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The Impact of Energy Conservation on Technology and Economic Growth

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Abstract

We present a model of growth driven by energy use and endogenous factor-augmenting technological change. Both the rate and direction of technological progress are endogenous. The model captures four main stylized facts: total energy use has increased; energy use per hour worked increased slightly; energy efficiency has improved; and the value share of energy in GDP has steadily fallen. We study how energy conservation policies affect growth over time and the long run. Policies that reduce the level of energy use are distinguished from those that reduce the growth rate of energy inputs. Although these policies may stimulate innovation, they unambiguously depress output levels. The former policy has no impact on long-run growth; the latter reduces long-run growth both in the short run and in the long run.

JEL codes: O41, Q43

Key words: economic growth, energy, innovation.

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1. Introduction

Central to the economic analysis of climate change policies are the interactions among energy use, technological change and economic growth. The stabilization of greenhouse gas concentrations requires reductions in fossil fuel energy use, which is a major essential input throughout all modern economies. Cuts in energy use are likely to seriously affect GDP and economic growth. However, if energy conservation can be realised through new energy efficient technologies, the trade-off between energy reduction and growth becomes less severe.

Economists have increasingly stressed the crucial role of technical change in the context of climate change, environmental and energy policy (see Loeschel, 2002, for a survey). It is found that the cost of such policies crucially depends on how fast energy efficiency improves. Technical change should be viewed as an endogenous variable: either directly or through changing energy prices, policies may induce innovation by providing incentives to allocate more resources to the development of energy-saving technologies. Climate policy assessments based on the conventional assumption of autonomous energy efficiency improvements ignore these effects. This is why recent studies stress evidence of induced technical change (see Jaffe et al., 2000), focus on learning effects associated with abatement activities and clean technology, and turn to (mostly ad-hoc) modelling of induced technical change (see the survey by Azar and Dowlatabadi, 1999).

To enhance our understanding of how environmental and energy policies induce technical change, and how they affect economic growth, we need a general-equilibrium analysis of the allocation of research and development activities in the total economy. Policy may not only affect innovation related to energy and clean technologies, but may also crowd out other innovation projects when changing the direction of technical change. We need to know how policy affects the *direction* of innovation as well as the aggregate *rate* of innovation. The interaction between these two is neglected in most of the literature so far.

The aim of this paper is to develop a growth model in which energy is an essential input and endogenous technical change drives long-run growth. We require that this model is consistent with the main stylised facts concerning energy use and growth. We model innovation as rational investment behaviour driven by profit maximization. We build the model in order to find analytical results concerning the

effects of a reduction in energy use (“energy conservation”) on the rate and direction of technical change, and on GDP and growth over time.

For our purposes, the model has to be consistent with at least four stylised facts. Jones (2002, based on EIA 1999) summarizes these for the US over the period 1950-1998. First, energy efficiency (GDP per unit of energy input) has improved at an annual rate of 1.4 per cent on average. Second, per capita energy use has increased at an average annual rate of about 1 percent. Third, the share of energy cost in GDP has declined at an average annual rate of about 1 percent. Fourth, energy prices per unit of labour cost have declined (see also Nordhaus, 1992; Simon, 1996). Needless to say, the trends for the period 1971-1980 are markedly different, with even faster improvements in the energy efficiency, falling per capita energy inputs, and a sharply rising energy cost share (from 2 percent in 1970 to 7 percent in 1980). In Table 1 and Figures 1 and 2, we present figures based on own calculations for the US, Japan, and three large European economies.¹ The trends after 1969 are similar to those of the US.

*** insert about here: Table 1, Figures 1 and 2 ***

In our model, per capita energy evolves exogenously and ongoing technical change explains the steady decline in energy intensity, energy share, and price of energy relative to wages. Labour and energy inputs enter the production function symmetrically as gross complements. Energy and labour are each combined with specific complementary intermediate inputs, to be interpreted as capital. Monopolistic firms supply these intermediate goods and have the opportunity to invest in improved quality of the goods. In the transition to the steady state, the effective supply of energy, corrected for these quality improvements, grows faster than the effective supply of labour, which results in a gradual decline in the share of energy.

We study the effects of energy conservation by exogenously reducing either the level or the growth rate of energy inputs in the model. Energy becomes scarcer and producers are willing to pay higher prices for energy services. The returns to

¹ We used data from the International Sectoral Database (OECD, 1999), and the OECD energy balances. Following the approach outlined in De Nooij et al. (2001), we used the sectoral data to include the transformation losses and the deliveries of the electricity sector to other sectors in the macro-economic energy use. From the Penn World Tables (Summers and Heston, 1991, mark 5.6) we used the data on population (1), real GDP per capita in constant dollars (3), real GDP per worker 1985 intl. prices (19) and non-residential capital stock per worker in 1985 intl. prices (20; numbers refer to the ordering in Summers and Heston).

investment in quality improvements of energy-related intermediates rise relatively to labour-related innovations. This spurs energy-related innovation, possibly at the cost of labour-related innovation. In the new equilibrium the direction of innovation has shifted to energy and rates of return are equalised over the two types of innovation projects. If this new common rate of return has increased, the aggregate rate of innovation is stimulated as well. We show that this may happen if innovators in energy-related sectors are better able to appropriate the social returns to innovation than those in other sectors.

We find that energy conservation reduces output levels both in the short and long run. These lower levels are typically associated with higher short-run per capita growth rates. Long-run growth rates are not affected by a permanent change in the level of energy input, but fall if the growth rate of energy inputs is permanently reduced. Induced technical change may result in smaller drops in output than when technological change is exogenous.

Our analysis is related to the literature on environmental policy and technology (Goulder and Mathai, 2000), and the literature on the environment and growth (Bovenberg and Smulders, 1995; Smulders, 2000). While the former typically concentrates on how environmental policy induces technological change and learning in particular directions or sectors in a partial analysis, the latter takes a general-equilibrium perspective with only one type of research. Goulder and Schneider (1999) and Buonanno et al. (2001) combine the two approaches in a calibrated model in which perfect competition prevails in all markets. We aim at integrating the induced technology and growth perspective, without giving up the analytical tractability and micro foundations of the endogenous growth models.

Our model builds on growth theory. Neoclassical resource-and-growth models assume exogenous technology but concentrate on endogenous depletion of non-renewable resources (see the surveys by Dasgupta and Heal, 1979; Withagen, 1991). We complement this approach by focusing on endogenous technology, with exogenous energy supply.² Other models of endogenous growth and energy use have

² Edenhofer (2000) allows for both endogenous extraction and endogenous direction of technical change in a central planner setting. Note that it would not suffice in our model to follow the standard modeling of non-renewable resource extraction with a given stock and constant extraction costs, since this would – contrary to the stylized facts – produce an ever-falling supply of energy. Note that in our simplification we admittedly sacrifice some completeness, but we also gain in terms of generality of the model, since the energy variable can now be broadly interpreted as a resource variable, e.g. a polluting input or a renewable resource variable.

focussed on a single type of innovation and Cobb-Douglas production functions (Aghion and Howitt, 1998, Chapter 5; Grimaud and Rougé, 2001; Van Zon and Yetkiner, 2001). We complement this literature by allowing for both labour-augmenting and energy-augmenting technological change, and elasticities of substitution below unity (that is, labour and energy are gross complements).³

Our modelling of production and innovation partly follows Acemoglu (1998, 2001) and Kiley (1999), who develop a framework to analyse the forces that shape the direction of technical change towards particular factors of production. We are interested in whether a change in the direction of technical change may accelerate aggregate growth, rather than in explaining the direction itself. We therefore explicitly relate forces that direct technological change to forces that shape the overall productivity of innovation. Our model deviates from Acemoglu's model in some important respects. First, innovation is undertaken in-house in our model (in the spirit of Smulders and Van de Klundert, 1995), while Acemoglu's model relies on creative destruction (as in Aghion and Howitt, 1992) and Kiley's model relies on labour division and variety expanding (as in Romer, 1990). In this respect, our approach is complementary to Kiley and Acemoglu by studying a third mode of R&D driven economic growth. Second, while in Acemoglu (1998, 2001) and Kiley (1999) the relative supply of primary factors is stationary, we allow for steady increases in the supply of energy relative to labour supply. Third, we stress that technological change may be biased because of differences in appropriability conditions for different investment projects (cf. Nahuis and Smulders, 2002).

Our analysis is divided in three stages to clearly disentangle the effects of (i) the presence of technical change per se, (ii) the endogeneity of the *bias* of technology (induced technical change), and (iii) the endogeneity of the *rate* of technical change. In section 2, we consider the production side of the economy and take technology as exogenous. We illustrate how exogenous reductions in energy use affect the aggregate growth rate for given technological change. In section 3 we introduce induced technological change by modelling how firms change the type of innovation projects if energy supply changes and the total research budget is held constant. In section 4, the total amount of innovation in the economy may respond to rates of return to innovation. Section 5 concludes.

³ Most of the older theoretical literature has used this assumption (Dasgupta and Heal, 1979). It implies

2. Production with Energy, Labour and Factor-specific Capital and Technology

2.1. Modelling production

We consider a closed economy that produces a single final consumption good. Inputs in the production process are labour, energy (or more general, natural resources) and intermediates (“capital”).⁴ The latter are produced according to the same production technology as final goods. Hence labour and resources, denoted by L and R respectively, are the primary (non-reproducible) inputs. Since we are focusing on the role of energy in growth of production rather than on its supply, we assume that energy supply is exogenous. In particular, we allow for a constant rate of growth of both energy and labour inputs.

The key feature of the production structure, borrowed from Acemoglu (1998), is that the productivity of labour (energy) mainly depends on the quantity and quality of intermediate goods that are complementary to labour (energy). Final goods producers optimally choose quantities, while the quality is a predetermined variable. This section derives how aggregate output can be expressed in terms of exogenous factor inputs and predetermined quality (technology) levels.

Final goods production

Final goods producers use labour services (Y_L) and energy (resource) services (Y_R) to produce final goods (Y). The two inputs are imperfect substitutes, the elasticity of substitution is denoted by σ , which we assume to be smaller than unity. The price of the final good is normalized to one and the (internal accounting) prices of labour and energy services are denoted p_{YL} and p_{YR} , respectively. Using a CES specification, we may write:

$$Y = A \cdot \left(Y_L^{(\sigma-1)/\sigma} + Y_R^{(\sigma-1)/\sigma} \right)^{\sigma/(\sigma-1)} \quad (1)$$

that both inputs are essential and necessary. Empirical evidence is inconclusive (cf. Neumaier, 1999).

⁴ Note that we simplify by modelling capital inputs as a flow variable. To avoid confusion we label them intermediate inputs.

$$Y_L / Y_R = (p_{YL} / p_{YR})^{-\sigma} \quad (2)$$

$$1 = A^{-1} [p_{YL}^{1-\sigma} + p_{YR}^{1-\sigma}]^{1/(1-\sigma)} \quad (3)$$

Equation (2) represents relative demand. Equation (3) reflects our choice of the numeraire. Labour (energy) services are derived from combining raw labour (energy) inputs and a range of specialized intermediate inputs x , each of which is available at a certain quality q . In particular, we assume that services of type $i = L, R$ are produced according to the following Cobb-Douglas/Romer (1990) production function:

$$Y_i = S_i^\beta \int_0^1 q_{ik} x_{ik}^{1-\beta} dk \quad (4)$$

where S_i is the use (or – in equilibrium – the Supply) of raw input i (i.e. $S_L=L$ and $S_R=R$), x_{ik} is the use of intermediates of variant k in the production of type i services, and q_{ik} is the associated quality level. The number of intermediates in each sector is normalized to unity. Note that intermediates x are input-specific. Thus, the productivity of energy services is determined by the quality and supply of the available intermediates specially developed for energy services. This allows us to model input-specific technical change.

The production possibilities defined by (1) and (4) can be written in terms of the more familiar production function with factor augmentation. To show this, we define

$$A_i = \int_0^1 q_{ik} \left(\frac{x_{ik}}{S_i} \right)^{1-\beta} dk \quad (5)$$

so that, after substitution in (4), we may write $Y_i = A_i S_i$ for production services, and, after substitution in (1),

$$Y = A \left((A_L L)^{(\sigma-1)/\sigma} + (A_R R)^{(\sigma-1)/\sigma} \right)^{\sigma/(\sigma-1)} \quad (6)$$

for total final output. Equation (6) is the conventional macroeconomic production function with factor augmentation, but in this model the factor augmentation (or technology) levels A_i are endogenous: according to (5) they depend on quality of intermediate inputs, as well as on quantity of these inputs per unit of raw factor input.

Final-goods producers maximize profits, taking prices as given. They demand labour, energy and intermediates up to the point where marginal productivity of these inputs equals their cost. Differentiating (4) and subsequently substituting (5), we find:

$$p_{Y_i} \frac{\partial Y_i}{\partial S_i} = w_i \Leftrightarrow p_{Y_i} \beta A_i = w_i \quad (7)$$

$$p_{Y_i} \frac{\partial Y_i}{\partial x_{ik}} = p_{x_{ik}} \Leftrightarrow p_{Y_i} (1 - \beta) q_{ik} (S_i / x_{ik})^\beta = p_{x_{ik}} \quad (8)$$

where w_i is the factor price for raw inputs, and $p_{x_{ik}}$ is the price of intermediate good x_{ik} . Equation (8) reveals that the elasticity of demand for each intermediate good equals $1/\beta$.

Intermediate goods production and price setting

Each intermediate good producer supplies a unique variety and sets a monopoly price. (Each also invests in quality improvement, but we postpone this to the next section). Their market is thus characterized by monopolistic competition (Dixit and Stiglitz, 1977).

The cost of producing one unit of x_{ik} at quality q_{ik} is q_{ik} units of the final good. Maximizing profits subject to the demand for the intermediate good given above, we find the monopoly price:

$$p_{x_{ik}} = q_{ik} / (1 - \beta) \quad (9)$$

According to this equation, prices are set as a mark-up over unit costs (q). As usual, the mark-up is negatively related to the elasticity of demand $1/\beta$.

Substituting the price in the demand function, we find that all intermediate goods producers within the same sector i produce the same level of output x_i :

$$(p_{Yi}(1-\beta)^2)^{1/\beta} S_i \equiv x_i = x_{ik} . \quad (10)$$

Static goods market equilibrium

We now substitute equilibrium quantities of intermediate inputs from (10) into the production and demand functions in order to express key variables in terms of primary inputs (R and L) and technology variables. It turns out that the level of technology is most easily captured by average quality of labour-related and energy-related inputs, to be denoted by Q_L and Q_R , and defined as:

$$Q_i = \int_0^1 q_{ik} dk , \quad i = R, L. \quad (11)$$

To summarize static goods market equilibrium, we first solving for relative prices, relative supply of intermediates, and other relative variables:⁵

$$p_Y^B = (Q^B R / L)^{-\beta/\nu} \quad (12)$$

$$x^B = (Q^B)^{-1/\nu} (R / L)^{-(1-\nu)/\nu} \quad (13)$$

$$w^B = (Q^B)^{-(1-\nu)/\nu} (R / L)^{-1/\nu} \quad (14)$$

where $\nu = 1 - \beta(1 - \sigma)$. The superscript B denotes ratios of energy to labour variables, e.g. $p_Y^B \equiv p_{YR}/p_{YL}$, $w^B \equiv w_R/w_L$. This B-superscript stands for “bias”, e.g. $Q^B \equiv Q_R/Q_L$ represents the bias in technology.

We next solve for aggregate variables. Combining (1), (3), (4), (10), and (12), we rewrite the production function as:⁶

$$Y = \left((Q_L L)^{(\nu-1)/\nu} + (Q_R R)^{(\nu-1)/\nu} \right)^{\nu/(\nu-1)} \quad (15)$$

⁵ From (4) and (5) we find $Y^B = A^B S^B$. Combining (5) and (10), we find $A^B = Q^B (p_Y^B)^{(1-\beta)/\beta}$. When we use this expression to eliminate A^B and (2) to eliminate Y^B , we find (12). From (10) we find $x^B = S^B (p^B)^{1/\beta}$. Using (12) to eliminate p^B , we find (13). Finally, we find (14) from (7) and (12).

This equation represents the production function for equilibrium levels of capital inputs (x_i). The quality indices Q_i now act as factor augmentation levels. The elasticity of substitution between *effective* labour input ($Q_L L$) and *effective* energy input ($Q_R R$) is $0 < v = (1 - \beta) + \beta \sigma < 1$, which is a weighted average of the elasticity of substitution between energy and labour services (σ , see (1)) and the elasticity of substitution between primary inputs and capital inputs (which equals 1, see (4)).

From (15), we can directly write output per capita (y) and its growth rate (g) as:

$$Y / L = Q_L (1 - \theta_R)^{v/(1-v)} \quad (16)$$

$$g \equiv \hat{Y} - \hat{L} = \hat{Q}_L + \theta_R (g_{R/L} + \hat{Q}^B) \quad (17)$$

where $g_{R/L} = \hat{R} - \hat{L} (= \hat{S}^B)$ and $\theta_i \equiv Y_i p_{Y_i} / Y$ denotes the cost shares of energy and labour services:⁷

$$\theta_R = 1 - \theta_L = \left[(Q^B R / L)^{(1-v)/v} + 1 \right]^{-1} \quad (18)$$

Important to note from (14) and (18) is that for poor substitution ($v < 1$) an increase in the bias of technology Q^B implies a fall in energy prices and in the energy share. An increase in Q^B therefore has the interpretation of energy-saving (or labour-biased) technical change. Hence, equation (17) shows three sources of growth (cf growth accounting): growing per capita energy inputs, labour-related technical change and energy-saving technical change.

⁶ We have chosen units of Y in (1) such that $A = (1 - \beta)^{2(\beta-1)/\beta}$, so that the scale constant in (15) becomes unity.

⁷ These shares include expenditures on factor-specific intermediates (“capital”). Note from (4) that the share of intermediates in total output equals $1 - \beta$, so that we have to multiply the expressions in (18) by the constant β to find the share of energy and labour cost in total output: $\beta \theta_R = w_R R / Y$ and $\beta \theta_L = w_L L / Y$. In the rest of the text we will focus on θ_R and simply refer to it as the energy share.

2.2. Energy conservation with exogenous technological change

Before we study the full model, we derive a set of results for the case of exogenous technological change. In the next sections, we make a comparison with the case of endogenous technology.

Suppose the supply of primary inputs (R and L) as well as technology variables (Q_R and Q_L) evolve exogenously over time. To make the model consistent with the stylised facts we assume that (i) $\hat{Q}_L > 0$, (ii) $g_{R/L} > 0$, which means that energy per capita steadily increases, and (iii) $g_{R/L} + \hat{Q}^B > 0$ but may approach zero (or become zero at $t > T$), so that relative effective energy inputs steadily grow and the cost share of energy steadily falls (until time T), see (18). The implication of this calibration is that the energy cost share falls to zero in the long run (or to a constant value at time T), and that long-run per capita income growth is driven by growth in the quality of labour inputs Q_L only, see (17). Since effective per capita energy use grows and substitution is poor ($\nu < 1$), effective labour input is the scarce production factor, which drives growth in the long run.

What is effect of energy conservation on output and growth? Policies that imply induce lower levels of energy use, without affecting the exogenous levels of labour and technology (L , Q_L , Q_R), unambiguously result in lower levels of (per capita) income, see (15). They also drive up energy prices and the energy cost share in production (θ_R , see (18)). However, lower income levels may go together with higher rates of economic growth (faster convergence to the steady state). On the one hand, (17) reveals that a *lower level* of energy use (R) affects growth positively through a higher energy share θ_R . The reason is that when energy is less abundant, its marginal product is higher so that a given growth rate of energy use has a larger effect on income. We label this the “neoclassical scarcity effect”. On the other hand, when energy conservation policies take the form of a *lower growth rate* of energy use, $g_{R/L}$, they negatively affect growth in (16) by reducing one of the three sources of growth in the growth-accounting sense. We label this the “source-of-growth effect”.

In the long run, energy conservation policies cannot affect growth. If $g_{R/L} + \hat{Q}^B > 0$ continues to hold in the long run, the energy share approaches zero ($\theta_R = 0$). The energy share becomes a constant if $g_{R/L} + \hat{Q}^B = 0$ in the long run. In

both cases the growth rate approaches $g = \hat{Q}_L$. In the long run, energy is not a scarce factor, its role in production becomes negligible, and exogenous technological change entirely drives growth (as in the standard Solow growth model). The results therefore crucially hinge on the assumption of exogenous technical change, which will be relaxed in the next sections.

3. Induced technical change

3.1. Modelling technical change

We now introduce induced technological change by assuming that each intermediate goods producer improves the quality of her good by investing in in-house research and development activities. The investment technology is:

$$\dot{q}_{ik} = [\xi_i Q_i D_i^{1-\omega_i}] D_{ik}^{\omega_i}, \quad (19)$$

where D_{ik} is resources spent on development by the firm. Apart from the scaling parameter ξ , the productivity in development activities depends on two types of spillovers.

First, an individual firm builds on the knowledge accumulated in the past by all firms in the sector (see Popp (2002) for evidence with respect to energy-related research). This knowledge stock is proxied by the current aggregate quality level Q_i . The firm takes it as given and neglects its own current development efforts expand the knowledge stock on which future development builds. Thus, intertemporal spillovers arise, which play an important role in preventing the returns to innovation to fall over time. Since production costs rise with the quality level of the product, the return on subsequent innovation tends to fall. However, intertemporal spillovers reduce the cost of innovation, which boosts the rate of return. Under the present specification, both forces exactly offset each other in the long run and rates of return can be sustained.

Second, quality development efforts become more productive when other firms are more active. This instantaneous intrasectoral research spillover is captured by parameter $1-\omega$. Whereas $1-\omega$ reflects the returns to innovation that leak to other firms, its complement ω reflects the share of returns to innovation that accrue to the inventing firm. We therefore label ω as the appropriability parameter. A higher value

implies that innovators can better appropriate the returns to R&D, which increases the marginal incentives to innovate.

Firms choose innovation efforts D_{ik} so as to maximize the net present value of the firm. This results in the following no-arbitrage equation (see appendix):

$$r = \left(\frac{\beta \omega_i \xi_i}{1 - \beta} \right) x_i \left(\frac{Q_i}{w_D} \right) \left(\frac{D_i}{D_{ik}} \right)^{1 - \omega_i} + \hat{w}_D - \hat{Q}_i - (1 - \omega_i)(\hat{D}_i - \hat{D}_{ik}) \equiv r_{ik} \quad (20)$$

where r is the interest rate, w_D is the cost of development D , and hats denote growth rates. The equation states that the firm invests until the marginal returns from investment (r_{ik}) equal the cost of capital r . The first term on the right-hand side is the direct return from higher quality. Profits rise with quality in proportion to its sales x_i . The other terms equal the expected rate of change in the shadow price of quality improvements. Fast quality growth in the economy (captured by \hat{Q}) implies large spillovers and cheaper development in the future, which provides an incentive to postpone innovation, that is, they reduce the current rate of return. A higher future cost of development (which is anticipated if $\hat{w}_D > 0$) has an opposite effect.

All firms active in development should earn the same marginal return. Equation (20) shows that this requires $D_{ik} = D_i$, that is, all firms within a sector choose the same level of development efforts. Moreover, the marginal return across the sectors is equalized ($r_{Rk} = r_{Lk} = r$). After substituting $x_i Q_i = \theta_i (1 - \beta)^2 Y$, which follows from (4), (10) and the definition $\theta_i = p_{Yi} Y_i / Y$, we may write (20) as:

$$r - \hat{w}_D = \beta(1 - \beta) \left(\frac{Y}{w_D} \right) \omega_L \xi_L \theta_L - \hat{Q}_L = \beta(1 - \beta) \left(\frac{Y}{w_D} \right) \omega_R \xi_R \theta_R - \hat{Q}_R \quad (21)$$

where the second equality implies (note $\hat{Q}^B = \hat{Q}_R - \hat{Q}_L$):

$$\hat{Q}^B = \beta(1 - \beta) \frac{Y}{w_D} [\omega_R \xi_R \theta_R - \omega_L \xi_L \theta_L]$$

This differential equation reveals how the bias in technical change, \hat{Q}^B , is affected by profit incentives. Technological change leads in the sector with highest $\omega_i \xi_i \theta_i$, which identifies three incentives for biased technological change: large markets (as measured by the value share θ), high average productivity of research (ξ), and high appropriability of research investments (ω). Noting from (18) that $\theta_L = 1 - \theta_R$, we may simplify the equation as:

$$\hat{Q}^B = \lambda_{BTC} \cdot (\theta_R - \theta_{NB}), \quad (22)$$

where

$$\begin{aligned} \lambda_{BTC} &\equiv \beta(1-\beta)(Y/w_D)(\omega_L \xi_L + \omega_R \xi_R) \\ \theta_{NB} &\equiv \omega_L \xi_L / (\omega_L \xi_L + \omega_R \xi_R) \end{aligned}$$

There is no bias in technology by construction if $\theta_R = \theta_{NB}$, which implies that the share of energy in GDP is high enough to offset relatively low research productivity and/or appropriability in energy-related technology. For higher energy shares, innovation becomes biased to energy. The adjustment speed parameter λ_{BTC} determines how strongly biased technical change responds to these increases in the market for energy technology: it captures *aggregate* appropriability and productivity conditions.

Since (18) implies that the change in the energy share θ_R depends on the change in Q^B and the exogenous change in R/L , we can combine (18) and (22) to find the following differential equation for the energy share:

$$\hat{\theta}_R = -(1-\theta_R) \left(\frac{1-\nu}{\nu} \right) [\lambda_{BTC} (\theta_R - \theta_{NB}) + g_{R/L}] \quad (23)$$

3.2. Energy conservation and growth with constant aggregate research

The building blocks of the model that are presented so far are sufficient to study the effect of endogenous changes in the *direction* of technical change in isolation from the effects of changes in the *rate* of innovation. Before we add the remaining building

blocks of the general-equilibrium version of the model, we assume as an intermediate step in the analysis that wages for researchers grow at the same rate as output so that Y/w_D is constant over time and that the total number of researchers is constant and equal to D , so that $D_L + D_R = D$ (in the next section we will see that these assumptions hold along a balanced growth path). In the resulting partial-equilibrium variant of the model, income growth is driven by exogenous growth in per capita energy use and by technological change of which the composition (direction or bias) is endogenous. We investigate in turn the following three questions: what are the dynamics of technology and growth if this partial model is calibrated to the stylised facts, how do energy conservation policies affect growth, and how does the presence of induced technical change affect the results compared to case with exogenous technology?

Technology and growth dynamics

We now show that, consistent with the stylised facts summarised in the introduction, the share of energy in national income, energy intensity, and energy prices relative to wages all steadily fall, if the total research effort (D) is assumed to be sufficiently large and $Q_R R / Q_L L$ is sufficiently small initially. With this calibration, the per capita growth rate falls over time, but may rise near the steady state.

The dynamics are represented by (23), which is a stable differential equation in one variable only, viz. θ_R . In the long run, the energy cost share approaches the following value:

$$\theta_R(\infty) = \theta_{NB} - g_{R/L} / \lambda_{BTC} \quad (24)$$

where the ∞ -index is used to denote long-run values. Note that the initial value of the energy share is given, since $Q^B R / L$ in (18) is predetermined. If the economy starts at an energy share above the value in (24), it falls over time according to (23).⁸

The associated technology dynamics are represented by (22). Technological change is energy-saving when the energy share is still high (Q^B increases, see (22)),

⁸ To rule out corner solutions, we assume that the expression at the right hand side of (24) is a value between 0 and 1, which requires a sufficiently small $|g_{R/L}|$.

but becomes energy-using for a small enough energy share. In the long run, there is energy-using (labour-biased) technical change if per capita energy supply steadily grows:

$$\hat{Q}^B(\infty) = -g_{R/L} \quad (25)$$

Initially, energy (measured in effective units) is relatively scarce, which induces firms to invest mainly in energy-related technological change. Together with the increase in energy supply this makes energy less scarce over time and causes the energy share to fall. However as energy becomes less scarce, innovation in labour-related technology becomes relatively more attractive. The composition of research gradually shifts away from energy and the decline of the energy share comes to a halt.

Energy prices per unit of labour cost ($w_R / w_L \equiv w^B$), which have declined according to the data, also fall according to the model, both during transition and in the long run, since (14) and (18) imply $\hat{w}^B = \hat{\theta}_R / (1 - \theta_R) - g_{R/L} < 0$.

To analyse the rate of technological change, we use the fact that all firms in a sector choose the same amount of research. As a result, average product quality grows at the same rate as firm-level product quality and (19) can be written as $\hat{Q}_i = \xi_i D_i$.

Together with the total research constraint $D_L + D_R = D$ and the definition

$Q^B \equiv Q_R / Q_L$, we may write:

$$\hat{Q}_L = \zeta D - \frac{\xi_L}{\xi_L + \xi_R} \hat{Q}^B, \quad (26)$$

where $\zeta \equiv \xi_R \xi_L / (\xi_R + \xi_L)$.

To find the total effect of induced technical change on growth, we substitute (22) and (26) into (17), which gives the growth rate as a quadratic function of the energy share. We plot this relationship in Figure 3. Since the energy share falls over time and approaches to the value denoted by $\theta_R(\infty)$, we move to the left along the curve. The growth rate falls over time for large values of the energy share, but starts to rise once $\theta_R < [\theta_R(\infty) + \xi_L / (\xi_L + \xi_R)] / 2$. The figure is drawn for

$\omega_L - \omega_R < g_{R/L} / \zeta \beta (1 - \beta) (Y / w_D)$, which ensures that $\theta_R(\infty) < \xi_L / (\xi_L + \xi_R)$. If ω_L exceeds ω_R so much that the last two inequalities are reversed, which holds if

$$\omega_L > \omega_R + g_{R/L} / \zeta \beta (1 - \beta) (Y / w_D), \quad (27)$$

the growth rate monotonically declines during transition. Note that (27) is the condition under which, when starting from a steady state, a marginal increase in the energy share increases growth.

***insert figure about here ***

Figure 3 Partial-equilibrium dynamics of the energy share and output growth with induced technical change

The growth rate tends to fall during transition. As long as the energy share is above its steady state value, energy-related innovation projects (investment in Q_R) have a high pay-off and research effort can be allocated to high-return projects. However, as energy-technologies have improved further and further, energy becomes effectively less and less scarce, the returns to further energy-efficiency improvements fall and research has to be reallocated to lower-return projects, viz. labour-related innovation. With this fall in returns to research effort, growth falls. This downward trend in growth may be reversed if the energy share is close to its steady state value and appropriability in labour-related innovation is relatively poor (ω_L small so that (27) is violated). Then the extent of underinvestment because of appropriability problems is highest in labour-related innovation. The gradual shift to labour-related innovation, which occurs when energy becomes less scarce, stimulates innovation in sectors with high economy-wide rate of return and thus boosts growth.

Finally, we consider the dynamics of energy intensity, or its inverse, energy efficiency (Y/R). Since we may write $\hat{Y} - \hat{R} = g - g_{R/L}$, energy efficiency improves (as consistent with the stylized facts) if the growth rate g is high relative to per capita energy growth. From (17) and (26), we see that this requires D to be sufficiently large. Hence with sufficient research effort, technical change endogenously creates energy efficiency improvements.

Energy conservation and growth

We can now investigate how energy-conservation policy affects growth through the channel of induced technical change. The policy affects the bias of technical change only through changes in the energy share (see (22)). Lower levels of energy use increase the energy share and stimulate energy-saving technical change. Growth increases if the energy share is high enough at the time of the policy, see figure 3. If (27) is satisfied, the growth rate increases for all energy shares above the steady state level.

What happens to long-run growth? Substituting (25) and (26) into (17), we find:

$$g^{(\infty)} = \left(\frac{\xi_L}{\xi_L + \xi_R} \right) g_{R/L} + \zeta D^{(\infty)} \quad (28)$$

This expression reveals that (since we fixed D) long-run growth is *not* affected by energy conservation policies if these reduce the *level* of energy use. Long-run growth is *negatively* affected by energy conservation policies if these reduce the *growth rate* of energy use. Note that this is the *sources-of-growth effect* identified in section 2.

What happens to output levels? Initially, lower energy use unambiguously results in lower output, since technology variables are predetermined. Even if the policy induces higher growth rates, long-run output levels are unambiguously lowered by energy conservation policies. This claim can be proven as follows. From (18) and (23), we see that θ_R is higher with energy conservation for all t . This implies that \hat{Q}^B is higher, see (22), and that \hat{Q}_L is lower, see (26). As a result, the level Q_L must be lower. With higher θ_R and lower Q_L , Y/L is lower, see (16).

Induced technology and exogenous technology compared

Although energy conservation policies reduce output, they may do so less than in the case of exogenous technical change. To illustrate this, we first calibrate both the exogenous technology model and the induced technology model to the same steady state, then marginally reduce energy inputs, and compare long-run output levels in both models.

First, for any set of parameters, we can construct a steady state (balanced growth path) for the model variant with induced technology (this section) by choosing an initial value for the energy share that exactly equals the one in (24). The same balanced growth path can be constructed for the same set of parameters in the model variant with exogenous technology (previous section) by setting the path of technology variable exogenously at the endogenous rates generated in the induced technology model. Note that this requires $\hat{Q}^B + g_{R/L} = 0$ to keep the energy share constant at the level in (24).

We now disturb this steady state by a permanent, marginally small, reduction in the level of energy use and compare the change in output levels in both model variants. In both models, output falls on impact by $\theta_R(\infty)$ percent for each percent of reduction in energy use. In the exogenous technology model, a new steady state is immediately reached with a permanently higher energy share, with output levels $\theta_R(\infty) \cdot |dR/R|$ percent lower, and with the growth rate the same as before the shock. In the induced technology model, technology levels adjust and the per capita growth rate temporarily deviates from its old level. In particular, the transitional growth rate will be higher (lower) if (27) is satisfied (violated). This change in growth during transition is exactly the additional impact of induced innovation. Hence, induced technological change induces higher long-run output levels than exogenous technology only if appropriability in energy-related innovation is relatively poor so that (27) is satisfied.

4. Aggregate research in general equilibrium

4.1. Modelling the capital and labour market

So far we have analysed production only. We were able to analyse growth because we fixed total resources devoted to research.⁹ By this assumption, the growth rate is supply-determined: the supply of energy R , labour L and research effort D determines growth. In this section we investigate whether a change in the bias of technology that is induced by energy policies affects *total* innovation efforts (D) in the economy. That

⁹ This resembles the assumption in the older literature on induced technological change (e.g. Kennedy 1964), which abstracted from the endogenous determination of total research expenditures.

is, we address the question whether energy policies crowd out or crowd in aggregate R&D investment.

To study this, we extend the model by adding a trade-off between growth and current consumption to introduce the mechanisms familiar from endogenous growth models with one type of technical progress (e.g. Romer 1990). Research is undertaken by skilled workers, who can also choose to produce a consumption good¹⁰ (C_H) instead of doing research. One unit of skilled labour produces one unit of C_H , which is sold under perfect competition. The total supply of skilled labour, H , is divided over research and production of C_H , that is, $C_H = H - D$. In equilibrium, skilled workers must be indifferent between working as researcher and producing the C_H -good. Hence, the price of the C_H -good equals the wage they earn in research, that is, $p_{CH} = w_D$.

The representative consumer maximizes intertemporal utility, specified as $\int_0^{\infty} [\alpha \ln C_H + (1 - \alpha) \ln C_Y] \exp(-\rho t) dt$, where C_Y and C_H are two consumption goods and ρ is the utility discount rate. The Cobb-Douglas utility specification implies that a fixed fraction of income, $1 - \alpha$, is spent on C_Y -goods and α on C_H -goods. In equilibrium, the quantities supplied are $C_Y = [1 - (1 - \beta)^2]Y$ and $C_H = H - D$ respectively¹¹, while the prices are 1 and w_D . Goods market equilibrium therefore implies the following expression for the wage of skilled workers:

$$w_D = \left(\frac{\alpha [1 - (1 - \beta)^2]}{1 - \alpha} \right) \frac{Y}{H - D} \quad (29)$$

The cost of research efforts relative to output w_D/Y , which was held constant above, is now endogenously determined: the ratio changes endogenously with the allocation of skilled labour over research and production.

The logarithmic form of the intertemporal utility function implies that the consumer chooses a consumption path along which total spending grows with the difference between the interest rate r and the rate of time preference ρ :

¹⁰ This good can also be interpreted as an intermediate input in production of final goods.

¹¹ Total output Y is used for consumption and intermediate goods production. From (4), (8), (9) and (11), we find that total intermediate goods production equals $Q_L x_L + Q_R x_R = (1 - \beta)^2 Y$.

$(1-\alpha)\hat{C}_Y + \alpha(\hat{C}_H + \hat{p}_{CH}) = r - \rho$. Substituting equilibrium prices and quantities $C_Y = [1-(1-\beta)^2]Y$, $C_H = H-D$, and $p_{CH} = w_D$, we can write the intertemporal consumption decision as:

$$\hat{w}_D - \frac{D}{H-D} \hat{D} = r - \rho \quad (30)$$

While (30) represents households' supply of funds on the capital market, (21) represents firms' demand for funds. We can characterise equilibrium in the capital market by combining (30) with the first equality of (21), substituting (26) to eliminate \hat{Q}_L , and substituting (22) to eliminate \hat{Q}^B . We choose to simplify expressions by setting $\beta(1-\beta)/[1-(1-\beta)^2] = \alpha/(1-\alpha)$; since we are not interested in comparative statics on β or α , this assumption is innocuous. We arrive at:

$$\hat{D} = \frac{H-D}{D} \{ \rho + \zeta D - \zeta [\omega_L - (\omega_L - \omega_R)\theta_R] (H-D) \}. \quad (31)$$

This differential equation reveals how total research effort (D), which was held constant above, changes over time in order to ensure that the rate of return that firms realize on their innovation efforts equal the rate of return that households require on their savings.

Substituting (29) into (18) and (22), we find how the energy share changes over time when research costs and allocation are endogenous:

$$\hat{\theta}_R = -(1-\theta_R) \left(\frac{1-\nu}{\nu} \right) \{ [\omega_R \xi_R + \omega_L \xi_L] (H-D) (\theta_R - \theta_{NB}) + g_{R/L} \} \quad (32)$$

The two differential equations in D and θ_R given by (31) and (32) characterize the dynamics of the model with endogenous technological change. Figure 4 depicts the associated phase portrait. Note that the $\hat{D} = 0$ locus slopes up (down) if $\omega_L > \omega_R$ ($\omega_L < \omega_R$); the $\hat{\theta}_R = 0$ locus slopes up (down) if $g_{R/L} > 0$ ($g_{R/L} < 0$). An interior steady state exists if $|g_{R/L}|$ is not too large. The model is saddlepoint stable

then. We solve for the long-run amount of research effort by setting (31) and (32) equal to zero. This gives:

$$D(\infty) = \frac{\Omega H - \rho / \zeta + [\omega_L \xi_L + \omega_R \xi_R](\omega_L - \omega_R) g_{R/L}}{1 + \Omega} \quad (33)$$

where $0 < \Omega \equiv \omega_L \omega_R (\xi_L + \xi_R) / (\omega_L \xi_L + \omega_R \xi_R) < 1$. As is common in endogenous growth models, the equilibrium amount of R&D increases if the average productivity of research (ζ) increases, if the total supply of potential researchers (H) increases, or if the discount rate falls. The last term in the numerator shows that slower energy growth reduces R&D in the long run when appropriability in energy-related innovation is relatively weak ($\omega_L > \omega_R$).

*** Insert about here: ***

Figure 4 General-equilibrium dynamics of the energy share and total research effort with induced technological change

The phase diagram shows that the energy share converges to a constant, as in the previous section. However, over time, total research effort may now change over time. In particular, the sign of the expression $(\omega_L - \omega_R)$, which represents relative appropriability for the two types of research, uniquely determines whether research falls or rises during the transition to the steady state. If appropriability is better for labour-related technology than for energy-related technology, $\omega_L > \omega_R$, the economy gradually allocates more skilled workers to research and development when the energy share in GDP falls. A lower energy share implies a smaller market for energy-related innovations so that innovation shifts to labour-related markets. If appropriability is better in these markets, the overall marginal rate of return increases and total investment in R&D increases. We have no direct empirical evidence on differences in appropriability conditions across technologies. However, it is a well-known stylised fact of post-war growth in the US that the fraction of the labour force allocated to R&D activities has steadily increased (cf. Jones, 1995). Although there are many alternative explanations for this development, in the present model it can be

replicated by assuming $\omega_L > \omega_R$. The stylised fact thus provides an argument to assume that appropriability is relatively poor in energy-related technologies.

4.2. Energy conservation with induced technical change and endogenous growth

First note that if $\omega_L = \omega_R$, the total amount of research (D) is constant in equilibrium, so that the analysis of the previous section goes through. If $\omega_L > \omega_R$, a reduction in the level of energy use increases the energy share and reduces research D along the saddlepath. In other words, energy conservation policy induces innovation in energy-related technology, not only at the cost of a fall in labour-related innovation, but also at the cost of a fall in total research effort. Research activity is crowded out in the short run. Whether growth increases or decreases as a result of the policy depends on the combined effect of the scarcity effect, the induced innovation effect and the reduction in research effort. Applying a similar logic as used in the previous section, cf. Figure 3, we find that for an energy share that is far enough from its steady state level, the growth rate must rise.

In the long run, a change in the level of energy use (at unchanged $g_{R/L}$) does not affect the growth rate. However, a change in its growth rate $g_{R/L}$ leads to lower long-run growth, not only through the sources-of-growth effect as in the previous section, but now also by a decrease in research effort (see (28)). The interesting result is that even when total research increases by the policy shock, which requires the opposite case with $\omega_L < \omega_R$, the long-run increase in research effort is never enough to completely offset the sources-of-growth effects. As a result, on balance the long-run growth rate always falls. We see this by substituting (33) into (28) and differentiating with respect to $g_{R/L}$: we find $dg/dg_{R/L} > 0$ for all admissible parameters.

Finally, it can be proven that energy conservation policies reduce long-run output levels, even when these policies induce higher growth and more research. It turns out that along the saddle path the growth of Q_L always falls if θ_R increases. A reduction in the level of energy use increases the energy share and thus depresses the growth of Q_L . In the long run, the energy share converges to the pre-shock level, and less Q_L has been accumulated. With higher θ_R and lower Q_L , Y/L is lower, see (16).

5. Summary of results and discussion

We have developed a growth model in which growth is driven by steady growth of energy inputs and endogenous technological change. When considering the model dynamics for plausible parameters and initial conditions [$g_{R/L} > 0$, $\omega_L \geq \omega_R$, $\theta_R(0) > \theta_R(\infty)$], we find an equilibrium path that is consistent with the main stylised facts: the energy share declines, energy efficiency improves, the energy price relative to wages declines, per capita income grows, and the number of researchers as a fraction of population grows. The growth rate of per capita income either monotonically falls or first falls and then slightly rises.

The effects of energy conservation policies on aggregate economic growth have been studied within the model. We have distinguished between policies that reduce the level of energy use and those that reduce the growth rate of energy use. We have separated transitional effects from long-run effects. We have isolated the effects of exogenous technical change from those of endogenous changes in the direction of innovation, and those of endogenous changes in the rate of innovation.

An important robust finding is that all energy conservation policies studied reduce per capita income levels. With induced technical change, the reduction in energy inputs is offset by faster improvements in energy-related technology, which may mitigate the drop in per capita income, but may never fully offset it. Thus, induced innovation cannot give rise to “win-win situations” in the spirit of Porter and Van der Linde (1995) – at least not within this model. In fact, the reverse result can be obtained in the model. Since non-energy-related R&D activities may be crowded out, and since even the total amount of research effort may fall, induced technical change not necessarily mitigates the long-run costs of energy conservation as compared to the case in which technological change comes for free as manna from heaven (cf. Smulders, 1998; 2000, for similar effects in the context of environmental policy).

Another robust finding concerns long-run growth effects of energy conservation in the presence of induced technical change. In the long run, energy policies that reduce the growth rate of energy use always reduce long-run growth. A reduction in the level of energy use leaves long-run growth unaffected. These results

sharply contrast with the case of exogenous technology, in which long-run growth is not affected.¹²

Following a reduction in the level of energy use, per capita growth is likely to accelerate. This is predicted to happen in the case of exogenous technical change, because of what we have labelled the “neoclassical scarcity effect”: increased scarcity of energy inputs implies a higher marginal product of energy and makes a given growth rate of energy supply contribute more to growth. In the case of induced technical change, the effect is reinforced by the shift in the direction of technological change toward energy efficiency improvements. Increased energy scarcity makes innovation more profitable and magnifies the effects of innovation.

Appropriability of the returns to innovation plays an important role in the analysis. If appropriability in energy-related innovation is much worse than in other types of innovation and if the energy share is already close to its steady state level, then growth falls in response to energy conservation.

We have focussed on the effects of growth rather than on welfare. A first reason why we stayed away from a welfare analysis is that this requires a careful modelling of the reasons for (and instruments of) energy conservation policies in the first place, which would make the model more complex. Obviously, if the external damage of energy burning is large enough, a small reduction in energy inputs always improves intertemporal welfare. Second, a welfare analysis is complex since several externalities play an important role in the model: monopoly pricing, intertemporal spillovers, and spillovers between firms distort production and innovation. Hence, energy policy is a second-best policy unless it is combined with the appropriate technology policy and product market regulations. An important form of technology policy in the model is providing subsidies to the type of research that suffers most from appropriability problems. The optimal must act as an increase in parameter ω , which has turned out to be an important determinant of how growth reacts to energy conservation policies. We expect that the energy conservation policies crucially depend on how they are combined with technology policies, a claim which is interesting to study in future work.

¹² This result is due to the assumption that the elasticity of substitution is below unity. In case of a Cobb-Douglas production function, the long-run growth rate would fall with reduction in energy growth in the exogenous technology case, too.

Appendix: derivation of the investment relation (20)

The firm maximizes the net present value of profits subject to (8) and (19). The associated Hamiltonian reads:

$$H_{ik} = \{ [p_{Y_i}(1-\beta)S_i^\beta]q_{ik}x_{ik}^{-\beta} \}x_{ik} - q_{ik}x_{ik} - w_D D_{ik} + p_{qik} [\xi_i Q_i D_i^{1-\omega_i}] D_{ik}^{\omega_i} \quad (\text{A.1})$$

where the first term represent revenue (the term in parenthesis is the price), the second term represents production costs, and the third term represents development costs; p_{qik} is the co-state variable of knowledge accumulation. The firm chooses output x , quality q and development effort D ; it takes as given all variables not subscripted ik . Taking the first order condition with respect to output, we find the price-setting rule in (9).

The first order condition with respect to development effort gives:

$$p_{qik} = w_D D_{ik}^{1-\omega_i} / \omega_i \xi_i Q_i D_i^{1-\omega_i} \quad (\text{A.2})$$

The equation of motion for the co-state variable reads:

$$\frac{\partial H_{ik}}{\partial q_{ik}} = \{ [p_{Y_i}(1-\beta)S_i^\beta]x_{ik}^{-\beta} \}x_{ik} - x_{ik} = r p_{qik} - \dot{p}_{qik} \quad (\text{A.3})$$

We find (20) from (A.3) after dividing by p_{qik} , substituting (9) as well as (the time derivative of) (A.2).

Appendix B: proof that per capita income falls with energy use

Consider a permanent reduction in R (without a change in subsequent growth rate of R , i.e. $g_{R/L}$ remains constant) in the model with endogenous direction and rate of technical change (section 4). In this appendix we proof that this shock unambiguously lowers output levels Y/L , even when the shock triggers more innovation.

Per capita income is determined by θ_R and Q_L only, see (16). In the long run, θ_R is not affected by the change in R , see (24). Hence, to find the effect on Y/L , we need to know how Q_L is affected. We will show that its growth rate \hat{Q}_L is unambiguously reduced by the shock so that the long-run level is lower.

From (26), (22) and (29), we solve for \hat{Q}_L in terms of θ_R and D .

$$\hat{Q}_L = \frac{\zeta}{\xi_R} [\xi_R D - \lambda(H - D)(\theta_R - \theta_{NB})]$$

Noting that D depends on θ_R since the equilibrium moves along the saddlepath (cf. Figure 5), we can derive:

$$\frac{\partial \hat{Q}_L}{\partial \theta_R} = \frac{\zeta}{\xi_R} \left[(\xi_R + \theta_R - \theta_{NB}) \frac{\partial D}{\partial \theta_R} - (H - D) \right] \quad (\text{B.1})$$

Our claim is that the sign of this expression is negative. Note that $H - D \geq 0$ because of the resource constraint. The sign of $(\xi_R + \theta_R - \theta_{NB}) \frac{\partial D}{\partial \theta_R}$ is ambiguous. We may

distinguish between four cases:

1. $\xi_R + \theta_R - \theta_{NB} > 0$ and $\omega_L > \omega_R$ so that $\partial D / \partial \theta_R < 0$;
2. $\xi_R + \theta_R - \theta_{NB} < 0$ and $\omega_L < \omega_R$ so that $\partial D / \partial \theta_R > 0$;
3. $\xi_R + \theta_R - \theta_{NB} > 0$ and $\omega_L < \omega_R$ so that $\partial D / \partial \theta_R > 0$;
4. $\xi_R + \theta_R - \theta_{NB} < 0$ and $\omega_L > \omega_R$ so that $\partial D / \partial \theta_R < 0$;

In case 1 and 2 the expression in (B.1) is negative, but cases 3 and 4 need further analysis. In particular, we need to know more about the exact magnitude of $\partial D / \partial \theta_R$.

From (31) we can derive that along the $\dot{D} = 0$ locus:

$$\left. \frac{\partial D}{\partial \theta_R} \right|_{\dot{D}=0} = \frac{(\omega_R - \omega_L)(H - D)}{\omega_L + (\omega_R - \omega_L)\theta_R + 1} \quad (\text{B.2})$$

Substituting (B.2) into (B.1) we find

$$\left. \frac{\partial \hat{Q}_L}{\partial \theta_R} \right|_{\dot{D}=0} = - \frac{(\xi_R \omega_R + \xi_L \omega_L)(H - D)}{\omega_L + (\omega_R - \omega_L)\theta_R + 1} \left\{ \theta_{NB} + \left(\frac{\zeta}{\xi_R} \right) [\theta_{NB} \omega_R + (1 - \theta_{NB}) \omega_L] \right\} \quad (\text{B.2})$$

so that $\partial \hat{Q}_L / \partial \theta_R < 0$ along the $\dot{D} = 0$ locus. However, what is relevant is the movement along the saddlepath rather than along the $\dot{D} = 0$ locus. Hence the expression in (B.2) overestimates $\partial D / \partial \theta_R$ if the saddlepath lies above the $\dot{D} = 0$ locus (cf. Figure 5). This is the case if $\omega_L > \omega_R$. The necessary downward adjustment of D affect growth according to (see (B.0)):

find $\partial D / \partial \theta_R$ along the saddlepath, D

the change in D We have to adjust the change in In case 3f

(Note that a change in R affects θ_R according to (18) at the time of the shock.

Subsequently, θ_R moves along the saddlepath of the Phase diagram in Figure 5 and converges to its pre-shock .

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Table 1

Annual average growth rates of labour and energy inputs and output (percentages).

		1960-69	1970-79	1980-90
Energy input ^a	US	4.03	1.71	1.04
	Japan	10.69	3.35	1.94
	France	5.97	2.58	1.37
	West Germany	3.73	2.69	-0.18
	UK	3.27	0.48	0.76
Labour input ^b	US	1.58	2.06	1.02
	Japan	1.57	0.82	0.72
	France	0.84	0.81	0.86
	West Germany	0.25	-0.06	1.20
	UK	0.49	0.47	0.47
Output ^c	US	3.86	2.81	2.37
	Japan	9.07	3.94	3.72
	France	5.06	2.92	1.99
	West Germany	3.92	2.44	1.92
	UK	2.50	2.12	2.56

- a. Energy use in tons of oil equivalent. Calculated from the International Sectoral Database (OECD, 1999), and the OECD energy balances. Following the approach outlined in De Nooij et al. (2001), we used the sectoral data to include the transformation losses and the deliveries of the electricity sector to other sectors in the macro-economic energy use.
- b. Employment in persons, calculated from the Penn World Tables (Summers and Heston, 1991, mark 5.6)
- c. Real GDP, calculated from the Penn World Tables.

Figure legends

Figure 1 Energy input per worker (energy use in 1000 tons of oil equivalent per worker). Data source: see table 1.

Figure 2 Energy efficiency (GDP per ton of oil equivalent). Data source: see table 1.

Figure 3 Partial-equilibrium dynamics of the energy share and output growth with induced technical change

Figure 4 General-equilibrium dynamics of the energy share and total research effort with induced technological change

Figure 1
Energy input per worker (energy use in 1000 tons of oil equivalent per worker). Data source: see table 1.

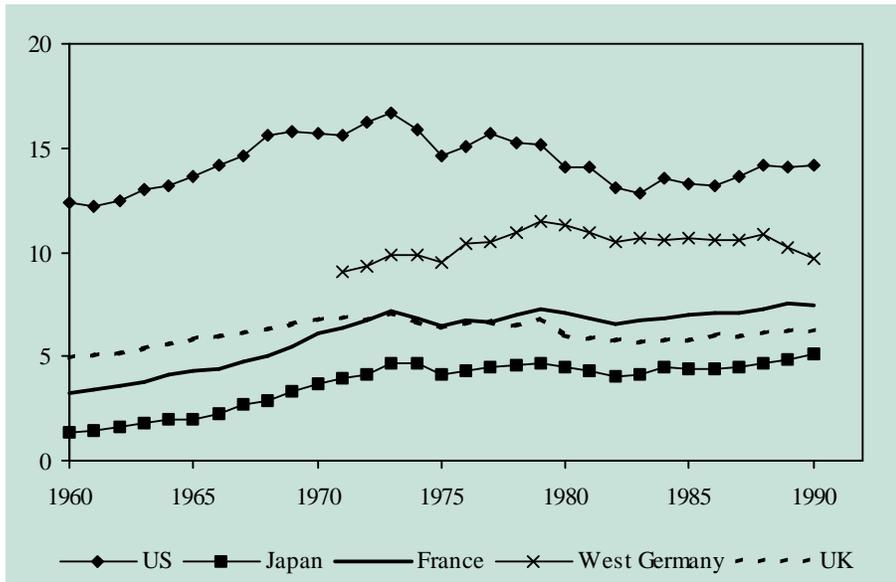
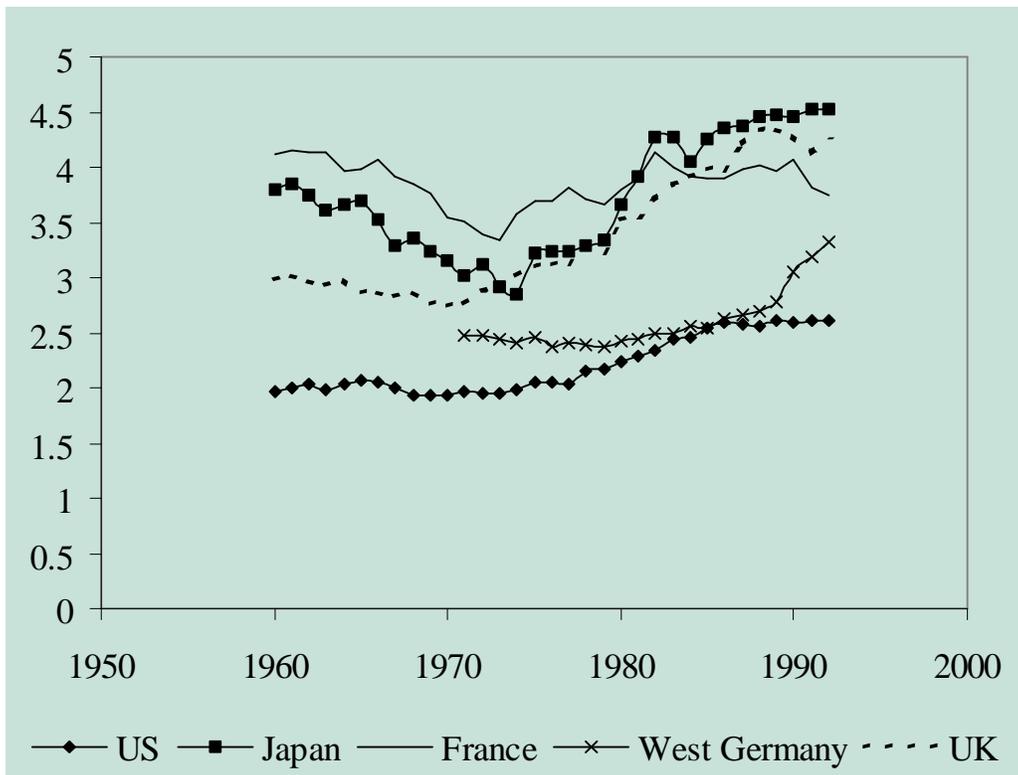


Figure 2 Energy efficiency (GDP per ton of oil equivalent). Data source: see table 1.



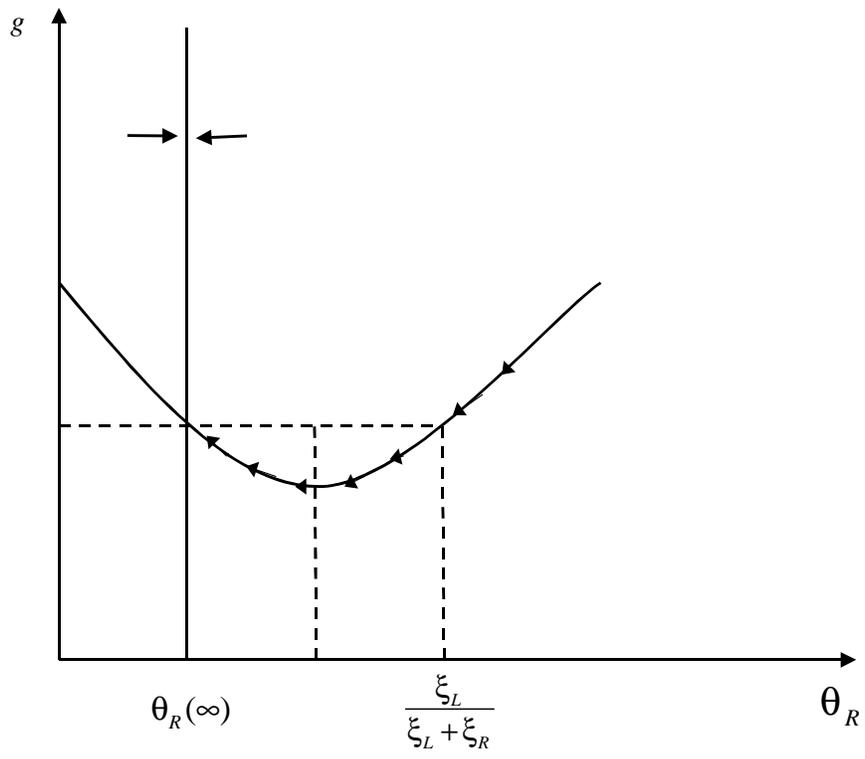


Figure 4

Figure 3 Partial-equilibrium dynamics of the energy share and output growth with induced technical change

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“The Impact of Energy Conservation Policies on Technology and Economic Growth”

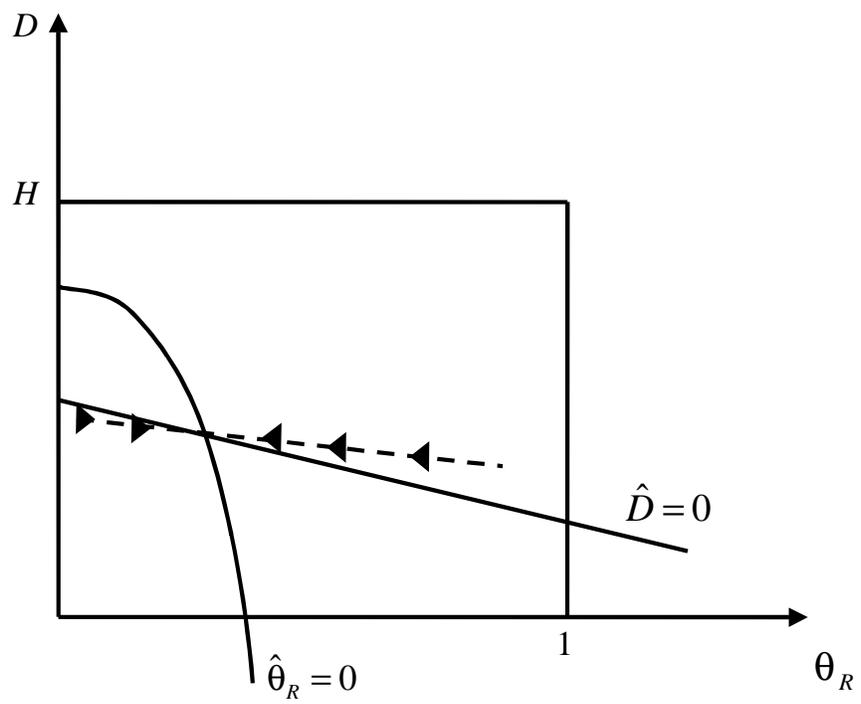


Figure 5

Figure 4 General-equilibrium dynamics of the energy share and total research effort with induced technological change

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