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Keywords: Induced biased technological change, Putty-clay Vintage Models, Energy, Renewable resources

JEL classification: E22, O31, O33, Q42, Q48

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1 Introduction

There is no free energy lunch: production activity necessarily entails the consumption of energy. The ongoing growth of the level of production by the industrialised countries since the end of WWII has thus led to an ever increasing dependence of these countries on (imports of) non-renewable energy resources like oil. This dependency on imports will continue to increase in the future, as more and more oil fields are depleted and oil production becomes concentrated in just a few geographical locations. In addition, in the Western world growth performance itself has become a yardstick for economic success, and so the availability of energy has become a condition sine qua non for maintaining Western living standards.

Nonetheless, our living standards are also positively affected by having a clean and healthy environment, i.e. growth has also negative effects, as the increasing consumption of fossil fuels leads to more and more GHG emissions, which in turn have an adverse effect on the environment. Even for the countries that are not growing, the GHG emissions by other countries have negative effects, as global warming may result in irreversible climate change (UNEP [2004]). Future environmental prospects are bleak for two main reasons: On the one hand, the world will continue to experience high population growth rates, mainly in developing African countries, but also in countries as China and India. This population effect will lead to an absolute increase in the total consumption of energy. On the other hand, real world output, and more particularly the average world living standard, is expected to grow too (UN [2005]). This real wealth effect raises energy consumption in per capita terms. Both effects taken together will lead to a drastic increase in total energy consumption and consequently to higher GHG emissions, ceteris paribus. As one can hardly demand from the developing countries to stop growing, we must do our utmost best to find a mechanism that weakens the adverse effect of rising output levels on the environment, for instance by steering the global growth process in a different direction rather than putting it in reverse.

Technological change is widely believed to be that mechanism. However, in economic energy models, there is no consensus about even the broad nature of this mechanism, let alone about its details. Many energy models, as for example Grübler and Messner [1998] and Mabey et al. [1997] treat technical change as an exogenous factor. However, from the technical change literature (e.g. Ruttan [2001]) we know that technical progress comes from inventions and the diffusion of their application in the real world. Therefore, Dowlatabadi [1998], Carraro and Galeotti [1997] amongst others, have argued that technical change is driven by economic incentives, is therefore sensitive to (anticipated) changes in economic circumstances, and should therefore in principle be an endogenous process driven by economic factors.

In the context of energy-economy models, the concept of induced technical change as proposed by Kennedy [1964] implies that an increase in the price of energy would invoke a higher level of energy-saving R&D activity, thus raising energy efficiency. To us, this seems to be an intuitively appealing idea that is worthwhile integrating in an energy-economy context. Kennedy [1964] has analyzed the induced bias in technological change hypothesis using a production function, which uses just capital and labour, because of the specific use he had in mind for his "induced innovation hypothesis".[1] His main assumption is that the choice of innovating in labour- or capital-saving technologies depends on the respective contributions to unit minimum costs. Moreover, Kennedy introduces the notion of an invention possibility frontier (IPF), describing a dynamic trade-off between labour-saving and capital-saving inventions. That frontier closely resembles a production possibility frontier known from e.g. the Heckscher-Ohlin model from the theory of international trade, and it also serves the same purpose conceptually, namely to describe all feasible and efficient combinations of labour- and capital-saving inventions (output combinations in the case of the Heckscher-Ohlin model) that one could choose from. Kennedy [1964] never provided the micro-foundations of his invention possibility frontier, but in this paper we will link it to R&D activities that are driven by economic incentives, i.e. cost reduction motives, as in Kennedys original work, and as has been done more recently by Acemoglu [2002].

Concerning the direction of the (skill) bias in technical change, Acemoglu [2002] has developed a straightforward framework to analyse the forces behind these biases. The two main factors he identifies are a) the price effect, which leads to the development of technologies used in the production of more expensive goods, and b) the market size effect, which encourages R&D in sectors with larger market shares. The former effect

[1] His aim was to find a convincing answer to the question why technical change should be purely labour augmenting as required for steady state growth in the context of the neo-classical growth model (cf. Jones [2005]).

therefore results in a bias towards technical progress favouring scarce factors, while the latter biases technical change towards abundant factors. Even though Acemoglu [2002] uses this model to investigate skill-biased technical change, there are clear parallels to technical change biased towards different types of energy resources.

In our model we will distinguish between two different types of energy used in combination with other production factors (in our case capital and labour) to generate output. Consequently, we will also introduce two types of innovations: those that are produced by an R&D sector trying to find non-carbon-based fuel-saving production technologies and another R&D sector that focuses on carbon-based fuel-saving innovations. Interestingly, but also somewhat perversely perhaps, the induced innovation hypothesis predicts that the introduction of a carbon tax might in fact lead to the development of better technologies in the carbon-based sector, rather than in the non-carbon sector, as currently the cost share of energy from non-carbon fuels is very low. Hence, the required type of technical change (i.e. the type of technical change that would increase the productivity of non-carbon based fuel technologies), does not necessarily arise on its own, as the increasing scarcity of carbon-based fuels drives up long term fuel prices. The model therefore suggests that the diffusion of non carbon based fuel technologies requires positive policy action, a result also found by Van Zon et al. [2003], in the context of growing energy prices in a Romer-type of endogenous growth model with intermediates made up of a capital-energy complex. In the latter model, rising energy prices reduce the profitability of producing and using new intermediates, and growth is seriously hampered as a result, unless carbon taxes are recycled in the form of R&D subsidies. In this paper, we will perform policy experiments of a similar kind, but then in an induced-bias-in-energy-saving-technical-change setting.

The induced innovation hypothesis describes how research activity, and hence the direction of technical change itself, will change in reaction to changes in the relative user costs of energy as these will be influenced by the introduction of a carbon tax, for instance. This approach also implies that even if the renewable R&D sector would be relatively efficient in increasing energy efficiency, an allocation of R&D to the renewable energy R&D sector does not necessarily generate the best outcome from a user perspective. For, if the share of renewable energy in total resource costs is relatively low, ceteris paribus, then the marginal gains of innovation (in terms of unit cost reduction) will be low as well, and so will be the incentives for engaging in this type of R&D activity.

The induced bias in technical change is one of the two building blocks of our model. The other one relates to the modelling of the production function. In a recent survey, Huntington and Weyant [2002] analyse several new contributions to energy modelling and the global climate change problem. They conclude that although various energy models deal with the transition to less carbon-intensive energy technologies, they suffer from the aggregate nature of the production function. Since these models do not account for individual technologies, they constitute a drawback in the analysis of the transition process to carbon-free energy resources, that would have to come about by switching between specific technology families implicitly defined by the use of equally specific fuels rather than by moving smoothly along an isoquant giving up the consumption of some units of a homogeneous input in favour of increasing the consumption of equally homogeneous units of another input. However, substitution as such is not a costless exercise either. The seemingly smooth movement along an isoquant entails the scrapping of specific equipment, or, if we are lucky, the retrofitting of this equipment, but also the installation of new equipment that is crucially different from the old equipment, either because it uses different inputs altogether, or because it uses the same inputs more efficiently than the old equipment. This is captured by so-called vintage models of production, and the model presented in this paper will make use of such a vintage structure where technical change is embodied in the latest vintage of effective energy-capital, giving rise to productivity differences between individual vintages.

Vintage models come in a number of varieties. These varieties address another critique expressed by Huntington and Weyant [2002] on recent energy models concerning the issue of new capital investments. According to the authors, almost all models assume that in making decisions about new capital investments, firms have complete flexibility in choosing among available technologies before (ex ante) the actual moment of investment.[2] However, there is no consensus in the definition of how much the characteristics of the capital equipment can be changed after (ex post) it has been

[2] In this case it is said that capital ex ante is like soft putty (see: Phelps [1962]).

installed. This distinction translates into two types of vintage models: putty-putty and putty-clay models.[3] Gilchrist and Williams [2005] suggest that, unlike a putty-putty model, a putty-clay model generates a favourable framework for modelling a steady adjustment of energy use in response to a more or less continuous change in energy prices. Atkeson and Kehoe [1999] investigate the performance of the putty-clay and putty-putty models in explaining the core findings of empirical data. In a number of simulations they conclude that the putty-clay model clearly constitutes an improvement over the putty-putty model when it comes to reproducing empirical data. Therefore, the vintage structure in our model will be of the putty-clay type.

Unfortunately, full putty-clay models are tedious to handle. Instead we will be using a simplified version of a putty-clay model, called the "putty-practically-clay model" as described in more detail in Van Zon [2005]. That model mimics the behaviour of a full putty-clay model, while it takes into account only two vintages (consisting of "old" and "new" equipment), and handles scrapping by means of updating the aggregate survival fraction of old equipment, rather than explicitly scrapping the individual vintages that together constitute "old" equipment.

The combination of both Kennedy [1964] induced innovation hypothesis and the putty-practically-clay vintage structure forms the core of our model. This paper questions the belief that a carbon tax in a model of induced technical change accelerates the substitution of non-fossil energy for fossil fuels (e.g. Gerlagh and Wietze [2003]). Also, since in aggregate production function models the ex post clay nature of capital is not accounted for, there is a potential risk of underestimating future adjustment costs. In addition, it is also risky to do too little too late in the face of the long policy response times implied by the embodiment of technical change in individual vintages. Hence, the fact that technical change is indeed largely embodied in new equipment, whereas the characteristics of this equipment are hard if not impossible to change ex post, may substantially weaken the effect of a carbon tax on the speed of transition towards non-carbon-based fuel usage, as compared to a putty-putty setting, even allowing for induced technical change. In that sense, the model presented here is of immediate

[3]Following Huntington and Weyant [2002], a putty-clay formulation assumes that the original equipment cannot be modified once installed. In contrast, a putty-putty formulation assumes that capital, once installed, can also be reshaped to fit the current price situation in each time period.

relevance for policy makers, since the structure of the model explicitly addresses the consequences of having an overly optimistic view on substitution possibilities between different technologies, whereas at the same time it shows that if production and R&D decisions are indeed driven by profit motives, then our a priori notions about the broad substitution patterns to be expected from changing relative fuel prices may simply be wrong.[4] The question is whether we can afford to be wrong, given the potentially long lags between the application of policy instruments and the full impact of their effects.

The paper is further organised as follows. Section 2 presents the vintage model with two different types of capital distinguished according to fuel type. Section 3 describes how we combine endogenous biases in capital- (hence fuel-) saving technical change with this vintage model. Section 4 describes the closure of the model. In section 5 we perform some illustrative simulations, while section 6 concludes the analysis and provides some policy recommendations.

2 The vintage model

2.1 Introduction

The basic idea underlying a vintage model is that the potential of technical change as an idea can only be realised in practice by first incorporating that idea into a piece of machinery and then subsequently using that machinery to produce output. While this does not deny that the ultimate source of technical change is still the idea produced by the R&D sector, it does emphasize the fact that complementary investment has to take place in order to realise the productivity gains conveyed by new ideas.[5] Phelps [1962] describes this concept as the marriage between investment and technology, where investment is seen as the carrier of technological progress. This is the above-mentioned

[4] The alternative is of course that our model is wrong. But even if this would be the case, this would obviously not imply that the standard aggregate production function model is correct. An aggregate production function with its usual asymptotic properties covers areas of the factor-space we have never ventured before. We do not know yet whether these regions are really accessible to us. That is what science is supposed to find out for us.

[5] Obviously, there is also technical change that comes in the form of new ideas with respect to the organisation of production, that is not as such linked to investment and that is called disembodied technical change in a vintage context. In this paper we will solely focus on embodied technical change, however, in order to simplify matters as much as possible.

embodiment character of technological progress. Embodied technical change results in a heterogeneous stock of capital. Depending on the degree of substitution between production factors ex post, the arrival of new superior technologies may render the old ones obsolete, as in Aghion and Howitt [1990]. Creative destruction is a straightforward consequence of the combination of embodiment and profit maximisation in a competitive environment.

Under the embodiment assumption, the average productivity characteristics of the total capital stock will change only slowly, as new capital goods fill the gaps left by the physical decay and scrapping of old capital goods. In our model we distinguish between two different technology families, i.e. a family using carbon-based fuels and one using non-carbon-based fuels, each with their own vintage structure incorporating different states of a particular energy-related technology in the line of Van Zon [2005]. In order to model this, we will define aggregates of energy and capital that constitute "effective capital" as in Romer [1990]. This "effective capital" is then used as a composite input to produce output at the vintage level. Technical change then occurs through changes in the productivity of this "effective capital" aggregate.

We will not allow for the possibility of substitution between the input factors after the vintage incorporating a specific technology level has been installed, because in practice it is hard, if not impossible at all, to change the nature of energy requirements of machinery and equipment ex post. Hence, we opt for a putty-clay vintage model (cf. Johansen [1959], Salter [1960]). The advantage of using a putty-clay model is that it implements the idea of irreversible investment decisions. In the putty-putty (e.g. Solow [2000]) version that allows for ex post substitutability, one can costlessly substitute away from factor combinations that become more costly due to changing factor prices. In a putty-clay situation, one would have to foresee these changes in factor prices ex ante, and incorporate them in the factor proportions that will be embodied in the new vintage under consideration.

In our energy model, that we want use to analyse the adjustment of the economy to environmental policy measures, a putty-putty model would therefore generate unrealistic results. The reason for this is that "[...] in the putty-putty model large parts of the current capital stock can be transformed into more efficient and less carbon-intensive alternatives [...]" (Huntington and Weyant [2002]). In the putty-clay setting, this is ruled out from the outset because the productivity impact of new investment is significantly limited by older vintages already installed. This means that short run environmental targets can be reached only at the expense of relatively high adjustment costs. The clay-clay model (e.g. Kaldor and Mirrlees [1962]) would have been an alternative to our putty-clay model, but it causes the problem that "there is only one efficient equipment design for any one vintage" (Wan [1971]), which we feel is too narrow a view on the nature of the set of production technologies available. In choosing the putty-clay perspective, we are backed up by many studies that underline its empirical relevance (e.g. Gilchrist and Williams [2005]).

2.2 The ex ante situation

The ex ante situation of our model is relatively standard. As shown in Van Zon [2005], being faced with an ex post clay situation forces entrepreneurs to take account of the present value of cumulative variable and fixed costs (but also output and sales) over the entire lifetime of a vintage. These define optimum factor proportions constrained by an ex ante production function.

To be more precise, we assume that total capacity output at time t, i.e. Y_t, consists of the sum of the part of old capacity left after technical and economic decay and the additional output generated by the new vintage. Let the decay fraction be ω_t In that case we have:

$$Y_t = (1 - \omega_t) \cdot Y_{t-1} + \Delta Y_t \tag{1}$$

The level of output at the vintage level is given by a linear homogeneous CES function:

$$\Delta Y_t = [(A_{\Delta Ke} \cdot \Delta Ke_t)^{-\alpha} + (A_{\Delta Ly} \cdot \Delta Ly_t)^{-\alpha}]^{-\frac{1}{\alpha}} \tag{2}$$

where ΔKe_t is the marginal addition to the effective capital stock (i.e. the 'size' of the newest vintage in effective capital terms) and ΔLy_t is the labour employed on the latest vintage. Both ΔKe and ΔLy are input factors for the vintage installed at time t. Equation (2) states that, ex ante at least, output is a CES aggregate of effective capital and labour. The embodiment of technical change is assumed to be completely tied to effective capital, as we will explain in more detail below. $1/(1+\alpha)$ is the elasticity of substitution between effective capital and labour at the (new) vintage level, while $A_{\Delta Ke}$ and $A_{\Delta Ly}$ are constant distribution parameters.

Effective capital corresponding to the vintage at time t is described by a nested CES function that describes substitution possibilities (ex ante) between carbon-based and non-carbon-based effective capital at the upper level, and (”virtually” nonexistent) substitution possibilities between raw capital and either carbon-based fuels (indexed by c) or non-carbon-based fuels (indexed by r for ”renewable”).

$$\Delta Ke_t = [(c_t^c \cdot x_t^c)^{-\rho} + (c_t^r \cdot x_t^r)^{-\rho}]^{-\frac{1}{\rho}} \qquad (3)$$

$$x_t^i = \min\left(\frac{k_t^i}{\kappa_t^i}, \frac{f_t^i}{\zeta_t^i}\right) \quad , \qquad i = c, r \qquad (4)$$

where x_t^c is the carbon-based effective capital input and x_t^r is the non-carbon-based effective capital input. c_t^c and c_t^r are the CES distribution parameters, and they can change due to R&D driven embodied factor-augmenting technical change. k_t^c is the amount of raw capital used to generate x_t^c units of carbon-based effective capital. Consequently, κ_t^c is the unit ”raw” capital requirement of carbon-based effective capital. k_t^r and κ_t^r are analogously defined for non-carbon-based effective capital. Likewise, f_t^c is the total amount of carbon-based fuels used to generate x_t^c units of carbon-based effective capital, while ζ_t^c are the unit carbon-based-fuel requirements of carbon-based effective capital. The final output sector now hires carbon-based and non-carbon-based effective capital in proportions that can not be changed ex post: it effectively creates a vintage in accordance with equation (3.A). Since the fuel and the capital services associated with each type of effective capital need to be paid for, this should be done in such a way that the total user costs of the vintage capital aggregate over the (effectively infinite) lifetime of the vintage are minimised. For that purpose we can set up the cost-minimizing Lagrangian of the effective capital sector.

$$M_t = p_t^c \cdot x_t^c + p_t^r \cdot x_t^r + \lambda_t \cdot (\Delta\overline{Ke} - \Delta Ke_t) \qquad (5)$$

where p_t^c and p_t^r are the present value of the expected cost streams associated with using either type of effective capital x_t^c and x_t^r, respectively, and λ_t is the Lagrange multiplier, while $\Delta\overline{Ke}$ is the required amount of effective capital at the aggregate level. Solving (4) for the levels of each type of effective capital, we find that the initial cost minimising ratio $\frac{x_t^c}{x_t^r}$ is given by:

$$\frac{x_t^c}{x_t^r} = \left(\frac{c_t^c}{c_t^r}\right)^{1-\sigma} \cdot \left(\frac{p_t^c}{p_t^r}\right)^{-\sigma} \tag{6}$$

where $\sigma = 1/(1+\rho)$ is the elasticity of substitution ex ante between the two types of effective capital. Using (3.B) in combination with (5), we find for the initial raw capital ratio and the initial fuel consumption ratio that:

$$\frac{k_t^c}{k_t^r} = \frac{\kappa_t^c}{\kappa_t^r} \cdot \frac{x_t^c}{x_t^r} = \frac{\kappa_t^c}{\kappa_t^r} \cdot \left(\frac{c_t^c}{c_t^r}\right)^{1-\sigma} \cdot \left(\frac{p_t^c}{p_t^r}\right)^{-\sigma} \tag{7}$$

$$\frac{f_t^c}{f_t^r} = \frac{\zeta_t^c}{\zeta_t^r} \cdot \frac{x_t^c}{x_t^r} = \frac{\zeta_t^c}{\zeta_t^r} \cdot \left(\frac{c_t^c}{c_t^r}\right)^{1-\sigma} \cdot \left(\frac{p_t^c}{p_t^r}\right)^{-\sigma} \tag{8}$$

2.3 The ex-post situation: the 'putty-practically-clay' model

In the absence of disembodied technical change, we have for a vintage installed at time T for the ex post development over time of effective capital by type, and for that of fuel demand by fuel type:

$$x_{T,t}^i = \frac{INV_T^i \cdot e^{-\mu^i \cdot (t-T)}}{\kappa_T^i} \quad , \qquad i = c, r \tag{9}$$

$$f_{T,t}^i = \frac{\zeta_T^i}{\kappa_T^i} INV_T^i \cdot e^{-\mu^i \cdot (t-T)} \quad , \qquad i = c, r \tag{10}$$

It should be noted that the factor proportions of putty-clay vintages will not change ex post, apart from disembodied technical change. Hence, when variable cost per unit of output on an old vintage rises above the total unit cost on a new vintage, total profits can be maximised (or total costs can be minimised) by replacing capacity associated with old inefficient vintages by new capacity. This is known as the Malcomson scrapping condition (cf. Van Zon [2005]). However, we would like to economise on the extensive bookkeeping requirements of a full putty-clay model, as we are interested in the evolution over time of aggregate factor demand rather than factor demand at the level of each individual vintage. Therefore, we define just two vintages. The first one consists of all old equipment, and the second one is the new equipment just installed. Total output is now by assumption the sum of all output on the newest vintage, and output on that part of the old vintage that would survive the Malcolmson scrapping condition explained above. To model this, we postulate a "non-linearised" version of the ex post production function for the old vintage.

As one recalls, ex post factor proportions in a putty-clay model are assumed fixed, implying that if the variable factor is the limiting input, then the level of output relative to capacity output will be equal to the level of input of the variable production factor relative to its corresponding capacity level. Moreover, as soon as the variable input reaches its capacity level, the level of output will not be able to rise any further. Consequently, the ex post production function looks as in Fig. 1. For a given rental price of the variable factor, one can turn this ex post production function into a corresponding marginal cost function that is shown in Fig. 2. In case of a Leontieff technology, the marginal cost function is flat at a constant level that depends on the unit user cost of the variable factor here called PV up to the point of full capacity utilisation.

The solid line in Fig. 1 is the ex post production function. q^Y and q^V act like rates of capacity utilisation, as they measure actual output and input relative to capacity output (Y) and input (V), respectively. The marginal cost (MC) associated with using q^V % of the capacity input level of the variable factor (i.e. V^*), will then look as in Fig. 2. The horizontal part of the marginal cost curve comes from the assumption of fixed factor productivities ex post. The vertical part comes from the fact that capital becomes the limiting factor for levels of $V > V^*$. If V rises above V^*, we find that costs still rise proportionally with V, while X remains at $X = X^*$. Hence, we do not get any additional output while we do have additional costs. Consequently, marginal costs become infinitely high at $X = X^*$ implied by $V = V^*$.

The dotted line labelled 1 corresponds with a relatively high level of the unit total user cost on the newest vintage. Hence, profits would be maximised by retaining the old vintage and not scrapping anything. Likewise, for a relatively low level of total unit

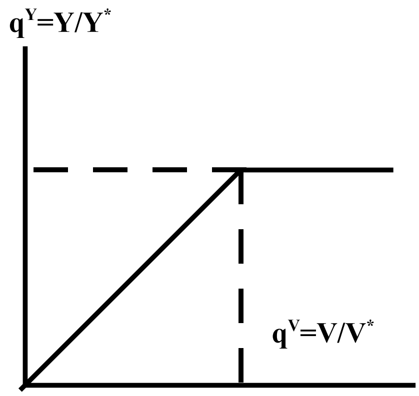


Figure 1:

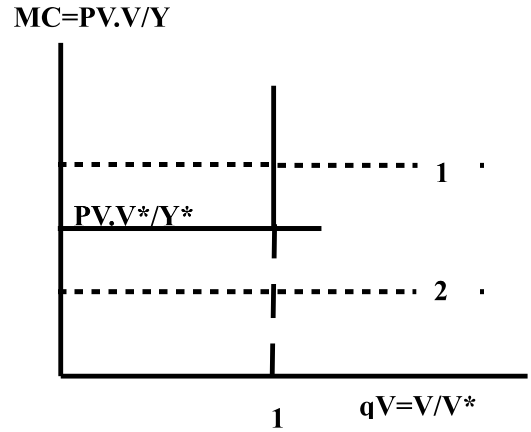


Figure 2:

user cost as given by the dotted lined labelled 2, profit maximising entrepreneurs would scrap all old capacity and replace it by new capacity.

Obviously, for total unit costs close to $PV.V^*/X^*$ a small change in PV may result in the scrapping of an entire old vintage. Since in our case all old capacity is contained in just one vintage, this may result in an infinitely high price elasticity of total capacity. In order to avoid this, we may assume that there is some "fine-structure" within our old vintage, that would generate a concave ex post production function that has the ex post production function from Fig. 1 as a limiting case (i.e. as an asymptote). A function that does the trick comes from UV-analysis where it has been widely used.[6] It has the form:

$$q^x = [1 + (q^v)^{-\beta}]^{-\frac{1}{\beta}} \tag{11}$$

where $\beta > 0$ is a constant parameter. For increasing values of β, the graph of equation (8) gets closer and closer to the graph of the ex post production function in Fig. 1. This follows immediately from the fact that for a value of $q^V \geq 1$ and for $\beta \rightarrow \inf$, we find $q^x \rightarrow 1$, whereas for $0 < q^V < 1$ we find that the term $(q^V)^{-\beta} \gg 1$, so that $q^x \rightarrow q^V$

[6]See e.g.: Sneessens and Drze [1986] and Kooiman and Kloek [1979]. This function can be shown to be a special case of the putty-semi-putty model as described in Van Zon [2005].

in this case. Using (8), the corresponding marginal cost function is given by:

$$MC(q^V) = PV \cdot \frac{\partial V}{\partial X} = PV / \frac{\partial X}{\partial V} = PV/(X^* \cdot \frac{\partial q^X}{\partial q^V}/V^*) = \frac{PV.V^*}{X^*} \cdot [1 + (q^V)^\beta]^{(1+\beta)/\beta} \quad (12)$$

It should be noted that equation (9.A) only solves our problem for cases like those represented by the horizontal dotted line labelled 1 in Fig. 2, i.e. for $MC > MC^* = P^*.V^*/X^*$. For a case like the dotted line labelled 2, we simply **postulate** that the marginal cost function will be the mirror image of (9.A), but then mirrored along the vertical through $q^V = 1/2$ and the horizontal through $MC^* = P^*.V^*/X^*$. In that case we would have for $MC < MC^*$:

$$MC(q^V) = \frac{PV.V^*}{X^*} \cdot [1 - (1 - q^V)^\beta]^{(1+\beta)/\beta} \quad (13)$$

In equation (9.B), replacing q^V in (9.A) by $1 - q^V$ takes care of the vertical symmetry axis given by $q^V = 1/2$. Changing the positive sign of qV into a negative one in (9.A) takes care of the horizontal symmetry axis through $MC = MC^*$.[7] Thus, Fig. 2 becomes Fig. 3. In Fig. 3, the curved line (that looks like the graph of the tangent function) now represents our "non-linearised" ex post marginal cost function.

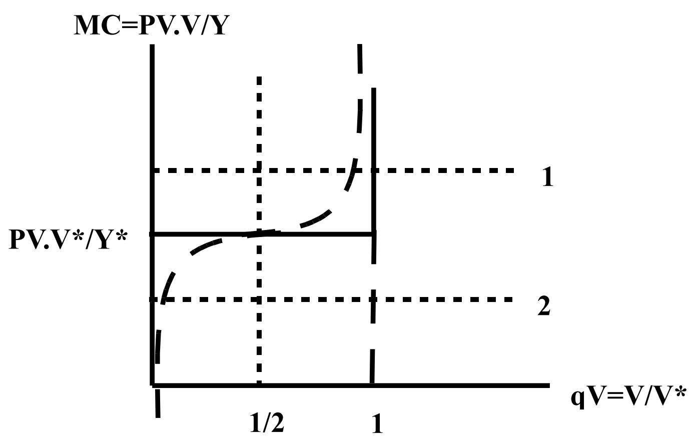


Figure 3:

The values of q^V that we can find for cases 1 and 2, for instance, will be taken to represent the survival fraction of the old vintage, further denoted by sf_t, given the fairly

[7]Note that the marginal cost function defined in this way is continuous in sf at $sf = 1/2$.

bold assumption that we can approximate the term $PV.V^*/X^*$ in the marginal cost function by the average variable cost of the old vintage. In this setup it follows that if the unit total cost of the new vintage is relatively high, then the survival fraction of old equipment will be high as well, and vice versa, as in a standard putty-clay model. In fact, the value of the survival fraction can be obtained directly from (9.A) and (9.B) by equating the marginal cost function of the old vintage with unit total cost on the new vintage and then solving for q^V (which we relabel here as sf). In that case we get:

$$sf = \{(utc/mc)^{\beta/(1+\beta)} - 1\}^{1/\beta} \quad , \qquad utc > mc \tag{14}$$

$$sf = 1 - \{1 - (utc/mc)^{\beta/(1+\beta)}\}^{1/\beta} \quad , \qquad utc < mc \tag{15}$$

$$sf = 1/2 \quad , \qquad utc = mc \tag{16}$$

where utc represents unit total cost on the newest vintage and mc is the marginal variable cost on the old vintage. The average productivity characteristics of the old vintage change both due to investment in new vintages that subsequently get old, and due to technical decay and the scrapping of old capacity. We can obtain an estimate of the new value of the average factor coefficients of the entire capital stock, by updating the old factor coefficients in accordance with the level of investment in new capacity. Thus we get:

$$F_t^i/Y_t = \{(F_{t-1}^i/Y_{t-1}) \cdot Y_{t-1} \cdot (1-\mu) \cdot sf_t + (\Delta F_t^i/\Delta Y_t) \cdot \Delta Y_t\}/Y_t \tag{17}$$

where F_t^i represents any factor used to produce output.[8] With respect to total output, we now have:

$$Y_t = (1-\omega_t) \cdot Y_{t-1} + \Delta Y_t = (1-\mu) \cdot sf_t \cdot Y_{t-1} + \Delta Y_t \tag{18}$$

thus implicitly defining the overall decay rate as $\omega_t = 1 - (1-\mu) \cdot sf_t$, μ being the physical rate of depreciation. Equation (11) shows how the average factor coefficients of total production capacity are a weighted average of the coefficients of old capacity

[8]Obviously, (11) can be used to obtain variable unit cost of the old vintage by lagging factor coefficients by one period and then multiplying the lagged factor coefficients by the current market price of the factor under consideration.

and of new capacity. The bigger the volume share of new capacity in total capacity, i.e. the larger $\frac{\Delta Y_t}{Y_t}$, the faster the average factor coefficients will change, ceteris paribus.[9] Obviously, absolute factor use can be obtained directly by multiplying the average factor coefficients (given by (11)) with the level of aggregate capacity output (given by (12)). This also applies to the capital stock(s).

3 Induced energy-saving technical change

We assume that technical change is the outcome of R&D efforts that are endogenously determined in the model. To this end, we use an R&D production function based on that of Romer [1990]. But contrary to Romer we assume that the marginal product of R&D workers is falling with the level of R&D effort, since we want to obtain an interior solution for the allocation of R&D workers over different types of R&D, rather than "bang-bang" reallocations of R&D workers as we would have in the case of linear R&D functions.[10] This approach has also been followed in Van Zon et al. [2003]. We postulate:

$$\Delta c_t^i = c_{t-1}^i \cdot \delta_t^i \cdot (R_t^i)^r \quad , \quad i = c, r \tag{19}$$

In equation (13), R_t^i is the amount of R&D labour that is engaged in carbon-based and non-carbon-based R&D, respectively. Furthermore, δ and γ are efficiency parameters corresponding to both types of R&D activities. Consequently, the growth rates of c_t^c and c_t^r are given by:

$$\hat{c}_t^i = \delta_t^i \cdot R_t^{i\gamma} \quad , \quad i = c, r \tag{20}$$

Equation (14) implies that the rate of effective capital augmenting technical change is increasing with R&D activities but, as we assume that $0 < \gamma < 1$, technological change will be characterized by diminishing marginal returns to R&D.

[9]The inverse of this capacity share is a rough estimate of the economic lifetime of machinery and equipment.

[10]Romer [1990] finds an interior solution because the alternative use of high skilled workers (production in the final output sector) still has a decreasing marginal product.

In our model, technological change is driven by the same cost reducing motivations that underlie Kennedy [1964] induced innovation hypothesis. The idea behind this hypothesis is that R&D activities will be distributed according to the cost shares of the particular energy capital in the total effective capital costs. These shares are a direct indicator of the impact that a cost reducing innovation associated with a specific input would have on total costs.

Endogenous technical change based on Kennedy-like cost-reduction incentives has important implications for the working of the model, since in reality, we observe that the renewable energy sector contributes relatively little to total energy supply. Consequently, the share of renewable energy in total energy costs is also relatively low, ceteris paribus. If the induced innovation hypothesis would hold, then R&D activities would tend to take place primarily in the non-renewable energy sector where the potential for significant cost reductions is greater, ceteris paribus.

In fact, these cost-reduction incentives are easily modelled by borrowing some of the notions from the Romer [1990] model (but also from e.g. Aghion and Howitt [1990]). In the Romer [1990] model, R&D labour earns a wage that is paid out of the rents that the producers of intermediate goods obtain from selling their produce to the final output sector. These rents are captured by the R&D sector by selling patents on their innovations. Similarly, the selling price of a patent for an improved version of a specific type of effective capital will consist of the present value of the cost savings made possible by using the improved effective capital type. Consequently, if these cost-savings are high, the wage-rate that can be paid to the R&D workers engaged in finding improved effective capital types can be relatively high as well. The latter would call for a bias of R&D effort in the direction of the activity that would generate the largest cost-reductions, ceteris paribus, thus in fact producing the kind of biased technical change described by Kennedy [1964].

In order to implement this induced bias in technical change concept we have to determine how technological change reduces the user cost of effective capital. These are defined as the minimum cost of using the two Leontief constructs x^c and x^r as described by (3.B):

$$p_t^i = \frac{pk_t^i}{\kappa^i} + \frac{q_t^i}{(r_t + \mu - \hat{q}^i) \cdot \xi^i} \quad , \quad i = c, r \tag{21}$$

where p_t^i are the present values of the user cost of a specific Leontief composite input per unit of the initial level of the Leontief composite input. In equation (15), r is the interest rate, μ is the rate of depreciation of capital and q_t^i are prices of a unit of non-renewable and renewable fuels at time t, respectively pk^i is the price of a unit of capital (which can be shown to be equal to the present value of the flow of the user cost of capital over an infinite lifetime). As mentioned before, ξ^i is the amount of energy resources necessary to produce one unit of the corresponding Leontief composite input. Finally κ_t^i is the amount of raw capital used per unit of x_t^i.

The present value of the minimum cost of operating a vintage over an infinite lifetime is then given by:

$$\lambda_t = [(c_t^c)^{\frac{-\rho}{1+\rho}} \cdot (p_t^c)^{\frac{\rho}{1+\rho}} + (c_t^r)^{\frac{-\rho}{1+\rho}} \cdot (p_t^r)^{\frac{\rho}{1+\rho}}]^{\frac{1+\rho}{\rho}} \tag{22}$$

From equation (16) it becomes apparent that an increase in the values of c_t^c and c_t^r would reduce the present value of operating a unit of effective capital.[11] Consequently, the present value of the cost of using a new vintage of size ΔKe is then given by:

$$PVC_t^{\Delta Ke} = \lambda_t \cdot \Delta Ke_t \tag{23}$$

We can now calculate the shares s_t^i of x_t^i in $PVC_t^{\Delta Ke}$. We find:

$$s_t^i = \frac{p_t^i \cdot x_t^i}{\lambda_t \cdot \Delta Ke_t} \quad , \quad i = c, r \tag{24}$$

Equation (18) can be simplified using (5):

$$s_t^i = (c_t^i)^{\frac{1}{1+\rho}-1} \cdot (p_t^i)^{\frac{1}{1+\rho}} \cdot (\lambda_t)^{\frac{1}{1+\rho}-1} \quad , \quad i = c, r \tag{25}$$

We can now find out how a change in c_t^i would affect λ_t, i.e. the present value of the user cost of one unit of a new vintage:

$$\frac{\partial \lambda_t}{\partial c_t^i} = (-1) \cdot (\lambda_t)^{\frac{1}{1+\rho}} \cdot (p_t^i)^{\frac{1}{1+\rho}} \cdot (c_t^i)^{\frac{1}{1+\rho}-2} \quad , \quad i = c, r \tag{26}$$

[11] For reasons of simplicity we assume that the actual construction of a vintage does not take any resources. Only its use in producing final output does so.

Substituting (19) into (20), we find that:

$$\frac{\partial \lambda_t}{\partial c_t^i} = \frac{-\lambda_t \cdot s_t^i}{c_t^i} \quad , \quad i = c, r \tag{27}$$

Based on (21), we derive the following conclusions. First, the right hand side is negative, implying that technological change reduces unit minimum costs. Furthermore, the higher the overall cost level, the larger will be the cost reductions. The level of technological change (represented by c_t^i) is in the denominator of (21), implying decreasing returns in marginal cost reduction with advancing technological change. Finally, the higher the cost share of Leontief composite i in total costs, the larger will be the marginal benefits from technological change in this direction. This finding is qualitatively the same as the assumption made by Kennedy [1964] regarding the importance of cost-shares as drivers of biased technical change.

As in Romer [1990] or Aghion and Howitt [1990], we assume now that labour market arbitrage will govern the allocation of skilled labour over R&D activities and final output production. For that purpose, we assume that wages are equal to the marginal benefits of doing research. These benefits are given by the present value of the total vintage user cost reduction that can be attributed to the R&D embodied in the latest vintage. In fact, this total cost reduction is given by:

$$\Delta PVC_t^{\Delta Ke} = \Delta Ke \cdot \Delta \lambda_t \approx \Delta Ke_t \cdot \frac{\partial \lambda_t}{\partial c_t^i} \cdot \Delta c_t^i \approx \Delta Ke_{t-1} \cdot \frac{-\lambda_t \cdot s_{t-1}^i}{c_{t-1}^i} \cdot c_{t-1}^i \cdot \delta_t^i \cdot (R_t^i)^{\gamma} \tag{28}$$

where we have introduced some lagged values in the final part of (22) in order to reduce the simultaneity of the model.[12] Finally, the wages received by the R&D workers are obtained by calculating the marginal present value product of total cost reductions from R&D activities:

$$w_t^i = \frac{\partial \Delta PVC_t^{\Delta Ke}}{\partial R_t^i} = \Delta Ke_{t-1} \cdot (R_t^i)^{\gamma-1} \cdot S_{t-1}^i \cdot \gamma \cdot \delta_t^i \cdot \lambda_{t-1} \quad , \quad i = c, r \tag{29}$$

[12]This makes it easier to solve the model numerically, while it doesn't change the long term properties of the model.

Because of labour market arbitrage, all wages should be the same. In that case we find for the distribution of R&D activity over its two uses that:

$$\frac{R_t^c}{R_t^r} = \varphi_t = \left[\frac{S_{t-1}^c \cdot \delta_t^c}{S_{t-1}^r \cdot \delta_t^r}\right]^{\frac{1}{1-\gamma}} \quad \Rightarrow \quad R_t^c = R_t \cdot \frac{\varphi_t}{1+\varphi_t} \quad , \quad R_t^r = R_t \cdot \frac{1}{1+\varphi_t} \tag{30}$$

where R_t denotes total labour available for doing R&D in both alternative uses. Equation (24) shows that in accordance with Kennedy [1964] induced innovation hypothesis, relative R&D activity will depend positively on the relative shares of the respective present values of the user cost of the Leontieff composite inputs.

4 Closing the model

We now need to put the two main building blocks of our model together and to specify the remainder of the model. To do this, we have to decide on the size of the newest vintage, and simultaneously on the distribution of labour over its three different uses (final output production and doing carbon and non-carbon based R&D).

As regards the first building block, it should be noted that present value cost minimisation determines the cost-minimising factor coefficients, both for the fixed factor of production and the variable factors of production (ex ante all factors are still variable). The cost-minimising (marginal) capital coefficient then determines the level of investment given the size of the new vintage in capacity output terms. In our case, we turn this relation around. Assuming that a constant fraction of output is saved and invested, we know the size of the newest vintage in capital terms, and we can use the marginal capital coefficient to obtain the corresponding level of output. Equation (5) already provided the 'present value cost minimising' factor proportions of the newest vintage in terms of the Leontief composite inputs x^c and x^r, while equation (6.A) provides the corresponding marginal capital ratio. Given the assumption that capital tied to the composite inputs x^c and x^r should completely exhaust available new 'raw' capital (i.e. savings=investment), we must have that investment in both composites is given by:

$$INV_t^c = \frac{k_t^c/k_t^r}{1+k_t^c/k_t^r} \cdot INV_t \quad and \quad INV_t^r = \frac{1}{1+k_t^c/k_t^r} \cdot INV_t \quad where \quad INV_t = s \cdot Y_t \tag{31}$$

where s is the constant savings rate of the economy. Given the level of investment for each composite input, we can calculate the actual level of that input, and then, using (3.B) also the corresponding level of consumption of the different fuels.

The evolution over time of the total consumption of fuels and capital services is described by the combination of equations (11) and (12). That of total current emissions E (as opposed to cumulative emissions) follows from the multiplication of the total use of carbon-based fuels with a given emission coefficient ε:

$$E_t = \varepsilon \cdot F_t^c \tag{32}$$

where we have assumed that non-carbon-based fuels do not cause any pollution. Therefore, in our model, the use of carbon-based fuels is solely responsible for all emissions in this economy. In addition to this, we have assumed that ε is independent of time. From a chemical point of view this certainly holds, but from an economic point of view that need not be the case (for instance due to end-of-pipe abatement). For our illustrative purposes we disregard the latter, however, even though the model could be generalized to cover endogenous technical change in this direction within the Leontieff composite.

The energy vintage model will be augmented by adding two price equations for carbon and non-carbon-based fuels. Again for reasons of simplicity, we assume that the growth rates of real fuel prices are constant and positive. Moreover, the growth rate of carbon-based fuels has been set equal to the real interest rate.[13] The reason for that is that with a depleting stock of carbon-based fuels its price must rise over the long-run in accordance with Hotelling's (1931) rule. The latter states that the growth rate of the spot price of the exhaustible resource $\hat{q}_t^c$ should be equal to the interest rate. Thus we have:

$$\hat{q}_t^c = r \tag{33}$$

Finally, the supply of labour LS is taken to be exogenously determined, and during the simulations outlined below, it has been fixed at a constant level equal to 1.

[13] By assumption, the real interest rate exceeds the growth rate of real non-carbon-based fuels.

5 Some illustrative model simulations

5.1 General considerations regarding the working of the model

Hotelling [1931] rule plays an important role when analyzing the dynamic behaviour of the energy vintage model. An increase in the price level of carbon-based fuels energy resource through a carbon tax, for example, will make its corresponding composite input more costly and therefore less desirable to use, ceteris paribus. But since the tax raises the user cost of carbon-based fuels, the cost shares of these fuels are likely to rise (which would be the case for an elasticity of substitution of fuels of less than one), and so there will be a tendency for the induced bias in technical change mechanism to allocate relatively more workers to the R&D sector focusing on the development of more efficient carbon-based fuel technologies.

This dynamic chain of events also influences the nature and timing of environmental policies. For example, a tax levied on the use of carbon-based fuels might bring about an unfavourable side effect, in the form of a reallocation of R&D labour towards the carbon-based fuel R&D sector, thus in fact reducing the need to economise on the use of carbon-based fuels, and therefore stalling the accumulation of non-carbon-based fuel technological know how. This reallocation of R&D effort is almost certain to occur,[14] as the main logic of the induced bias is that, if a factor of production becomes more expensive, there will be contemporaneous substitution (as given by the ex ante production function for new capacity and the ex post function for old capacity) between different types of equipment using carbon- and non-carbon-based fuels. In addition to this, there will also be a more fundamental change in substitution possibilities themselves, as the reallocation of R&D efforts change the ex ante production function. This is a form of intertemporal substitution of current output for higher future output through R&D driven increases in the productivity of the scarce production factors.

The actual values of these substitution possibilities between factors of production and the particular nesting of these factors are extremely important for the type of results one could expect. A relatively high elasticity of substitution between labour and capital, for instance, would call for strong contemporaneous substitution reactions, and hence for relatively large shifts in the labour-capital ratio. This would tend to raise the

[14] We come back to this in more detail later on.

equilibrium wage rate, which in turn would depress the level of both types of R&D, that in this setup are only geared at saving fuels, rather than all production factors.[15]

A faster pace of technical change also leads to creative destruction, with a corresponding loss of old capacity, that, production-wise, cannot be completely compensated for by new capacity, as part of the resources tied up in new capacity have been used to counter the cost-raising effects of a fuel price rise, both through contemporaneous substitution, and through an induced reallocation of labour between R&D activities and final output production. This creative destruction also has a positive side effect in that the new vintage embodying the improved state of fuel technologies is bigger, ceteris paribus, so that the actual diffusion of the new technology takes place at a faster rate. In this context, we stress again that emissions per unit of aggregate output depend on the vintage composition of the capital stock too. Indeed, as we will illustrate below, this technological diffusion, as it is governed by the creative destruction process implied by the Malcolmson scrapping condition, adds its own flavour to our endogenous bias in and endogenous diffusion of technology.

The rest of this section is organized as follows. In section 5.2 we present the base run that we will use for two purposes. First, it is used to illustrate the principal working of the model. Secondly, it will be the frame of reference for four different policy experiments we have conducted. These policy experiments are described in more detail in section 5.3.

5.2 The base-run

In order to make the analysis less complicated, the model has been simulated by using arbitrary values for the parameters as well as arbitrary data for the exogenous variables and lagged endogenous variables. More extensive research has been planned to find out about the working of the model in other regions of the parameter space. Our aim now, however, is to illustrate that the effectiveness of environmental policies in the long term may be seriously compromised by the existence of endogenous biases in technical change. If, through future research, such unwanted spin-offs can be expected to occur also for regions in the parameter space that are directly relevant in practice,

[15] The model is however fairly easily generalised in this direction.

then obviously, (environmental) policy makers would be well-advised to incorporate these induced bias in technical change effects in their decision making from the outset. Meanwhile, the only thing we want to show here and now is that problems can occur for fairly reasonable parameter assumptions.

The way in which the base run has been set up is as follows. As the model uses old capacity next to new capacity, and as we use arbitrary initial values for the stocks, we use the first 100 time periods to get rid of initial value problems. To this end, we let fuel prices remain constant until period 100, after which they are allowed to rise at the percentage rates provided in Table 1. Then in period 125, we allow for the possibility of endogenous biases in technical change, whereas up to period 125, we had set the total level of R&D labour equal to zero, thus effectively leading to a zero rate of fuel-saving technical change up to that point in time. The policy experiments explained in more detail in section 5.3, will also start in period 125, and will end in period 150, after which we have 50 periods until the end of the simulation period during which we can see whether (some of) the temporary policy effects will persist or not.

Par	Value	Par	Value	Par	Value	Par	Value
α	3	ζ^i	0.1	β	25	$\hat{q}^c = r$	0.025
ρ	2	μ	0.05	LS	1	$\hat{q}^r$	0.020
$A_{\Delta Ke}$	10	δ^i	0.63	κ^i	1	$q^i_{t=100}$	0.1
$A_{\Delta Ly}$	1	γ	0.75	s	0.1	$c^i_{t=100}$	1

Table 1: Structural parameter values

Base-run outcomes

Using both the parameter values and the simulation procedure outlined above, we have obtained the development over time of a number of important variables. These are the level of output itself (labelled Y), the share of new capacity in total capacity (labelled DY_OVER_Y), the survival fraction of old capacity, labelled SF, the number of R&D workers in carbon-based and non-carbon-based R&D (labelled RC and RR, respectively), and total current emissions (labelled $EMISSIONS$) and its percentage growth rate (labelled $GEMISSIONS$).

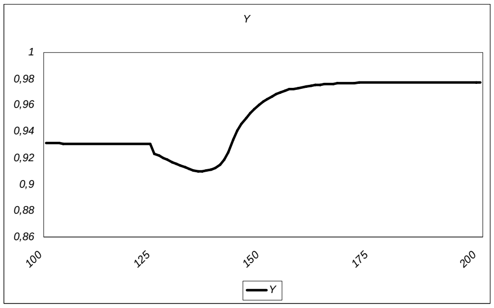


Figure 4:

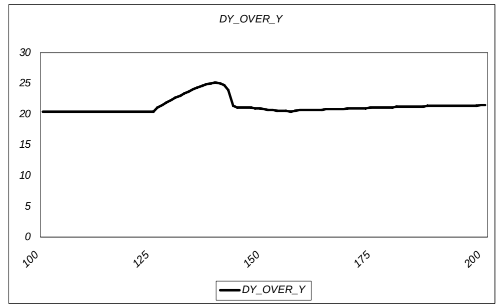


Figure 5:

Fig. 4 shows the level of output Y. We see that the lack of (labour-saving) technical progress in combination with a fixed saving rate leads to a constant level of output until period 125, from which time on R&D-based technical change can take place, as depicted in Figs. 6 and 7. It is clear that technical change does indeed take place from period 125 on. The level of R&D peaks before period 150 and then is reduced to very low levels up to the end of the simulation period. This is due to the fact that increased R&D activity cannot actually eliminate the impact of the continuing rise of carbon-based fuel prices on the user cost of (carbon-based fuel using) capital, and so leads to an ever increasing demand for labour, that is increasingly drawn away from the R&D sector. However, in period 125, something else is happening. At that moment in time, when the rates of fuel-saving technical change rise relatively quickly, we see the creative destruction effects of this surge in technical change. For, as Fig. 4 shows, in the short term, output actually **drops** below its initial level, before it starts rising again, once all the old capacity has been discarded.

The reduction in economic lifetime implied by faster technical change is illustrated more directly in Fig. 9, showing the survival fraction of old equipment. That fraction drops by about 5 percentage points, and once all equipment has been renewed, the survival fraction return to its previous level, and from about period 160 onwards, starts falling very slightly for the rest of the experimental period. The latter is due to the fact that technical change is still taking place, but now at a relatively low rate, since

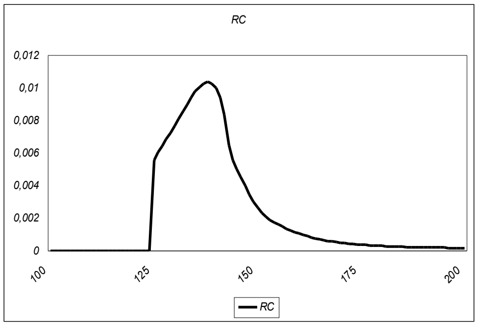
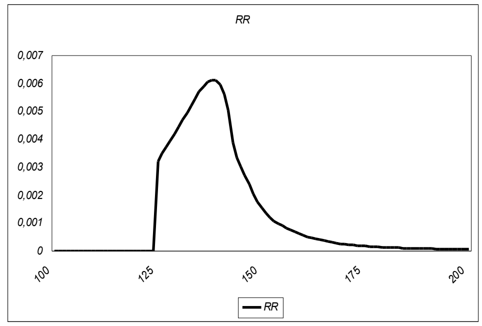


Figure 6:



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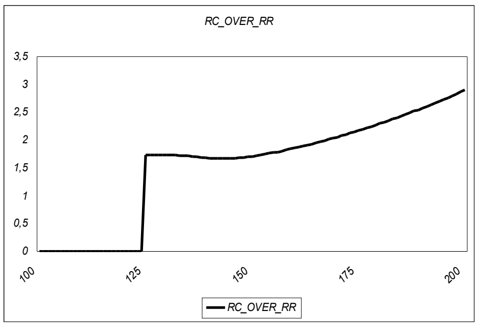

Figure 8:

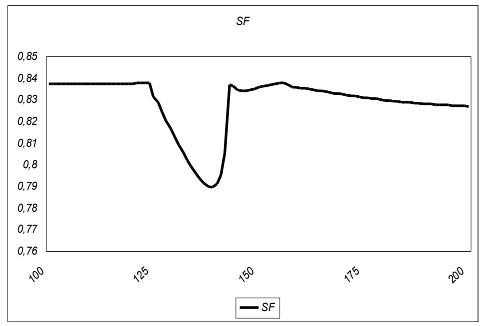

Figure 9:

only little R&D is done. In addition to this, the average characteristics of the old capital stock have now come closer to the new capital stock, thus leading to a smaller difference between unit total cost on the new vintage and marginal variable cost on old equipment, and hence to lower (but still positive) rates of scrapping, ceteris paribus.

Fig. 8 shows that even as both levels of R&D are positively affected by the continuous rises in fuel prices, carbon-based R&D activity is higher than non-carbon-based activity, since RC_OVER_RR is equal to the ratio of employment in carbon-based and non-carbon-based R&D activities. We see that the ongoing increase in the relative price of carbon-based fuel, does indeed bring about an ongoing increase in this employment ratio, even though the absolute levels of employment are falling after having reached a peak in period 135. Figs. 10 and 11 show what happens to emissions. They reach a minimum around period 135, when output is at an all-time low, and R&D is at an all-time high. When economic lifetime picks up again, as indicated by the drop in DY_OVER_Y and the rise in SF, emissions are picking up too, but a slightly negative trend sets in from about period 160. This is due to both contemporaneous substitution between labour and capital, and fuel-saving technical change. The net long term effect on output is that it has risen above its initial level, remaining roughly constant until the end of the simulation period at that higher level, whereas emissions are falling until the end of the period from a peak level that is actually below the initial level when endogenous technical change sets in. Hence, R&D generates an environmental dividend in this setup that comes from both contemporaneous and intertemporal substitution (trading output now for more efficient production methods through R&D in the future).

Figure 10:

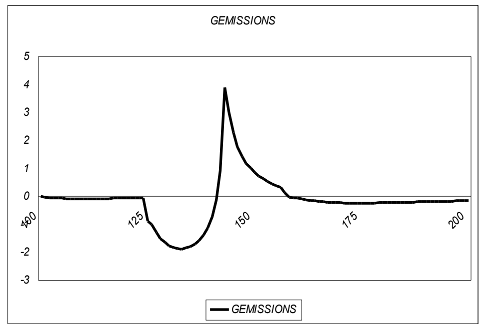

Figure 11:

5.3 Policy experiments

In this section we describe the results of four different experiments. These are:

1. a carbon-tax on the carbon-based fuel price of 1%, that is recycled as a subsidy on the non-carbon-based fuel price;

2. a carbon-tax on the carbon-based fuel price of 0.1%, that is recycled as a subsidy on the non-carbon-based fuel price;

3. a carbon-tax on the carbon-based fuel price of 0.1%, that is recycled as a subsidy on R&D wages on non-carbon-based energy technologies;

4. a carbon-tax on the carbon-based-fuel price of 0.1%, that is recycled as a subsidy on R&D wages on carbon-based energy technologies.

Experiment 2 is a small prelude to experiments 3 and 4, showing that the qualitative results do not change with different tax rate values. The reason to show this is that if we want to recycle the tax revenues from taxing the use of carbon-based fuels in the form of a subsidy to R&D wages, then we need to have a very low tax rate, because the R&D wage sum is relatively low (roughly 1-2% of the total wage sum). And although fuel costs in final output production are fairly low in comparison with labour costs at the aggregate level, they are still about an order of magnitude higher than the total wage sum of researchers.

In experiment 3 we want to show how a recycling of the tax revenues in the form of a subsidy on non-carbon-based R&D costs would affect output and emissions. The tax rate is low in absolute terms for the reasons outlined above. Nonetheless, experiments 1 and 2 generate qualitatively similar results, suggesting that also for a higher tax rate the same kind of results could be obtained.[16] In order to be able to make a fair judgment about the most effective way of recycling the tax revenues, we also perform experiment 4, in which the revenues are recycled in the form of a subsidy to research in the carbon-intensive sector.

In the figures below, we show how the results of experiments 1-4 compare with the results from the base run. We show all experiments in each figure. Relative percentage deviations from the base run are denoted by adding the post-fix 'R' (for "relative") to a certain variable name. Absolute deviations from the base run values have post-fix 'A' (for "absolute") added to their name. That name also contains the relevant "experiment number" (1-4) before the postfix.

Experiment 1

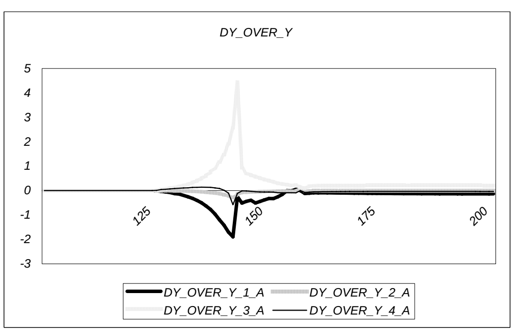

Figure 12:

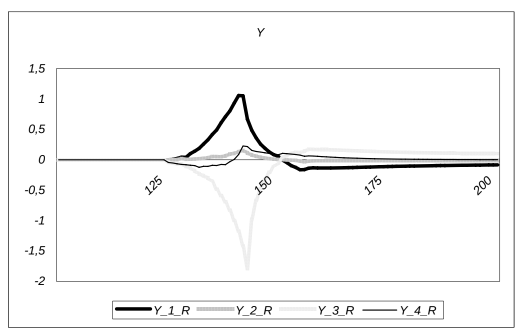

Figure 13:

[16]That is, apart from the possibility that the subsidy would result in negative wage costs, in which case the model numerically breaks down. That is why we have had to choose such low tax rates.

Figs. 12 and 13 show what happens to total and to marginal output (the latter as a fraction of total output). In experiment 1, we see that output in the short term is positively affected. In the long term, however, output falls slightly below the base-run level. The reason is, quite unexpectedly perhaps, that R&D activity actually falls in both sectors, as is shown in Figs. 14 and 15. However, as expected and as shown in Fig. 16, the ratio of carbon-based fuel R&D activity relative to non-carbon-based fuel R&D activity increases, as one would expect from Kennedy's induced innovation hypothesis. The reason for this somewhat unexpected sequence of events is that the cost-raising effects of the carbon tax increases the user cost of carbon-based fuel-using capital by so much that the user cost of capital of the new vintage rises, and with that total unit cost on the new vintage. This has two major consequences. First economic lifetime increases, as indicated by the rise in the survival fraction SF in Fig. 18. This has immediate consequences for the emission level that rises above the base run, because more old capacity is now used, which is also less clean than the base run capital stock.

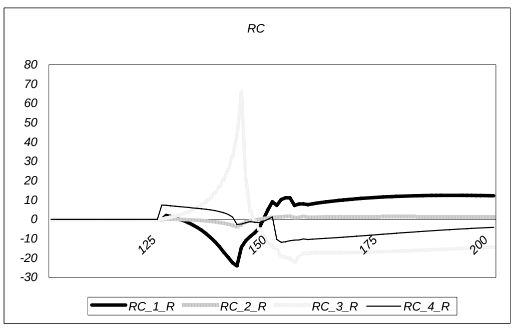

Figure 14:

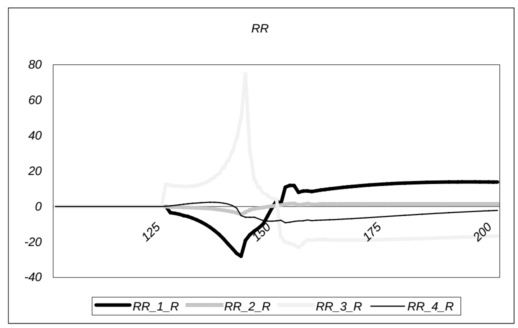

Figure 15:

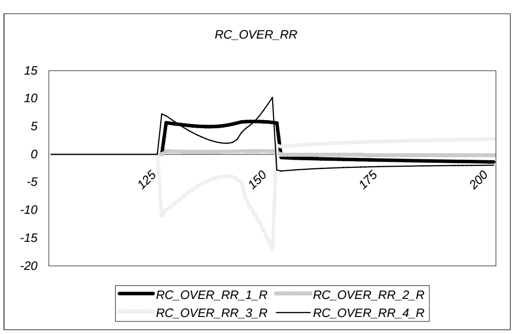

Figure 16:

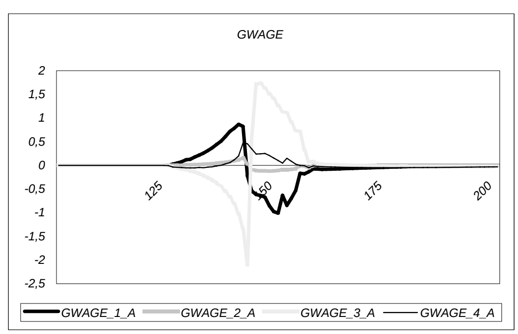

Figure 17:

It should moreover be noted from Fig. 12 that the rise in output levels is a temporary phenomenon, as in the long term, after the tax is removed in period 150, output quickly drops below the base run level. The reason is that the high wage growth caused by the rise in carbon-based fuel prices that makes labour more attractive as a substitute for aggregate capital, has led to a lower demand for R&D labour on two accounts: First, wages determine the cost of doing R&D, and secondly, due to the cost raising effects of the carbon tax, the user cost of capital has risen, resulting in lower demand for (aggregate) capital, hence for a lower actual value of cost-reducing innovations (cf. equation (23)). These two effects obviously lead to a fall in the level of R&D for non-carbon-based fuels. These effects are so strong that they also lead to a fall in the level of R&D for carbon-based-fuels, even though the incentive for doing that kind of R&D has strengthened. Both levels of R&D therefore fall, but R^c less than R^r, see also Fig. 16. So, the contemporaneous substitution effect outweighs the intertemporal substitution effect in this case.

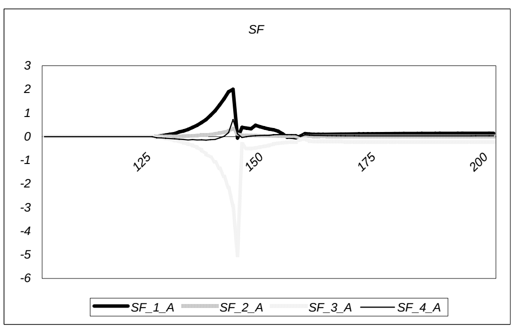

Figure 18:

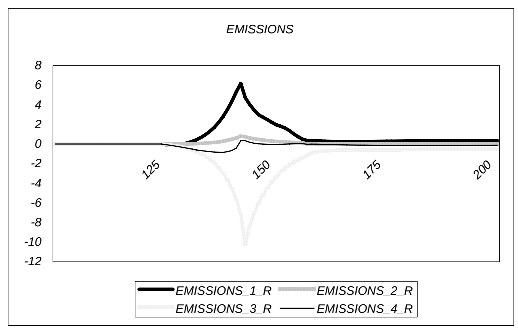

Figure 19:

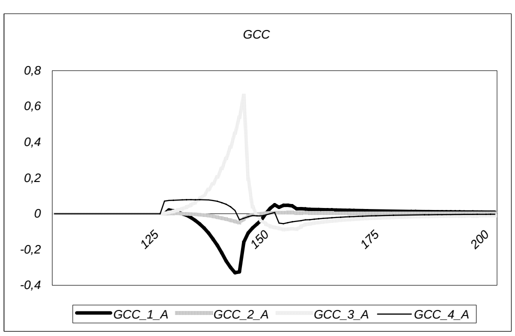

Figure 20:

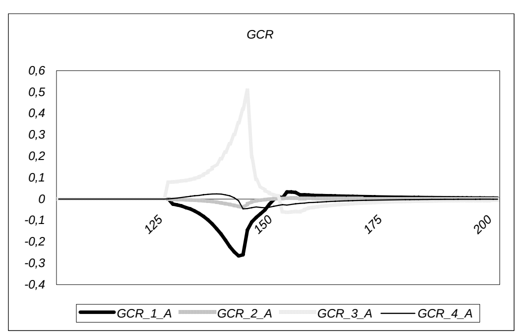

Figure 21:

Still, technical change is taking place, although at a lower rate than before, as shown in Figs. 20 and 21. The latter figures are particularly interesting, since they show that whereas R&D activity in the non-carbon sector drops from the beginning in period 125, the level of R&D in the other sector rises slightly above that in the base run, for just a few periods starting in period 125. In the long run however, the rates of technical change are slightly above their base run values. It should be noted that in the long run, output is then slightly lower, while emissions are slightly higher than in the base run, the latter being due to the fall in the rate of technology diffusion as indicated by the fall in the relative share of new capacity in total capacity next to the survival fraction of old capacity.

Experiment 2

The results for this experiment, which is the same as experiment 1, except for the tax rate that is 0.1% instead of 1%, indicate that that the time pattern of the variable changes is the same as in experiment 1. Only the size of the changes is correspondingly smaller. This means that, apart from numerical difficulties that may arise for negative wages and so on, the scale of things does not matter significantly for the qualitative behaviour of the model.

Experiment 3

In this experiment, we recycle the tax revenues obtained from a 0.1% consumption tax on the price of carbon-based fuels through a subsidy on wages in the non-carbon-based fuel technology R&D sector.

In this experiment, we observe a drop in the level of output as soon as the experiment starts. This is due to technology induced scrapping (the survival fraction SF decreases substantially). It should be noted that this short term drop in output is followed by a long term rise in the level of output that is actually above the base-run level. This reflects the intertemporal trade off mentioned earlier, between output now and future output through increased R&D efforts. We see that, contrary to the previous experiments, the levels of R&D activity in both sectors are positively affected. The carbon-based fuel technology R&D sector experiences a rise in activity (relative to the base run) because there is now more scope for R&D-based cost reductions, whereas non-carbon-based fuel technology R&D activity is influenced positively through the wage-subsidy. However, R&D does shift in favour of non-carbon-based fuels, as is apparent from Fig. 16.

It should be noted that the induced scrapping effect of the acceleration in the rate of fuel-saving technical diminishes after a while, and as soon as all inefficient equipment has been scrapped, general R&D activity falls again, thus mitigating the creative destruction effects of technical change and so reversing the initial drop in the growth rate of output. This leads to a rise in the growth rate of wages. The removal of the tax and the wage subsidy in period 150, when R&D activity is already low, changes the situation only marginally.

One of the effects of this experiment is that the wage-sum in the final output sector (which accounts for almost 100% of the total wage sum, since total R&D sector employment is so low (certainly after period 150)) is permanently higher in the long term. This is due to the fact that the vintage capital stock has become more efficient on the one hand, while on the other hand DY_OVER_Y is also structurally higher. This indicates that the rate of diffusion of technical change through new investment must be higher, too. So, output can rise on two accounts: Firstly, individual vintages become more productive (see Figs. 21 and 22) and secondly, the capital stock is younger on average than in the base run. With roughly the same labour resources as in the base run available for producing final output, the quality increase of the capital stock allows for a rise in (output) labour productivity, and hence leads to a rise in the level of final output itself. Finally, we notice that even as output grows above its base run level in the long term, emissions remain below their base run level, again due to the quality increase of the capital stock.

Experiment 4

In this experiment, we raise a 0.1% consumption tax on the price of carbon-based fuels and recycle that in the form of a wage subsidy on carbon-based fuel technology R&D. There are a number of remarkable results to be seen. First, even though the parameters of the R&D sectors are all the same, and even though this also applies to tax revenues, the impact of this experiment on the model variables is far smaller than in experiment 3. We also find the same reaction pattern over time, except for the timing of the sign-reversals of the deviations from the base run. That comes slightly earlier in experiment 4 than in experiment 3. Third, we find no significant effect on emissions, relative to the base-run. The latter is caused by two things. First, increased carbon-based fuel R&D changes the technology embodied in the latest vintage in favour of carbon-based fuels, while secondly, the rate of diffusion of technical change is hardly changed at all.

6 Summary and Conclusion

In general, one can say that energy-related R&D activities, which increase energy efficiency through technological change, can be an effective way to reduce GHG emissions. In this context, technological change allows for the potential coexistence between rising output levels and moderate GHG emissions as the direct positive impact of output growth on emissions becomes weaker.

According to new growth theory, technical change is mainly the result of successful R&D activities that are driven by economic incentives. However, in case market forces do not generate the required type and pace of technical change, the application of environmental policies, such as a carbon taxes and subsidies, is needed, e.g. by countries that are obliged to achieve short- or medium run environmental targets, as with the Kyoto targets. Nevertheless, the implementation of a carbon tax is associated with the risk of pushing R&D in the wrong direction. As the induced innovation hypothesis emphasises, a carbon tax will increase the user price of carbon-based fuels. This in turn will create the incentives to engage in developing a better technology that will compensate at least part of the price rise. As this form of R&D will take place in the sector for carbon-based fuel technologies, finding the structural solution to the environmental problem will only be postponed. It will not be addressed directly, since no direct incentives have been created to intensify the use of non-carbon-based fuels. In addition, if technical change is largely embodied, then the existing capital stock using carbon-based fuels represents large sunk costs, meaning that it cannot be reshaped and substituted for by other inputs, and that it will only gradually be phased out, thus effectively limiting the impact of policy measures, because, due to the embodiment of technical change, its impact is proportional to gross investment, rather than the entire capital stock. Therefore it may either take a fairly long time to achieve some preset policy targets or draconian policy measures to achieve these same targets in the short run.

The objective of this paper has been to investigate how an environmental policy could be implemented in order to deal with the environmental problems outlined above. For this purpose, an energy model has been developed which distinguishes between an R&D sector developing non-carbon-based fuel using technologies, and a sector that develops carbon-based fuel using technologies. The model presented in this paper combines two major building blocks, i.e. Kennedy [1964] induced bias in innovation hypothesis and a simplified representation of a putty-clay vintage model called a "putty-practically-clay" model (Van Zon [2005]). We have used a nested CES production function to describe ex ante substitution characteristics between labour and effective capital. The latter consists of Leontieff composite inputs of raw capital and carbon- and non-carbon-based fuels. We then introduced two R&D sectors changing the quality of the equipment making use of either fuel. The other main building block is the putty-practically-clay model that has the flavour of a full putty-clay model, but lacks the extensive bookkeeping requirements of a full vintage model, as we distinguish between just two vintages (an old one and a new one).

Using a simulation version of this model, we have analysed its dynamics when a carbon tax is introduced. The experiments show that the reduction in emissions depends very much on the way in which the tax revenues are recycled. When the recycling takes the form of a subsidy on R&D wages in the non-carbon-based fuel technology R&D sector, emissions in the long term are below their base run level. But when the tax revenues are recycled in the form of a wage subsidy for the carbon-based R&D sector, emissions are not reduced. If the revenues are recycled in the form of a subsidy on the consumer price of non-carbon-based fuels, long term emissions are not reduced either, even though long term output is slightly below its base run level. The reason is that the subsidy on the consumer price of non-carbon-based fuels leads to more contemporaneous substitution, but also lower cost reduction incentives to engage in non-carbon-based fuel-saving technical change. In addition, the relative lack of technical change calls for an expansion of the economic lifetime of equipment, thus in effect reducing the fuel-consumption quality of the capital stock (as compared to the baserun). The latter result contrasts with the existing belief that a carbon tax in a model of induced technical change accelerates the substitution of non-fossil energy for fossil fuels. For the parameter set we have used, we can state that this belief is at least incomplete, and maybe even wrong in the short term, while it is certainly wrong in the long term. The reason for the potential lack of short term performance of such a policy is that a change in the rate of technical change also changes the lifetime of equipment. This in turn may lead to potentially large changes in the level of investment which in turn provides an additional change in incentives to do R&D, and may so have unwanted long term effects. The reallocation of R&D activity in the direction of carbon-based fuel saving technical change is responsible for the lack of long term performance of such a tax policy.

The policy recommendations that can be drawn from the experiments above are quite general in nature. First, a tax on carbon-based fuels may seem to be a good idea when emissions need to be reduced relatively sharply and quickly, because it invokes contemporaneous substitution reactions away from the more costly input. However, under the induced innovation hypothesis, this also redirects R&D activity towards bypassing this tax barrier. This has the negative spin-off of drawing R&D resources away from finding the true solution to the problem of reducing emissions, i.e. to improve the productivity of non-carbon-based fuel technologies. These negative side effects must thus be counteracted, for instance through the recycling of the tax revenues as we have done in experiment 3. This would make for a better transition from dirty to clean technologies, which is perfectly in accordance with the observation by Chakravorty and Tse [2000], who state that: "R&D in renewable energy resources may play only a limited role in the short run, while creating the basis for a transition to a sustainable energy economy over the longer time horizon".

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