderate substitutes or have sufficient increasing returns to scale, say $½<\sigma\omega(y)<1$, for $y=((½)^{\sigma/(\sigma-1)}\bar{y})$, then the denominator in (59) is halved because of ITC. The additional effect of ITC on output levels exceeds the primary effect of factor and technology substitution.

Figure 4a portrays the shift in the mapping $\Lambda(.)$, taking account of endogenous technology levels, caused by a change in production costs ξ_1. The dashed line represents the mapping for $\xi_1=\xi_2$. When the production costs of the first technology increase, $d(\xi_1/\xi_2)>0$, output prices for the first technology increase, given output shares as determined by s_y, and demand for the output good produced by the first technology decreases. The mapping $\Lambda(.)$ adjusts downwards. The stable steady state C shifts to C' where the first technology has a lower share.

ITC has more drastic impact when substitutability and returns to scale produce one dominant and one minor technology, as presented in Figure 3b, when two stable steady states exist, one in which the first technology is dominant (D), the other in which the second technology is dominant (B). In principle, it is possible that the denominator of the right-hand-side of equation (59) becomes zero, since $\sigma\omega(y_1)>1$. That is, the price elasticity of resource use with ITC may become infinite. Figure 4b portrays the shift in the mapping $\Lambda(.)$ when production costs ξ_1 increase for the first technology. The mapping $\Lambda(.)$ shifts to the right, the stable steady state D shifts downwards, and the unstable steady state C shifts upwards. (Indeed, the denominator of the right-hand-side of equation (59) is negative, since for C, $\sigma\omega(y)>1$, $y=y_1=y_2$.) When the resource price continues to increase, at a certain moment, the steady states C and D coincide, making a bifurcation equilibrium G. A further increase of the tax will set the curve $\Lambda(.)$ loose of the diagonal, and the steady states C and D vanish.

We picture the so-called equilibrium surface in Figure 4c (cf. Magill 1977, Fig. 2b). The line *FDGCHBI* presents the set of steady states (shares for first sector on y-axis) as a function of the relative production costs for the two technologies, ξ_1/ξ_2.[10] The segments *FDG* and *HBI* represent stable steady states, these segments are called the stable sub-manifolds. The segment *GCH* represents the unstable steady states, called the unstable sub-manifold. The points *G* and *H* represent so-called bifurcation equilibria. The situation with equal production costs is depicted by the vertical line with $\xi_1=\xi_2$. *D* and *B* denote the stable steady states, with dominance of the first and second technology, respectively, *C* is the unstable steady state in which both technologies have equal shares. A tax on a resource that is intensively used in the first technology (in the figure, that is a shift to the right) will shift both stable steady states *B* and *D* downwards, towards a more favorable share for the second technology; the curves *BI* and *DG* are downwards sloping. When, initially, the economy is in equilibrium in *D*, a continued increase of the tax will lead to a continuous fall in the share of the first technology until, at point *G*, the system jumps to the next stable sub-manifold at point *I*. At this point *G*, a small increase in the resource tax induces technological change that leads to a major change in long-run dynamic behavior. After a jump, the economy has locked in another stable sub-manifold in which the second technology becomes dominant. The first technology will not regain its dominant position, even after complete lifting of the tax. The economy will then converge to *B*.

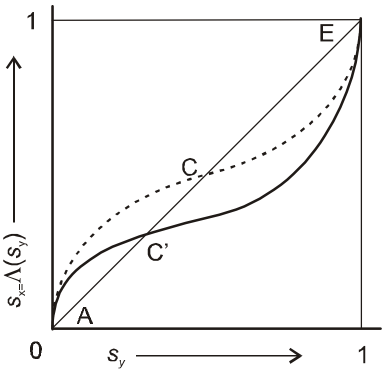

FIGURE 4a. *Shift* d(ξ_1/ξ_2)>0 *in Mapping* $\Lambda(.)$ *for* $\sigma\omega(0)<\sigma\omega((½)^{\sigma/(\sigma-1)}\bar{y})<1$

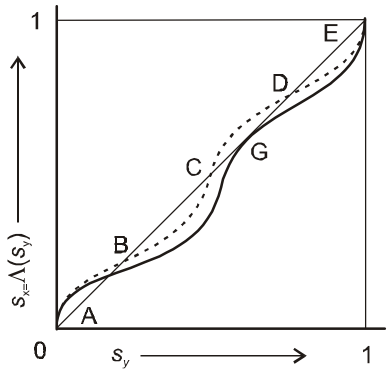

FIGURE 4b. *Shift* d(ξ_1/ξ_2)>0 *in Mapping* $\Lambda(.)$ *for* $\sigma\omega(0)<1<\sigma\omega((½)^{\sigma/(\sigma-1)}\bar{y})$

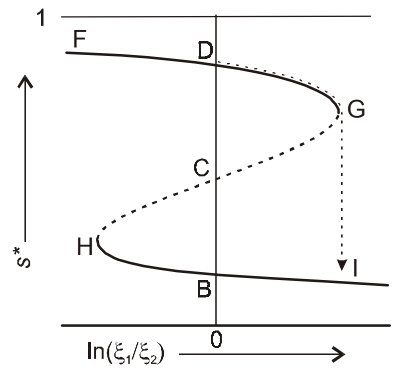

FIGURE 4c. *Equilibrium surface for* $\sigma\omega(0)<1<\sigma\omega((½)^{\sigma/(\sigma-1)}\bar{y})$

To conclude this section, we continue the numerical assessment of ITC as presented at the end of Section 4. We follow the suggestion by Weyant and Olavson (1999) and consider a

[10] In the figure, we use $\ln(\xi_1/\xi_2)$ on the horizontal axis to have symmetry over the axis with $\xi_1=\xi_2$.

carbon-rich energy technology in competition with a carbon-free energy technology; the elasticity of substitution between both technologies is assumed $\sigma=3$.[11] We abstract from changes in the overall energy demand, and focus on the substitution between the energy sources. Let us consider a future period, say 2025, in which carbon-rich energy sources capture a stable market share of 90%, whereas the carbon-free energy sources produce the remaining 10%. We maintain the basic numbers from Section 4. A carbon tax of 25 \$/tC increases fossil fuel prices by 25%. Primary energy sources have a cost share of 50 per cent, $\beta=0.5$. We furthermore assume increasing returns for both energy technologies of 20 per cent, $\omega=0.2$. Results are presented in Table 1. The elasticity of end-use carbon-rich energy without ITC amounts to –0.28. The elasticity of primary carbon-rich energy use without ITC is –0.78. These values are comparable with the values for the one-technology model, see Table 1. The elasticity of end-use energy with ITC is –0.70. The elasticity of primary energy use with ITC is –1.50. A carbon tax of 25 \$/tC decreases fossil fuel primary energy use by 17.7 %, without ITC, and by 31.4 %, with ITC. In contrast with the one-technology model, the effect of ITC is rather substantial in the two-technology model.

7. ITC and climate change

Induced technological change makes pollution control less costly in the long run. In this paper, we have studied the response of output and resource use to changes in factor costs as caused by e.g. environmental taxes. We studied two models with endogenous R&D expenditures. In the first model, there is one technology available for production of a certain good. In the second model, two technologies compete, that is, two technologies can be used to produce goods that are good substitutes. For both models, we calculated explicit expressions for the elasticity of output and resource use, with and without ITC. Based on sensible parameter values, we found that ITC will not prove a substantial contribution to resource reduction when there is one technology and demand is inelastic. This configuration applies to the energy savings debate. Our analysis suggests that ITC has not much potential to improve on the direct factor substitution of capital, labor and other production factors for energy, for given technology. In this context, our analysis sketches a pessimistic perspective, suggesting that there are limits to improvements in energy efficiency. These limits to substitution, away from energy in favor of other factors, can also be understood

[11] In many applied models, various energy sources are assumed perfect substitutes, $\sigma=\infty$. We choose a less extreme value for σ to account for some complementarity between energy sources.

from a physical perspective. They arise because various basic activities (e.g. heating, cooling, transportation) require a minimum amount of energy, given by the thermodynamic laws of physics. Also, while there is scope for sectoral shifts from highly energy intensive activities to energy extensive activities, ultimately sectoral shifts are limited too.

Yet, our analysis proves more optimistic when there are competing resources, e.g. when we aim at carbon dioxide emission reductions through a substitution away from carbon-rich energy sources toward carbon-poor or carbon-free energy sources. In this setting, ITC acts as a powerful multiplier for the price elasticity of resource use. Moreover, it is possible that multiple balanced growth paths exist, each with another dominant energy technology. Indeed, if the current energy system is biased towards fossil-fuel based energy sources, because of spill-over effects, an alternative (imaginary) energy system in which the carbon-free energy sources have traded in place with fossil-fuel energy sources can exist. Then, the configuration of multiple steady states applies to the current energy system and the economy exhibits path dependency. A pessimistic feature of this configuration is that the current economy is locked-in in fossil-fuel technologies. Carbon-free technologies will not gain a substantial market share under their own steam. The optimist feature is that, nonetheless, a carbon tax may render the current fossil-fuel dominance of the energy system unstable, setting in motion a major transition.

Having said so, it will be a challenge to develop renewable energy sources that are truly good substitutes for fossil-fuels. Solar, wind and new biomass seem too land intensive to displace fossil fuels at large scale. Moreover, solar and wind are intermittent, greatly limiting the amount that can be used to directly produce electricity, while storage of solar and wind energy (e.g. as hydrogen) remains a very expensive option. There is a need to search for new concentrated sources of energy, such as nuclear fusion, or geothermal sources from below the earth's mantle, capable of eventually displacing fossil fuels. The development of these sources naturally is a very long-term enterprise, and the commencement of such development requires more than a modest increase in fossil-fuels prices.

Acknowledgments

The author is grateful to David Popp, Chris Green, and Sjak Smulders for their suggestions and comments on an earlier draft. The usual disclaimer applies. The research has been funded by the Dutch National Science Foundation (NWO) under contract nr. 016.005.040.

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(l) This paper was presented at the Workshop "Growth, Environmental Policies and Sustainability" organised by the Fondazione Eni Enrico Mattei, Venice, June 1, 2001
(li) This paper was presented at the Fourth Toulouse Conference on Environment and Resource Economics on "Property Rights, Institutions and Management of Environmental and Natural Resources", organised by Fondazione Eni Enrico Mattei, IDEI and INRA and sponsored by MATE, Toulouse, May 3-4, 2001
(lii) This paper was presented at the International Conference on "Economic Valuation of Environmental Goods", organised by Fondazione Eni Enrico Mattei in cooperation with CORILA, Venice, May 11, 2001
(liii) This paper was circulated at the International Conference on "Climate Policy – Do We Need a New Approach?", jointly organised by Fondazione Eni Enrico Mattei, Stanford University and Venice International University, Isola di San Servolo, Venice, September 6-8, 2001
(liv) This paper was presented at the Seventh Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Université Catholique de Louvain, Venice, Italy, January 11-12, 2002
(lv) This paper was presented at the First Workshop of the Concerted Action on Tradable Emission Permits (CATEP) organised by the Fondazione Eni Enrico Mattei, Venice, Italy, December 3-4, 2001
(lvi) This paper was presented at the ESF EURESCO Conference on Environmental Policy in a Global Economy "The International Dimension of Environmental Policy", organised with the collaboration of the Fondazione Eni Enrico Mattei , Acquafredda di Maratea, October 6-11, 2001
(lvii) This paper was presented at the First Workshop of "CFEWE – Carbon Flows between Eastern and Western Europe", organised by the Fondazione Eni Enrico Mattei and Zentrum fur Europaische Integrationsforschung (ZEI), Milan, July 5-6, 2001
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