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Abstract

In this paper, we extend the Romer (1990) model in two ways. First, we include energy consumption of intermediates. Secondly, intermediates become heterogeneous due to endogenous energy saving technical change. However, aggregate effective capital is still subject to endogenous technical change of the 'love of variety' type, as in the original Romer model. We show that the resulting system can still generate steady state growth, but the growth rate depends negatively on the growth of real energy prices. The reason is that real energy price rises will lower the profitability of using new intermediate goods and hence the profitability of doing research, ceteris paribus. Hence, in this set-up rising real energy prices are not countered by stepping up research, but provide a negative stimulus to R&D instead. We also show that in these circumstances the introduction of an energy tax that is recycled in the form of an R&D subsidy may actually increase growth, while increasing the capital intensity of production at the same time.

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1.1 Introduction

In most energy-economy models currently in use, technology is an important determinant of energy efficiency improvements. Nonetheless, in those models technology itself is weakly handled, mainly because of the focus on the energy impact of (autonomous) technological change rather than on the underlying forces that drive it.[1] Modern growth theory by contrast, and especially the work by Romer (1990) and Aghion and Howitt (1992), focuses on some of the Schumpeterian aspects of endogenous technical change, i.e. profit seeking motives as incentives to engage in research and development, and creative destruction as a disincentive. The latter brings technical change itself within the reach of policy makers.

In this paper, we extend the Romer (1990) model in two ways. *First*, we introduce intrinsic productivity differences between intermediates that are embodied in those intermediates. In this way we acknowledge the empirical observation that productivity growth and investment in equipment and machinery are positively correlated (see e.g. Gregory and James (1973) and Hulten (1992)). These productivity differences between intermediates provide a horizontal product differentiation setting, giving rise to 'creative wear and tear' instead of the 'full destruction' known from the Aghion and Howitt model. *Secondly*, we regard effective capital as a bundle consisting of 'raw' capital and energy. This enables us to see what policy conclusions can be derived from a model that exhibits endogenous technical progress fuelled by economic incentives. More in particular, we want to have a look at what rises in (real) energy prices may mean for the inducement of technical change, for long term growth perspectives and the role of (technology) policy in this respect.

In order to keep the analysis as simple as possible, we do not pay any serious attention to the question of the sustainability of growth. For our present purposes, we take that for granted by assuming that energy can be made available in any quantity at given real energy prices.

The set-up of this paper is as follows. In section 2 we briefly summarise how we have modified the Romer (1990) model. In section 3, we show what continuously rising real energy

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[1] See Verberne (1995) for an overview.

prices may mean for growth, and how an energy tax (possibly recycled in the form of a subsidy on research costs) may affect growth. Finally, we provide a summary and some concluding remarks in section 4.

1.2 The Modified Romer Model[2]

The Final Output Sector

As in Romer (1990), we use an Ethier production function for final output *Y*:

$$Y = L_Y^{1-\alpha} \int_0^A (x_i^e)^\alpha di \tag{1}$$

where L_Y is labour input used in final-output production and x_i^e are the effective capital services obtained from using the i^{th} type of intermediate good.

The level of demand for each intermediate follows from the first order conditions of the final output sector which provide the inverse demand functions for the various inputs, i.e. all the individual intermediates and labour.

The profits for the representative final-good producer are given by:

$$\Pi_Y = P_Y \cdot L_Y^{1-\alpha} \int_0^A (x_i^e)^\alpha di - \int_0^A p_i^e x_i^e di - w_Y L_Y \tag{2}$$

where P_Y is the price of final-good, w_Y is the wage-rate in the final-goods sector, and p_i^e is the rental price of the effective services of the i^{th} intermediate good. We now take final output to be

[2] We simplify the original Romer model somewhat by distinguishing only high skilled labour. For more mathematical details, one is referred to van Zon et al. (1999).

the numeraire, i.e. $P_Y = 1$. Then, in a situation of perfect competition on the final output market and the factor input markets, the first order conditions for profit maximisation are given by:

$$\frac{\partial \Pi_Y}{\partial x_i^e} = \alpha L_Y{}^{1-\alpha} (x_i^e)^{\alpha-1} - p_i^e = 0 \tag{3.A}$$

$$\frac{\partial \Pi_Y}{\partial L_Y} = (1-\alpha)\frac{Y}{L_Y} - w_Y = 0 \tag{3.B}$$

Equation (3.A) provides the inverse demand function for the sector that produces the i^{th} intermediate, whereas equation (3.B) describes the requirement that the real wage rate must equal the marginal productivity of labour. Equation (3.A) implies a price elasticity of the demand for effective capital services equal to $\varepsilon = -1/(1-\alpha)$.

The Intermediate Goods Sector

We define effective capital x_i^e supplied by the intermediate goods sector as a Cobb-Douglas aggregate of raw capital x_i and energy e_i:[3]

$$x_i^e = \lambda_i (x_i)^{\beta} (e_i)^{1-\beta} \tag{4}$$

Note that λ_i is here the 'total-factor' productivity of raw capital and energy taken together, in terms of effective capital. λ_i is represented as Hicks-neutral technical change (i.e. the type of

[3] In a growth context, a Cobb-Douglas function comes in very handy indeed. Opportunistic as we are though, it should be stressed that the literature describes two polar cases with regard to capital-energy substitution. The first case assumes that substitution possibilities are non-existent which implies capital/energy complementarity. The idea of capital-energy complementarity is supported by e.g. Berndt and Wood (1979) and, at least from a macro-economic perspective, by Solow (1987). In the other case, energy is a direct substitute for other factors of production, like labour, materials, etc. (see e.g. Jorgenson and Wilcoxen (1990) and Dean and Hoeller (1992)).

technical change that augments all factors in the same way), with proportional rate $\hat{\lambda}_i$, but since we have used a Cobb-Douglas function, it can also be interpreted as 'energy augmenting/saving' technical change at rate $\hat{\lambda}_i/(1-\beta)$. In order for our model to be able to generate steady growth, we furthermore define:

$$\lambda_i = \lambda_0 \cdot i^{\varsigma} \tag{5}$$

with $\varsigma \geq 0$. Assuming profit maximisation behaviour by the intermediate sector again, it follows that the intermediate goods sector must also be minimising the costs of producing an effective unit of capital at the same time. Assuming that factor prices are given for an individual producer of intermediate goods, the real unit minimum cost function for that producer is given by:

$$c_i(r,q) = \lambda_i^{-1}\left(\frac{r}{\beta}\right)^{\beta}\left(\frac{q}{1-\beta}\right)^{1-\beta} \tag{6}$$

where *r* is the real rental rate of raw capital, and *q* is the real price of energy. Unit costs of producing an effective unit of capital fall with the blueprint number *i*, since they depend negatively on 'total factor productivity' λ_i. The total cost of producing all effective units of capital using blueprint *i* is simply the product of $c_i(r,q)$ and x_i^e. Because of perfect competition on the factor markets and the linear homogeneity of equation (4), it follows for an individual producer of intermediate goods that $c_i(r,q)$ is also the marginal cost of producing x_i^e. Consequently, the profit maximising rental price of an effective unit of capital for the final goods producing sector, i.e. p_i^e, is given by the Amoroso-Robinson condition (cf. (3.A) and (6)):

$$p_i^e = c_i(r,q)/\alpha = \lambda_i^{-1}\left(\frac{r}{\beta}\right)^{\beta}\left(\frac{q}{1-\beta}\right)^{1-\beta}/\alpha \tag{7}$$

Note that it follows directly from Shephard's Lemma and (7) that:

$$\frac{x_i}{x_i^e} = \frac{\partial c(r,q)}{\partial r} = \lambda_i^{-1} \left(\frac{r}{\beta} \right)^{\beta - 1} \left(\frac{q}{1-\beta} \right)^{1-\beta} \tag{8.A}$$

$$\frac{e_i}{x_i^e} = \frac{\partial c(r,q)}{\partial q} = \lambda_i^{-1} \left(\frac{r}{\beta} \right)^{\beta} \left(\frac{q}{1-\beta} \right)^{-\beta} \tag{8.B}$$

After substitution of (8.A) and (8.B) into the definitions of aggregate physical capital (i.e. $K = \int_0^A x_i di$), effective capital (i.e. $K^e = \left(\int_0^A (x_i^e)^\alpha di \right)^{1/\alpha}$, cf. equation (1))[4], and total energy demand (i.e. $E = \int_0^A e_i di$), we readily obtain through direct integration over all technologies:

$$K^e = KA^{(1-\alpha+\alpha\varsigma)/\alpha} \left(\frac{1-\alpha}{1-\alpha+\varsigma\alpha} \right)^{(1-\alpha)/\alpha} \lambda_0 \left(\frac{r}{\beta} \right)^{1-\beta} \left(\frac{q}{1-\beta} \right)^{\beta-1} \tag{9.A}$$

$$E = K \frac{r(1-\beta)}{q\beta} \tag{9.B}$$

Assuming that the growth rate of real energy prices, the real rate of interest and L_Y are constant in the steady state, it follows from equations (1) and (9.A), (9.B) that the steady state growth rate is given by:

$$\hat{Y} = \hat{K} = \frac{1-\alpha+\varsigma\alpha}{1-\alpha} \hat{A} - \frac{\alpha(1-\beta)}{1-\alpha} \hat{q} \tag{10}$$

Equation (10) shows that the steady state growth rate *tends* to exceed the growth rate of the number of blueprints, if $\varsigma \geq 0$. However, continuous rises in real energy prices call for a more intensive use of raw capital as a substitute for energy, which would lower the steady state growth

[4] Note that K^e is actually a CES aggregate of the underlying services of intermediates.

rate in turn. Moreover, the higher the effective capital elasticity of energy (i.e. $1-\beta$) is, the stronger will be the decrease in the growth rate of output for a given growth rate of real energy prices.[5]

The Blueprint Sector

The blueprint sector uses labour to produce blueprints next to the experience accumulated during the production of all previous blueprints:

$$\frac{dA}{dt} = \delta A L_A \;\Rightarrow\; \hat{A} = \delta(L - L_Y) \tag{11}$$

where δ represents the productivity of the blueprint generation process, while $L_A=L-L_Y$ is the amount of labour used in generating blueprints. L is the total labour force. The proceeds from selling blueprints are paid as wages to R&D workers:

$$w_A L_A = \frac{dA}{dt} V_A = \delta A L_A \frac{\Pi_A}{r-\hat{\pi}_A} = \delta A L_A (1-\alpha)\alpha L_Y^{1-\alpha} (x_A^e)^{\alpha} / (r-\hat{\pi}_A) \tag{12}$$

where we have used (3.A), (7) and (11) as well as the expression for instantaneous profits. Note that $V_A = \Pi_A/(r-\hat{\pi}_A)$ is the present value of the newest blue print, and $\Pi_A = (1-\alpha)p_i^e x_i^e$ is instantaneous profit. Moreover, $\hat{\pi}_A = -(a(1-\beta)/(1-\alpha))\hat{q}$ is the ex-post growth in profits due to changes in marginal costs.[6]

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[5] A high value of *1-β* implies that the marginal costs of effective capital consist largely of energy costs.

[6] Note that we assume that only real energy cost may change in the steady state.

Labour Market Equilibrium

Labour market arbitrage ensures that $w_Y = w_A$. Substitution of equations (12) and (3.B) into this arbitrage condition results in: [7]

$$L_y = \frac{r}{\alpha\delta z'} + \frac{(1-\beta)\hat{q}}{(1-\alpha)\delta z'} \tag{13}$$

where $z' = (1-\alpha+\varsigma\alpha)/(1-\alpha)$. From equation (13) it is clear that continuously rising real energy prices reduce the profitability of generating new blueprints. In that case, the allocation of labour will change in favour of final output generation. This also happens if the real interest rate rises, which calls for less round about ways of producing output, i.e. less knowledge intensive production.

Steady State Results

Equation (13) can be substituted into equation (11), the result of which in turn can be substituted into equation (10), giving us the steady state growth rate that the system is able to generate, for given values of *r* and $\hat{q}$:

$$\hat{Y} = \delta z' L - r/\alpha - \hat{q}\left(\frac{(1-\beta)(1+\alpha)}{1-\alpha}\right) \tag{14}$$

Likewise, the 'growth demand-side' as given by optimum saving behaviour is implicitly described by the requirement that:

$$\hat{C} = \hat{Y} = (r-\rho)/\theta \tag{15}$$

[7] See van Zon et al. (1999) for the mathematical details.

where $\sigma = 1/\theta$ is the intertemporal elasticity of substitution and ρ is the discount rate, and *C* is private consumption..

The equilibrium steady state growth rate is now easily obtained by eliminating the real interest rate r from equations (14) and (15), giving:

$$\hat{Y} = \left(\frac{\alpha}{\alpha+\theta}\right)\left(\delta z' L - \rho/\alpha - \hat{q}(1-\beta)\left(1+\alpha\right)/(1-\alpha)\right) \tag{16.A}$$

The corresponding equilibrium value of the real interest rate is then given by:

$$r = \left(\frac{\alpha\theta}{\alpha+\theta}\right)\left(\delta z' L - \hat{q}(1-\beta)\left(1+\alpha\right)/(1-\alpha) + \rho/\theta\right) \tag{16.B}$$

By substituting (16.B) into (13), we obtain the corresponding equilibrium allocation of labour:

$$L_Y = \frac{1}{\delta(1-\alpha)z'(\alpha+\theta)}\left(\delta z'(1-\alpha)\theta L + \rho(1-\alpha) + \hat{q}\alpha(1-\beta)(1-\theta)\right) \tag{16.C}$$

Equation (16.C) shows that the amount of labour allocated to the final output sector increases with the rate of discount (future consumption possibilities are valued less, hence the greater emphasis on current consumption through an increase in final output). Moreover, an increase in δ would lower the amount of labour allocated to final output production, while an increase in θ has ambiguous effects. Note too that an increase in ς favours growth (cf. equation (16.A)), while equations (16) reproduce Romer’s growth results for $z'=1$ and $\hat{q} = 0$.

The analysis is graphically represented in Figure 1, which will also be of help later in evaluating changes in steady state growth results arising from policy changes. By connecting each point of the relation $L_Y(r)$ in quadrant IV to a corresponding point in quadrant I, passing through quadrants III and II, we can show how a shift in $L_Y(r)$ leads to a change in the equilibrium steady state growth rate. A downward shift in $L_Y(r)$ in quadrant IV as depicted in the Figure I due to, for instance, an increase in $\hat{q}$, leads to a steady state with lower growth, as indicated by the curved arrow in quadrant I.

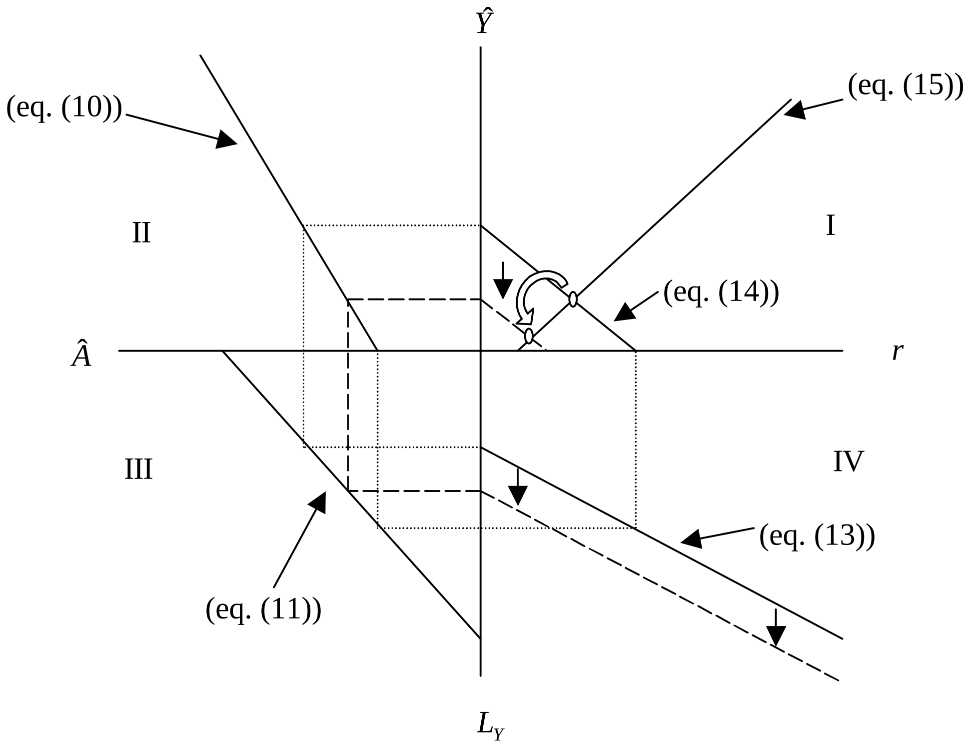

Figure 1. *Steady State Equilibrium*

Concluding Remarks

The model just described shows that economic growth is favoured by technical change that improves the productivity of raw capital and/or energy in generating effective capital. The model also shows that steady state growth is possible in a situation where real energy prices are growing. However, in that case the rate of growth of the system is lower than with constant real energy prices. Moreover, the equilibrium real interest rate would be lower too. The reason is simply that substitution away from energy towards raw capital leads to more capital intensive production, and hence to a lower marginal productivity of capital.

We conclude that in our set-up continuously rising real energy prices have a negative effect on economic growth, but this effect is counteracted to some extent by changes in the productivity of the factors which generate effective capital services. However, it seems probable that the Cobb-Douglas specification we have chosen for that generator function over-estimates long run substitution possibilities between raw capital and energy as they exist in practice. Because of that, it is also likely to under-estimate the negative growth effects of rising real energy prices. Holding this in mind, we will now turn to the effects of introducing an energy tax with and without recycling in the form of an R&D subsidy.

1.3 Policy Implications

Introduction

The policies we want to investigate are the introduction of an energy tax, with and without recycling in the form of an R&D subsidy to the same amount. Obviously, the introduction of a tax will change the marginal cost of the provision of effective capital services by intermediates and hence the profitability of producing these intermediates. That in turn will influence the allocation of labour over its two uses: R&D and final output generation. The latter will definitely influence the steady state growth rate, apart from having level effects as well. In the remainder of this section, we will concentrate on the growth effects, though.

Equilibrium Growth Effects of an Energy Tax Without R&D Recycling

The effects of an introduction of an ad valorem energy tax with rate τ without recycling are easily traced through adjusting the labour market arbitrage condition. We do this by replacing the price of energy q by $(1+\tau)q$ in the marginal cost of effective capital services as given by equation (6). In that case, equations (16.A) and (16.C) have the following counterparts:

$$\hat{Y} = \frac{\alpha(\delta z' L - (\rho/\alpha)(1+\tau)^{\alpha(1-\beta)} - \hat{q}(1-\beta)\left((1+\tau)^{\alpha(1-\beta)} + \alpha\right)/(1-\alpha))}{\alpha + \theta(1+\tau)^{\alpha(1-\beta)}} \qquad (17.A)$$

$$L_Y = \frac{\delta z'(1-\alpha)\theta L + \rho(1-\alpha) + \hat{q}\alpha(1-\beta)(1-\theta)}{\delta z'(1-\alpha)(\alpha(1+\tau)^{\alpha(\beta-1)} + \theta)} \tag{17.C}$$

Equation (17.A) shows that growth will be negatively affected by the introduction of an energy tax, since the numerator decreases and the denominator increases with τ. From (17.C), we see that the denominator decreases with τ, thus leading to a reallocation of labour from research and development towards final output. This is consistent with lower growth.

Equilibrium Growth Effects of an Energy Tax with R&D Recycling

In the case of R&D recycling, the labour market arbitrage condition can be rewritten as:

$$w_Y / w_A = 1 + \tau q E / ((L - L_Y) w_A) \tag{18}$$

The other structural equations of the 'growth supply-side' (i.e. equations (10) and (11)) remain unchanged. Unfortunately, the effects of the introduction of an energy tax plus recycling are not easy to trace analytically, but we can develop an intuition as follows.

By using (3.A), (7) and (11) again as before, as well as (9.B) and the expression for instantaneous profits, the ratio of the real wage rate in the final output sector and in the R&D sector (i.e. the *LHS* of equation (18)) is given by:

$$LHS = w_Y / w_A = \frac{(r(1-\alpha) + \alpha(1-\beta)\hat{q})(1+\tau)^{a(1-\beta)}}{\alpha\delta(1-\alpha)z'}\frac{1}{L_Y} \tag{19.A}$$

Similarly, the *RHS* of equation (18) is given by:

$$RHS = 1 + \frac{\alpha((1-\alpha)r + \alpha(1-\beta)\hat{q})(1-\beta)\tau}{\delta(1-\alpha)^2 z'}\frac{1}{L - L_Y} \tag{19.B}$$

The question now is how the relation $L_Y(r)$ that is implied by the equality between *LHS* and *RHS* changes with τ, i.e. how a change in τ would shift $L_Y(r)$ in the L_Y, r –plane (cf. Figure 1). This enables us to infer the effects of the introduction of an energy tax with R&D recycling on the equilibrium steady state growth rate as follows. If the introduction of an energy tax with recycling lowers L_Y for a given value of r (and $\hat{q}$), this results in an upward shift of the supply-side relation between $\hat{Y}$ and r in the ($\hat{Y}$, r) plane. Since the 'growth demand-side' remains unchanged, this implies a rise in equilibrium steady state growth rate, that depends solely on the labour allocation effects of the introduction of an energy tax accompanied by an R&D subsidy.

Through implicit differentiation of (18), we obtain the derivative of L_Y with respect to τ, while making use of equations (19.A) and (19.B):

$$\frac{\partial L_Y}{\partial \tau} = -\frac{\frac{\partial RHS}{\partial \tau} - \frac{\partial LHS}{\partial \tau}}{\frac{\partial RHS}{\partial L_Y} - \frac{\partial LHS}{\partial L_Y}} = \frac{L_Y(L-L_Y)\alpha(1-\beta)(-(L-L_Y)(1-\alpha)(1+\tau)^{\alpha} + L_Y\alpha(1+\tau)^{1+\alpha\beta})}{-((L-L_Y)^2(1-\alpha)(1+\tau)^{\alpha} + L_Y^2\alpha^2(1-\beta)\tau(1+\tau)^{1+\alpha\beta})} \qquad (20)$$

Because the denominator of (20) is negative, the derivative of L_Y with respect to τ is negative if the numerator is positive. But the latter requires the ratio of R&D workers to final output workers to be smaller than $(\alpha(1+\tau)^{1-a(1-\beta)})/(1-\alpha)$. For $\tau \approx 0$ and reasonable values of α, this is almost certainly true. Hence, we conclude that in this case, the introduction of an energy tax with recycling will raise the growth of output, while the energy/capital ratio will continue to decrease.

Concluding Remarks

There are two important conclusions to be drawn from the policy analysis above. *First*, we have shown that the introduction of an energy tax in the context of the revised Romer model is not enough by itself to spur R&D efforts. Rather, these are negatively affected, because either real energy price changes or the introduction of a tax lowers the present value of a blueprint, which in turn reduces the marginal productivity of research labour. In that case, we would expect a decrease in the allocation of labour to R&D. However, the subsidy on wage cost in the blueprint sector can actually more than compensate the fall in the marginal productivity of labour, so that in this case we can observe faster growth than before the tax. Nonetheless, the model is clear about what happens to R&D: an increase in the user price of effective capital will not induce energy saving technical change, as one would expect that to happen at first sight. While new (already known) energy technologies that aren't economically feasible at low prices of carbon based fuels might be adopted at sufficiently high fuel prices, this does not imply that (basic) research will necessarily be stepped up at these higher prices.[8] Moreover, the low mark-ups implied by the use of a Cobb-Douglas production function provide little incentive for the research sector to engage in energy saving technical change in the first place. Conversely, we would expect research activity to fall less in a situation with relatively low substitution possibilities between labour and other production factors (including energy). The latter implies lower price elasticities of the demand for intermediate goods. Our *second* conclusion therefore is that a Cobb-Douglas production function probably underestimates the level of activity in the research sector after the introduction of a tax on energy use and a corresponding subsidy on wage costs in the research sector.

1.4 Summary and Conclusion

In this paper, we have presented a model that is an extension of the Romer (1990) model. We have introduced endogenous energy saving technical change into that model by assuming effective services of intermediates to be provided by a raw-capital/energy bundle. Moreover, we have allowed intrinsic productivity differences between intermediates that are due to embodied technical change. We show that the model is still able to generate steady growth. Moreover, the growth rate now depends positively on the rate of embodied technical change, and it is higher than the original growth rate in the Romer (1990) model. However, the rate of growth of the system now also depends negatively on the rate of growth of real energy prices, implying that continuously rising real energy prices will tend to slow-down growth. Due to the use of a Cobb-Douglas function to describe the substitution possibilities between energy and raw capital, we

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[8] In reality, one might expect a spur in applied research regarding newly adopted energy technologies that have become profitable at higher energy prices. We did not cover ex post improvements in technologies, however.

probably under-estimate the negative growth effects of rising real energy prices. The reason is that certainly in the long run substitution possibilities between raw capital and energy are likely to be more limited than is implied by the use of a Cobb-Douglas function. This is because there are absolute limits to the efficiency of energy conversion that are implied by the laws of nature: physics ‘abhors’ an infinitely high (marginal) productivity of energy. This implies that the asymptotic properties of a Cobb-Douglas production function (or any production function obeying the Inada conditions with respect to energy) exaggerate actual substitution possibilities between capital and energy in the long run. The relevance of physical limits to the efficiency of energy conversion is recognised by Smulders (1995), for instance. However, Smulders argues that the implied limits to sustainable growth may be circumvented by increasing the use of unlimited inputs like knowledge in the provision of goods and services. The (rhetorical) question is whether there are limits to the substitutability of knowledge for material inputs, since the more immaterial inputs to some product are, the less material the final product will have to be. Obviously, human needs like food, shelter and so on, can not be fulfilled with largely immaterial products. In the long run then, Baumol’s law is probably as harsh as physics.

We have also seen that the growth in real energy prices will decrease the profitability of using new intermediate goods and hence the profitability of doing research. In addition to this, the final output producers can easily substitute labour for effective capital in the case of a Cobb-Douglas production function. The implied price elasticity of the demand for effective capital results in a relatively low mark-up for intermediate goods producers on their marginal production costs. This reduces the present value of the profit streams in comparison with a situation with relatively low elasticities of substitution between labour and effective capital. The latter would provide bigger incentives to do research. But, in order to have the model work as one would expect it a priori (i.e. increasing R&D activities when rising real energy prices indicate that there is a supply problem), one would have to consider to adjust the general framework in such a way that it also allows for applied R&D that improves the productivity characteristics of an intermediate ex post. Pending such adjustments of our model, we conclude that at least the negative growth effects of continuously rising real energy prices or the introduction of an energy tax, can be mitigated by recycling the tax proceeds in the form of subsidies to R&D.

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