



# Innovation and Threshold Effects in Technology Responses to Climate Change

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## Contents

<b>Abstract</b>	3
<b>I. Introduction</b>	3
<b>II. Non-Linearities and Price Substitution Effects</b>	4
<b>III. Sensitivity to Initial Conditions, Parameters and Exogenous Variables</b>	6
a) Additional Sources of Non-Linearities	7
b) Emissions, Accumulations and the Marginal Costs of Abatement	10
<b>IV. A More General Model</b>	12
a) Energy Demand Equation	13
b) Investment in New Technology	15
c) Cost of Old Technology Relative to New	15
d) Relative Prices	17
e) Market Shares	17
f) Price of Energy	18
g) Demand Met by Non-Carbon Technologies	18
<b>V. Results</b>	19
a) Model Runs	19
<b>VI. Threshold Effects, External Benefits and Option Values of Innovation</b>	31
a) Externalities	31
b) Threshold Effects in Marginal Benefit and Cost Curves	33
c) Uncertainties and the Economic Value of Exploring Options	34
<b>VII. The Costs of Non-Carbon Technologies Relative to Fossil Fuels</b>	36
<b>VIII. Conclusions and Next Steps</b>	40
<b>Acknowledgements</b>	42
<b>References</b>	42
<b>Appendix 1: Parameter Values for the Base Case</b>	44

## **Summary**

The paper develops a way of characterising technological change in energy systems in a form suitable for economic analysis. The focus is on technological responses to climate change. A large array of non-carbon options is emerging, though their costs are generally high relative to those of fossil fuels. However, costs are also declining relatively with innovation, investment and learning-by-doing. The process of substitution is also argued to be highly non-linear, involving threshold effects.

One consequence of this is that policies may be capable of engendering changes in the industry out of all proportion to the scale of the policy itself; and it is suggested that the external benefits of the policies, when they take root, may be far larger than marginal analysis often assumes. Much of course depends on the scale of the policy impetus—and equally on the durability of the policy, for policy initiatives followed by reversals or a lack of willingness on the part of policymakers to persevere, is no better than no policy at all. A number of implications for policy and economic analysis are drawn.

## **1. Introduction**

When a new technology or practice is being substituted for another, it is possible for highly non-linear or threshold effects to arise when relative prices become comparable. This is the case for example when a new technology or practice with low polluting characteristics is being developed to displace an existing technology with high levels of pollution while providing the same product or service, such as kWh of useful energy or passenger miles of transport. The evidence suggests that (a) the difference in costs between low polluting technologies and the polluting ones they displace are often relatively small, and (b) the extent of substitution arising from correspondingly small shifts in prices, brought about for example by environmental policies to favour the low polluting options, may rise to 100%.<sup>1</sup> In these situations substitution elasticities may reach extraordinary levels, and threshold or switching effects arise. Examples are the emergence of combined cycle gas-fired power stations in the 1990s, the substitution unleaded for leaded fuels in vehicles, and the rapid uptake of electrostatic precipitators to reduce PM emissions from coal fired power plant in the 1950s and 1960s; but there are many others.

The possibility of threshold effects is compounded if, in addition, costs change with discovery, with the innovations associated with ‘learning-by-doing’, and with scale economies. Even technologies with similar learning curves may exhibit appreciably different rates of cost reduction if they are at different stages of development. For example, a technology with a 20% reduction in costs with each doubling of cumulative investment would experience a three-to four-fold drop in costs if its market share rose from, say, 0.1% to 5. In contrast, mature technologies having the same learning curve co-efficient but occupying say 30% of the market would experience only a one-third decline even if they rose to occupy the whole of the market. In other words, the effects of learning are most pronounced in the early phases of a technology’s development and use.

This paper examines these effects in a dynamic model of technology substitution in which the costs of both the new technologies and the technologies in place decline in a non-linear way with cumulative investment, and in which the price substitution effects are also highly non-linear. The model has chaotic features similar to that of an ‘S-curve’ model encountered in the physical sciences (May, 1976), with the difference that innovation, demand growth and policy shifts

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<sup>1</sup> There are numerous examples of this happening with respect to local pollution from industrial activities, electricity generation and transport, and water pollution from industrial and municipal effluents. Anderson, D (2001). “Technical Progress and Pollution Abatement: an economic view of selected technologies and practices.” *Environment and Development Economics* 6: 283-311

introduce further degrees of non-linearity, and sometimes threshold effects. It is applied to the analysis of technology responses to climate change.

Much of the analysis of such models is concerned with their chaotic behaviour. This is, however, not the main concern of this paper, since as will be seen chaotic behaviour in economic systems can be mitigated by reducing time lags between cause and effect, for example by more prompt feedback of market information. Its main concern is a second characteristic of non-linear systems, which is their extreme sensitivity to small changes in initial conditions and the exogenous variables, such as tax and innovation policies. It is shown that, when a technology takes root in a system in which switching or threshold effects are possible, relatively small investments in its development may lead to levels of use in the long term out of all proportion to the initial scale of effort (and the initial scale of the policies); correspondingly, the external benefits of the initial effort, which take the form of the benefits of the technology developments themselves, plus the benefits of pollution abatement (where they relate to low-polluting technologies) may also be exceptionally large in relation to the initial costs—appreciably larger than marginal analysis often suggests. By the same token, small events, such as might arise from equivocations or reversals in policy, may lead to failure, whatever the economic promise of a technology. The willingness of innovators and policymakers alike to persist with an approach until the evidence is clear one way or the other seems crucial for successful technologies to emerge.

The next two Chapters introduce the approach using simplifying assumptions. The assumptions are relaxed in Chapters 4 and 5 when a more general model is developed and applied to policies for addressing climate change; it is shown that threshold effects or ‘disruptive change’ in technology responses to climate change are not beyond the bounds of possibility, as indeed the scenarios of industry, the IPCC and many others have concluded. Chapter 6 turns to the problem of estimating external costs and benefits in such non-linear systems. Chapter 7 summarises evidence on innovation and the expected costs of low carbon technologies; it is placed late in the text since the preceding chapters pose new questions for cost analysis based on learning curve that frequently escape close scrutiny when modelling responses to climate change; in particular, estimates of the levels to which costs might decline in the long-term are neglected by learning curve analysis, which implicitly assumes no lower bound to costs; the analysis in this paper combines evidence from learning curves with engineering evidence on this possible (if uncertain) lower bound. Chapter 8 presents the conclusions.

## **2. Non-Linearities and Price-Substitution Effects**

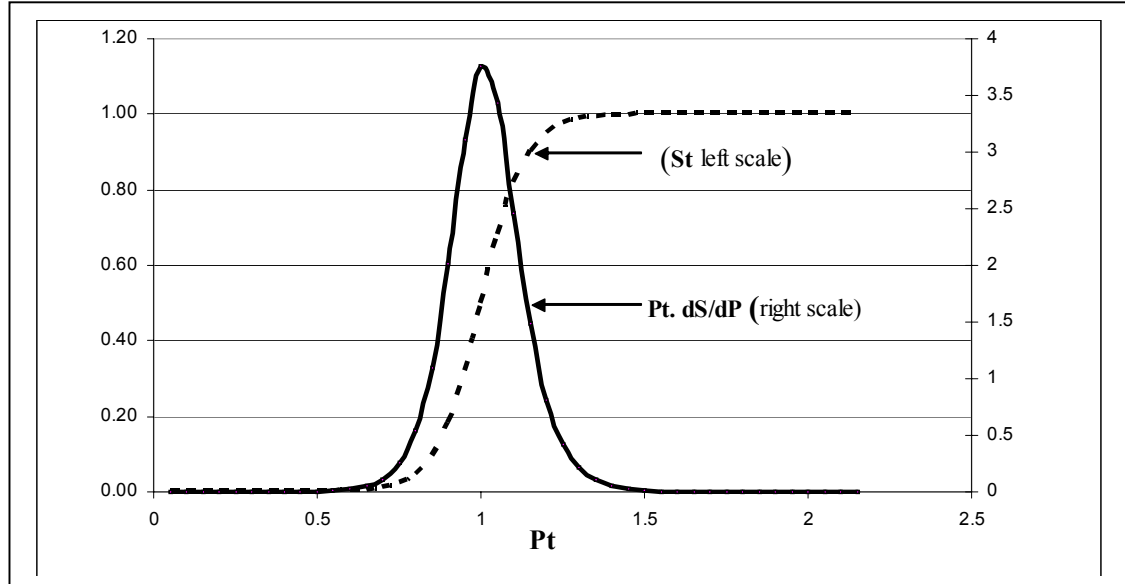
Consider the way one technology might be substituted for another as relative prices change. Schematically, we might expect the effects to be as in Figure 2.1. Let  $P_t$  denote the ratio of the price of the old (polluting) technology to that of the new (low polluting) technology, inclusive of the effects of taxes and subsidies on prices. We might expect (a) low rates of substitution when  $P_t$  is low, (b) high rates when  $P_t$  is close to unity, tapering off to (c) low rates again when  $P_t$  is high and the market for the new technology is saturated. In the figure, market shares are denoted by  $S_t$  ( $0 \leq S_t \leq 1$ ). The market shares relate to the demands for new investment not to shares in total capital stock. The term  $P(dS/dP)$  is shown indicate the effects of a per unit change in prices on the share of the new technology in investment.<sup>2</sup>

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<sup>2</sup> The actual elasticity of substitution is given by:

$\eta = (p/r)(\partial r / \partial P)$ , where  $r = X^n / X^o$ , the ratio of investment in new to new technology. For the logistic form given in equation (2) below  $\eta = aP$ . For the value of  $a = 15$  in Figure 1 it rises from 7.5 when  $P = 0.5$  to 22.5 when  $P = 1.5$ .

**Figure 2.1:** Effects of Relative Prices on Market Share ( $S_t$ )



The relationship between  $S_t$  and  $P_t$  postulated here is the familiar logistic or ‘S’ curve long used for the analysis of the demand for new durable goods, except that the rate of change in market share is expressed with respect to the change relative prices rather than the change in time, which seems to us to have more economic appeal. In continuous form:

$$dS / dP = aS(1 - S) \quad (1)$$

The solution to which is:

$$S(t) = e^{a(P(t)-1)} / (1 + e^{a(P(t)-1)}) \quad (2)$$

Both  $S$  and  $P$  change over time. Rearranging and using discrete time steps (1) takes the form:

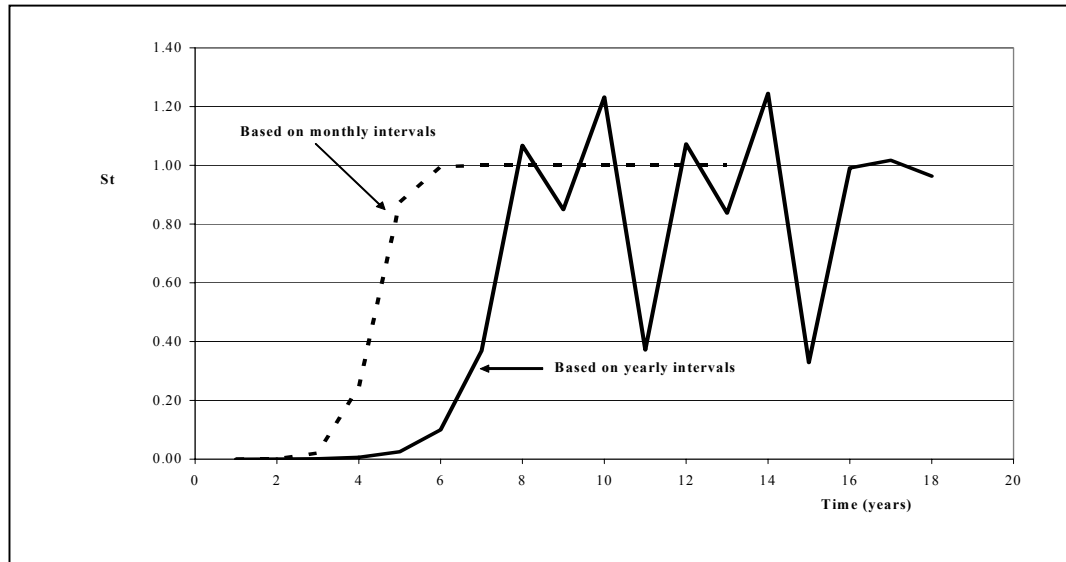
$$S_t = S_{t-1} + aS_{t-1}(1 - S_{t-1})(P_t - P_{t-1}) \quad (3)$$

For certain values of the parameter  $a$  equation (3) is *chaotic*. A more familiar form of such equations, which have received extensive treatment in the literature<sup>3</sup>, is  $X_t = \alpha X_{t-1}(1 - X_{t-1})$ . For values of  $\alpha \geq 3.57$  the long run solution starts to become chaotic; in fact, for  $\alpha \geq 3.8284$  “there are cycles for every integer period, as well as an unaccountable number of asymptotically aperiodic trajectories.”<sup>4</sup> Figure 2.2 illustrates the effect for the following variant of this equation,  $S_t = S_{t-1} + \alpha S_{t-1}(1 - S_{t-1})$ , with  $\alpha = a(P_t - P_{t-1})$ . In this case an unstable and chaotic region begins for values of  $\alpha$  above  $\approx 2.3$ .

<sup>3</sup> See R. M. May (1976) “Simple mathematical models with very complicated dynamics.” *Nature*, 261:151-159.

<sup>4</sup> *Ibid.* p 154.

**Figure 2.2:** Chaotic Behaviour of Equation 2, and its Stabilisation Using Monthly Series



The unstable behaviour of the equation has an economic interpretation. The assumption underlying (3) is that the growth of markets in the current period relates to estimates of market shares in prices in the previous period (since changes in prices affect the value of  $\alpha$ ). If the demand for a technology is going through a rapid growth phase, and if the time interval between  $t - 1$  and  $t$  is long (a year say) then boom and bust cycles may appear if investors fail to spot that the market is approaching saturation and assume a continuation of ‘buoyant’ growth—a not uncommon phenomenon. Such effects can be neutralised by the continual feedback of more up-to-date information, as can be seen when we use the same equation with the same parameters and initial conditions but using monthly intervals (the dotted curve in Figure 2). Looked at another way, we can effectively reduce the value of what is a parameter in the simpler logistic model, namely  $\alpha = \alpha(P_t - P_{t-1})$ , by reducing the time interval and the change in prices.<sup>5</sup>

### **3. Sensitivity to Initial Conditions, Parameters and Exogenous Variables**

This paper is less concerned with the problem of chaotic behaviour, however, except to alert us to the complexities it might introduce when relationships such as (3) are used larger-scale models, than with another familiar feature of highly non-linear relationships such as (1) and (3). This is the extra-ordinary sensitivity of the trajectories to the initial conditions, parameters and the exogenous variables (such as policy variables). The effects may be compounded in such models if relative prices  $P_t$  also drop steeply with the innovations induced by the rise in market share, e.g. with further invention and learning-by-doing.

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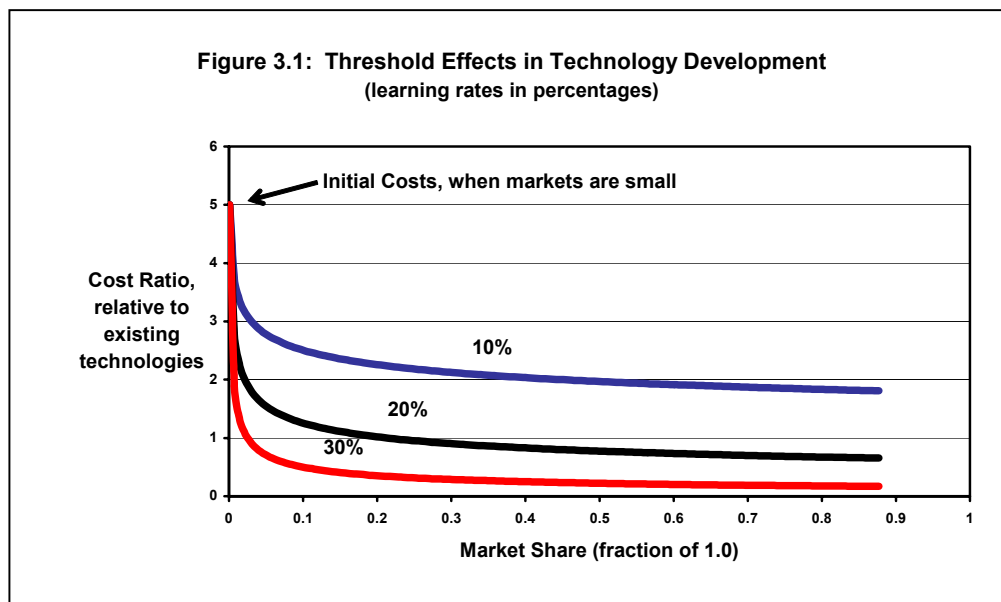
<sup>5</sup> Alternative forms of stabilisation are also possible, for example, short-run supply shortages may arise when markets are growing rapidly and lead to short run increases in the prices of the new technology; analysis of these is beyond the scope of this paper.

### 3.1 Additional Sources of Non-Linearities: Learning Curves and Scale Economies

It is necessary to look at the investment and cost equations underlying  $P_t$  and its initial values in more detail. In studies of innovation, a relationship that has often been fitted to cost data is the ‘learning curve’.<sup>6</sup> This has the form

$$C_t = C_0(X_t / X_0)^{-b} \quad (4)$$

where  $C_t$  are the unit costs at time  $t$ ,  $C_0$  initial costs,  $X_t$  the cumulative investment (taken as an indicator of experience) in the technology by time  $t$  from the time of its first introduction and  $b$  is the ‘learning-curve parameter’. This relationship is highly non-linear, especially in the early phases when  $X_t$  is small and experience accumulates rapidly. Figure 3.1 below shows the effect, in which market share is taken as a proxy for  $X_t$ .<sup>7</sup> Since prices are equal to costs plus or minus any taxes or subsidy, it is evident that innovation introduces an extra order of non-linearity is introduced in relationships like (3). Let us consider the problem this poses further.



<sup>6</sup> A. McDonald and L. Schrattenholzer (2001), “Learning Rates for Energy Technologies”, Energy Policy 29: 255-261, who give estimates for several other technologies and from other sources.

<sup>7</sup> The term learning rate in Figure 3 refers to the per unit decline in costs with each doubling of cumulative investment, which is equal to  $1-2^{-b}$ .

In finite difference form, the learning curve relationship assumes that the change in cost for each per unit change in cumulative investment ( $\Delta X_y / X_t$ ), is proportional to the difference between the current costs and their lowest possible level,  $C_{min}$  say, or:

$$\Delta C_t / (\Delta X_t / X_{t-1}) = -b(C_{t-1} - C_{min})$$

$$\text{Rearranging: } C_t = C_{t-1} - b(C_{t-1} - C_{min})(X_t - X_{t-1}) / X_{t-1} \quad (5)$$

By using the form shown in (4), all studies so far have tacitly put  $C_{min}$  to zero, and perhaps have only escaped misfitting in the relationship because the values of  $C_t$  in the early phases of a technology's development, when statistical fitting is most often applied, tend to be high relative to  $C_{min}$ . Extrapolations based on (4) may be reasonably accurate over short periods, and in the early phases of a technology's development, but there is a danger of large inaccuracies if applied over longer periods.

To take the analysis further, let us substitute (5) into (3) on two assumptions, both of which will be relaxed later. First, that the existing technology with which the new one is competing is on the flat part of its learning curve such that changes in its price can be ignored and  $P_t = (1+T_t)/C_t$ , where  $T_t$  is a pollution tax on the existing technology; for convenience, the cost of the existing technology is put at unity and the costs of the new technology are expressed relative to the existing technology. The second assumption is that the size of the market is constant such that  $X_t$  is proportional to the cumulative value of the (annual) market share, or:

$$X_t \propto \sum_0^{t-1} S_v \quad \text{and} \quad X_t - X_{t-1} \propto S_{t-1}$$

Substituting for  $X_t$  in (5) and repeating (3) for convenience, we now have two coupled non-linear dynamic equations, plus a third relating prices to costs and a time dependent policy variable; market shares are now determined by prices, and prices by market shares, relative costs and tax policies:

$$S_t = S_{t-1} + aS_{t-1}(1 - S_{t-1})(P_t - P_{t-1}) \quad (3)$$

$$C_t = C_{t-1} - b(C_{t-1} - C_{min}) \frac{S_{t-1}}{\sum_{v < t-1} S_v} \quad (6)$$

$$P_t = (1 + T_t) / C_t \quad (7)$$

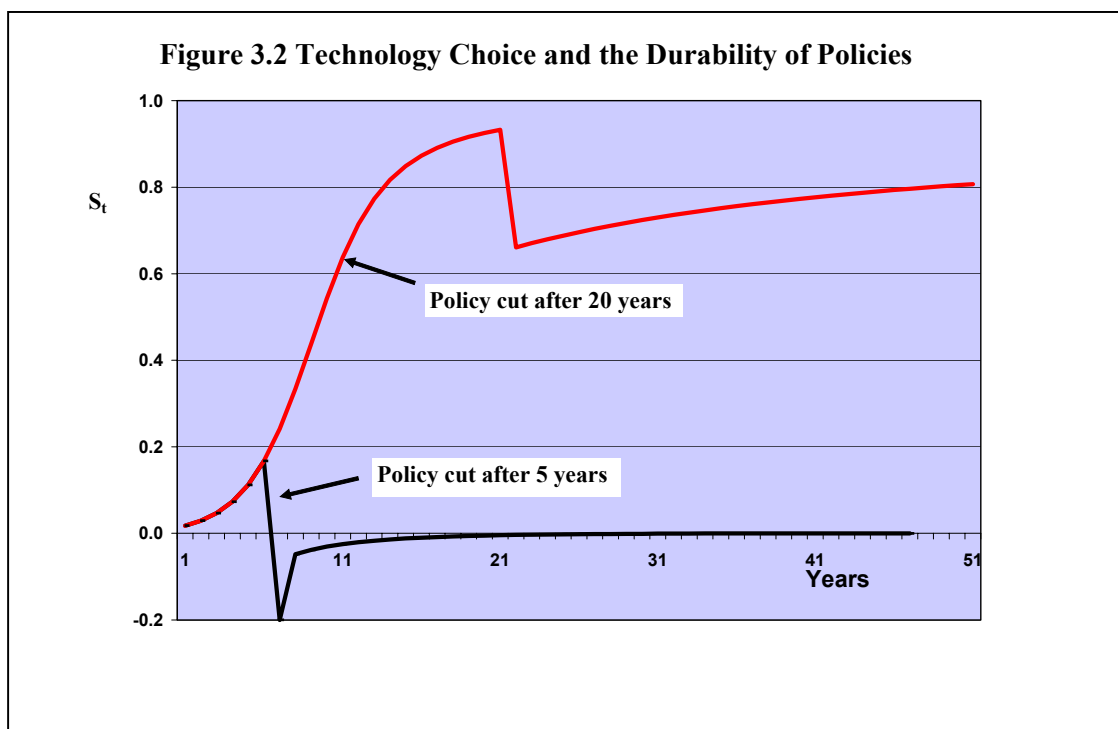
where the denominator in (6) represents the cumulative experience up to  $t = 0$ .

In these relationships there are two parameters in question ( $a$  and  $b$ ), two initial conditions ( $C_0$  and  $\sum_{v < t-1} S_v$ )<sup>8</sup>, a vector of exogenous policy variables ( $T_t$ ,  $t = 0, 1, 2, \dots$ ), and an exogenously estimated cost-expectation parameter ( $C_{min}$ ). None of these quantities are known accurately: the range of  $a$  might plausibly be 5-15 (possibly wider, see below); estimated values for  $b$  for non-carbon technologies ranges is 0.06 for nuclear power, 0.08-0.32 for wind energy, and 0.18-0.32 for solar photovoltaics; there are appreciable disagreements in the engineering literature as to what the long term costs ( $C_{min}$ ) might decline to (see Chapter 7); even the initial conditions for costs and taxes are difficult to estimate reliably since quoted costs vary greatly with bids while

<sup>8</sup> There is also an initial condition for  $S_0$ , which needs to be specified such that the difference equation roughly satisfies the condition  $S_t \approx 0.5$  when  $P_t = 1.0$ . In the following analysis,  $S_0$  is derived from equation (2) using a value of  $P_0$  derived from  $C_0$  and  $T_0$  using (7).

governments have used a range of instruments—feed in laws, tradable permits, capital grants, regulatory and regulatory targets—which make it difficult to ascertain with precision the imputed value of  $T_0$ . Yet as will be seen only small changes in estimates and assumptions may lead to radically different results.

Figure 3.2 illustrates the point with two runs of the model. It considers cases where an incentives policy is introduced sufficient to raise the ratio of the costs of fossil to non-fossil fuels by 50% ( $T = 0.5$ ), either by taxing the former, subsidising the latter or by a combination of the two. In one case the policy is cut after 5 years, in the other after 20 years. In the former, the ‘copping’ of the policy leads to the collapse of the non-carbon industry, from which it never recovers. In the latter, the industry is sufficiently well developed to survive the shock and to recover and grow. It shows how important the willingness of policy makers to persevere with a policy will be; we might term this the durability of a policy, which in this case is as important as the scale of the policy itself.



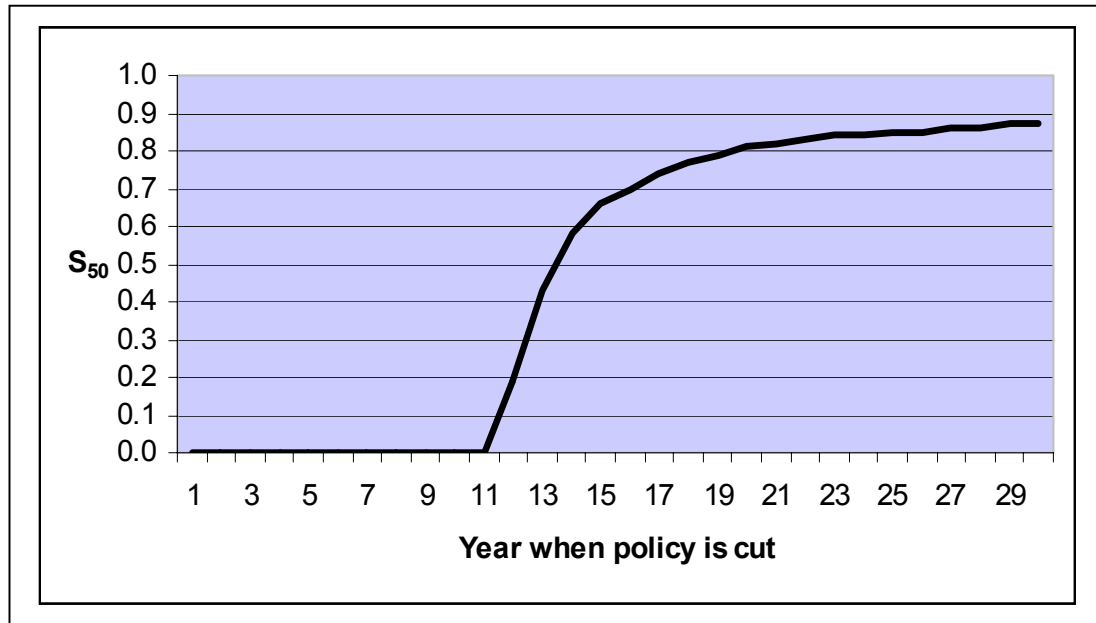
The effects of alternative assumptions on such results will be explored once the fuller model has been described below.<sup>9</sup> Suffice it to note here that (i) higher values of the threshold effect parameter  $a$  merely make the contrast between the two policies greater, in the sense that with higher values of  $a$  switching would occur sooner and more rapidly in the case where the policies take root. (ii) Lower values of the learning curve parameter,  $b$ , not surprisingly imply that stronger policies would be needed for longer periods, as do lower values of  $a$ . (iii) A permanent policy of taxing carbon would be unnecessary if the long-run costs of the non-fossil fuels ( $C_{min}$ ) were to become significantly less than those of fossil fuels, and necessary if they were to be

<sup>9</sup> The parameters and assumption for the runs shown in Figure 3.2 are as follows:  $a = 10.0$ ,  $b = 0.3$ ,  $C_0 = 2.5$ ,  $C_{min} = 0.8$ ,  $\sum_{v < 0} S_v = 0.02$ , about four times  $S_0$ , which is calculated from the initial price ratio,  $T_t = 0.5$  for the first 5 years in one case and the first 20 in the other, after which it is zero.

higher. However, it is the initial policies themselves, and the willingness of policy makers and industry to persevere with them, that are of over-riding importance.

Figure 3.3 shows the possible effects of perseverance (or the lack of it) in another way by plotting the market share in year 50 ( $S_{50}$ ) against the year when the policy is cut. It illustrates how a reversal of a policy might lead to its failure when it is on the brink of success.

**Figure 3.3:** Effects of perseverance on long term market shares



### 3.2 Emissions, Accumulations and the Marginal Costs of Abatement

Consider the case where a non-carbon energy source is displacing fossil fuels. The extra cost of investments made in non-carbon sources in year  $t$  is  $(C_t - 1)S_t$ . If all investments were in fossil fuels ( $S_t = 0$ ) the costs would be unity (since the costs are being expressed relative to those of fossil fuels). Hence the present worth of the total relative costs ( $PWTRC$ ) over the period of interest ( $t = 1 \dots Z$  say), as compared with the present worth of the costs of using fossil fuels if investments there were no investments in non-carbon energy sources, is given by:

$$PWTRC = \frac{\sum_1^Z a_t (C_t - 1) S_t}{\sum_1^Z a_t} \approx r \sum_1^Z a_t (C_t - 1) S_t \quad (8)$$

where  $a_t$  is the discount factor and  $\sum_t a_t \approx 1/r$ , where  $r$  is the discount rate.

Turning to emissions and accumulations, investments in fossil fuels will have emissions proportional to their contribution to output, or to  $(1 - S_t)$  in the above notation. However, climate change is a function of accumulations or concentrations in the atmosphere, so we need to add up the emissions over its lifetime, from the year it is installed through to the end of the period of interest ( $Z$ , say). For investments in fossil fuels introduced in  $t$  the cumulative emissions by  $Z$  will thus be given by  $(1 - S_t)(Z - t)$ . Summing up over all vintages of investments, the contribution of

fossil fuels to carbon concentrations of investments made over the whole period is proportional to:

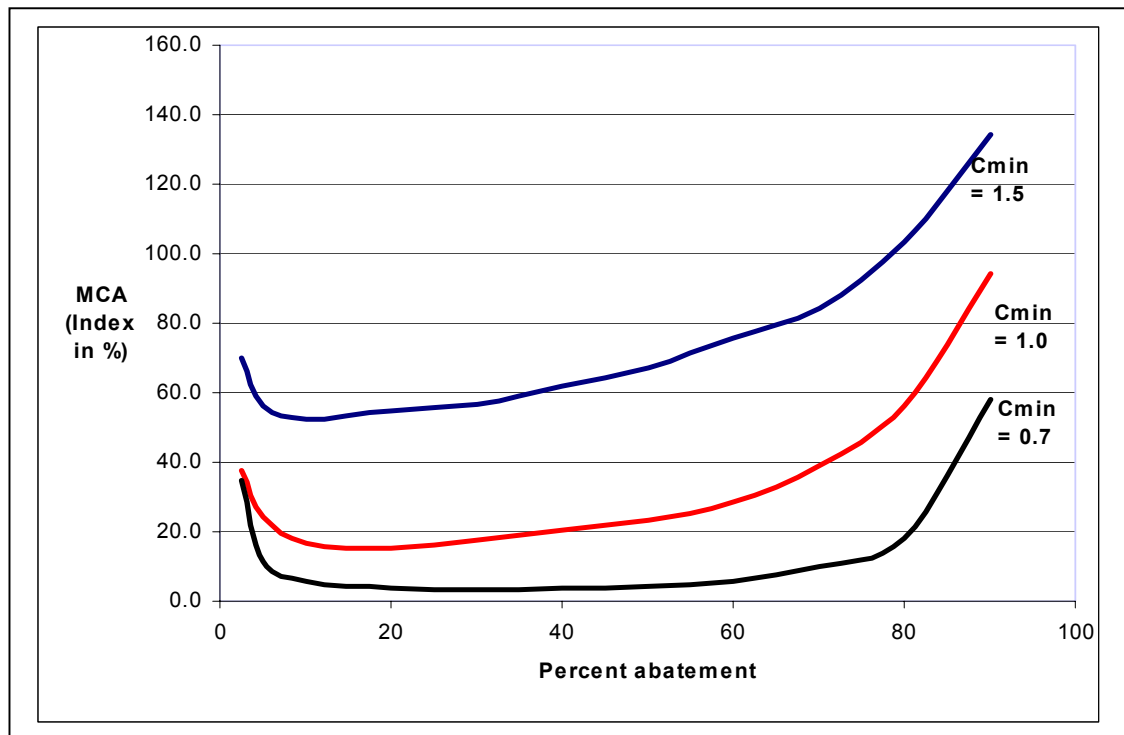
$$\sum_{t=1}^Z (1 - S_t)(Z - t) = A_z, \text{ say} \quad (10)$$

$A_z$  is an index of the additions to carbon concentrations in the atmosphere over the period. The index of additions in the 'reference case' when there is no investment in the non-carbon alternative is given by putting  $S_t = 0$ , which gives a value of  $A_z = (1+Z)Z/2$ . Hence the per unit abatement ( $PUA$ ) of accumulations arising from the alternative technologies being introduced is given by:

$$PUA = 1 - 2A_z / (1 + Z)Z \quad (10)$$

To find an index of the marginal costs of abating (the cumulative volume of) emissions it is necessary to estimate the change in  $PWTRC$  with respect to changes in  $A_z$ . This can be done by varying the tax term  $T$  in (7). The results are shown in Figure 3.4, using the preceding equations for three values of the cost parameter  $C_{min}$ . The index of the marginal cost of abatement ( $MCA$ ) =  $100 \times \Delta(PWTRC) / \Delta A_z$ .

**Figure 3.4:** An Index of the Marginal Costs of Abatement (MCA) versus the Cumulative Volume of Emissions Abated on Different Assumptions for  $C_{min}$  (hundred year period)



The marginal costs of abatement rise steeply as the level of abatement of cumulative emissions reaches high levels, as is commonly discussed in economic texts. However, at low levels of

abatement, marginal costs are also high, since the technologies to reduce emissions are initially far more expensive<sup>10</sup>-- as we are seeing with current efforts to reduce CO<sub>2</sub> emissions in many countries. It takes appreciable experience, and opportunities for innovation and scale economies in the manufacture and installation of the required technologies, before marginal costs decline significantly; expectations as to the costs and the performance of the technologies in the long-term, and of course as to the incentives provided, are crucially important, as are alternative assumptions about  $C_{min}$  in the above figure show. Not the least of the dilemmas facing policymakers and industry is that the values of  $C_{min}$  are highly uncertain; in the case of climate change, the range of possibilities is even greater than assumed above, both on account of uncertainties as to the prices of fossil fuels (assumed constant so far) and the scope for innovation. A further discussion of possible values is provided in Chapter 7.

It is not only the marginal cost curve which may have unfamiliar shapes in the presence of threshold effects and non-linear cost functions; the marginal benefit curves may well have them too. This topic is discussed in Chapter 6.

#### **4. A More General Model**

The following extensions are made to the above model:

- (i) The size of the market is no longer constant, but increases with incomes, populations and decreases in energy prices. The market in question is the *world market*, reflecting the global nature of energy markets.
- (ii) The world market is divided into two: the mature, low growth but still large scale markets of the rich countries (OECD) and the high growth, populous markets of the developing countries.
- (iii) The retirement of old energy technologies as they come to the end of their economic lifetimes provides further opportunities for new investment.
- (iv) Reductions in the costs of the hydro-carbon technologies with which the non-carbon technologies compete also decline with learning-by-doing.
- (v) The costs per unit of capacity (e.g. per kW of electrical capacity) are similar across countries on account of the influences of trade, investment and the international exchange of knowledge and experience. The learning curve function for costs is therefore based on world markets. However, the benefits of using energy technologies may differ between countries on account of differing resource endowments; for instance the energy produced by solar technologies in the tropics is three times that produced in the northern industrial countries because the solar input is three times higher. To allow for such possibilities, a yield parameter is introduced in the equations relating market shares to prices.
- (vi) The learning curve equation is based on world markets, again reflecting the global nature of the energy industry, and the rapid transmission of experience and technological information across countries. Coupled with the differing cost parameters, this raises the possibility of economically mutually beneficial externalities across countries arising from trade, investment and international co-operation.
- (vii) Relative prices are derived from costs and taxes as before.

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<sup>10</sup> In the above case, the initial costs of the non-carbon technologies are assumed to be 2.5 times those of fossil fuels. Other than the different values of  $C_{min}$ , shown in Figure 6, all other parameters and conditions are the same as those assumed for Figures 4 and 5.

(viii) The prices of fossil fuels are assumed to be constant for the time being.

The equations remain deterministic, which is of course a limitation; the stochastic case, in which the equations have error terms and the parameters are uncertain will be considered in a future paper.

#### 4.1 Energy Demand Equations

We have used a form commonly found in the economic literature:<sup>11</sup>

$$\frac{D_t}{D_0} = \left( \frac{Y_t}{Y_0} \right)^\alpha \left( \frac{Pe_t}{Pe_0} \right)^\beta \left( \frac{N_t}{N_0} \right) e^{-\gamma t} \quad (4.1a)$$

$$\frac{D_t^D}{D_0^D} = \left( \frac{Y_t^D}{Y_0^D} \right)^{\alpha^D} \left( \frac{Pe_t^D}{Pe_0^D} \right)^\beta \left( \frac{N_t^D}{N_0^D} \right) e^{-\gamma t} \quad (4.1b)$$

$Y_t$ : per capita income, in purchasing power parity prices

$N_t$ : population

$Pe_t$ : price of energy

$\alpha_t$ : Per capita income elasticity

$\beta$ : Energy price elasticity ( $\beta = -0.5$  for industrial countries,  $\beta = -0.3$  for developing)

$\gamma$ : Rate of technical progress in energy efficiency ( $\gamma = 0.005$ )

Equation 4.1a represents energy demand in the industrial countries, 4.1b demand in the developing countries (for which the superscript  $D$  is used).

For commercial energy income elasticities are zero below a certain threshold or ‘poverty line’, rise to around 1.5 as countries become more industrialized and motorized and household demand for energy using appliances increases, and then decline to one-fifth less of this at high per capita incomes as markets mature.<sup>12</sup> To reflect these changes we have used  $\alpha_t = 0.88e^{-0.00004Y_t}$ , based on the work of Judson *et al.* The initial value of alpha for industrial countries is 0.30 corresponding to an initial income of \$25,000, and for developing countries it is 0.78 corresponding to an initial income of \$3,000.

There is a problem with the use of the so-called energy efficiency parameter  $\gamma$ : it has to our knowledge not been estimated econometrically, since economists have widely ignored the energy efficiency term in econometric work, which must necessarily lead to biases in the estimates of price and per capita income elasticities; available estimates of  $\gamma$  come from engineering studies, which as Grubb *et al.* (1992) noted range from under 0.005 to over 0.015. We plan to explore the effects of such uncertainties on equation structure and parameters later.<sup>13</sup>

The per capita incomes for the industrial and developing countries ( $Y_t$  and  $Y_t^D$  respectively) are determined exogenously through a simple growth relationship:

<sup>11</sup> E.g. Bates and Moore (1992) and Dargay and Gately (1995)

<sup>12</sup> Bates and Moore (1992), Dargay and Gately (1995) and Judson, *et al.* (1999).

<sup>13</sup> See Papanthasiou and Anderson (2001), which explore the effects using Monte Carlo analysis, using an earlier version of the model presented below.

$$Y_t = Y_{t-1} + g_t Y_{t-1} \quad (\text{Industrial Countries}) \quad (4.2a)$$

$$Y_t^D = Y_{t-1}^D + g_t^D Y_{t-1}^D \quad (\text{Developing Countries}) \quad (4.2b)$$

Where:

$$g_t = g_{t-1}(1 - v)$$

$$g_t^D = g_t \left[ 1 + 0.32 \left( \frac{Y_{t-1}}{Y_{t-1}^D} - 1 \right) \right] \quad (4.3a \text{ and } 4.3b)$$

and  $v$  is a parameter representing the long-term rate of decline of economic growth in the industrial countries. For countries such as the UK and the US, it has not declined at all in more than a century, having averaged around 2% per year. The late starters in the industrial revolution—such as France, Germany and, especially, Japan—experienced higher growth rates over their long periods of ‘catch up’, but their long-term growth rates too converged to that of the US and UK in recent decades, which has given a downward trend to the long-run weighted average rate of per capita income growth in the industrial countries. Whether or not a 2% long-term rate of growth can be sustained over the course of another century (it would imply a further seven fold increase in per capita incomes and wealth) is not known. We have put the initial value of  $v = 0.01$ , implying that the long-run growth rate would decline to around 0.4 of its present level over the century.

The equation for  $g_t^D$  allows for catch up of the developing countries, which is notable especially in East Asia, and to a lesser extent in parts of South Asia and Latin America, though not alas in most of Africa. The closer their per capita incomes approach those of the industrial countries, the more their growth rates converge to those of the industrial countries.

Population levels are projected from the following, the assumptions for which can be estimated from the projections of the World Bank and United Nations:

$$N_t = \frac{MN_0}{N_0 + (M - N_0)e^{-kt}} \quad (4.4a)$$

$$N_t^D = \frac{M^D N_0^D}{N_0^D + (M^D - N_0^D)e^{-k^D t}} \quad (4.4b)$$

$M$  is the stable population level and  $k$  a growth parameter. The populations are estimated separately for the industrial and the developing countries. The initial level for the population of industrial countries is 0.89 billion, whereas the initial level for developing countries is 5.1 billion. The growth parameter  $k$  is given as 0.006 for industrial countries and 0.016 for developing countries. The stable population level is 2.0 billion for industrial countries and 8.4 billion for developing countries.<sup>14</sup>

The price variables for the demand equations will be presented later, once the equations for costs have been derived.

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<sup>14</sup> World Bank. 2001. *World Development Report 2000/2001: Attacking Poverty*. New York: Oxford University Press.

#### 4.2 Investment in New Technology during Period $t$

Investment opportunities stem from demand growth and the retirement of old assets:

$$I_t = (D_t - D_{t-1}) + \delta D_{t-1} \quad (4.5a)$$

$$I_t^D = (D_t^D - D_{t-1}^D) + \delta D_{t-1}^D \quad (4.5b)$$

where  $\delta$  = the retirement rate of assets that have come to the end of their economic lifetime. For energy production investment typically has a 25-35 year lifetime ( $\delta \approx 0.03$ ). Investment is calculated for each region using the regional demand equations (4.1).

#### 4.3 Cost of Old Technology Relative to New: (a) using existing forms for learning curves

Consider first the case where the model is not separated into regions. From the equations representing changes in demand, new investment and market shares ( $S_t$ , to be derived from the equations on relative prices below), it is possible to estimate the cumulative investments in the new and old technologies, denoted by  $U_t^N$  and  $U_t^O$  respectively:

$$U_t^N = U_{t-1}^N + S_{t-1} I_{t-1} \quad (4.6a)$$

$$U_t^O = U_{t-1}^O + (1 - S_{t-1}) I_{t-1} \quad (4.6b)$$

$U_0^N$  and  $U_0^O$  are initial conditions, to be estimated separately from historical records.<sup>15</sup> Costs can then be derived from learning curve formula discussed in the preceding section. (Note that since they depend in period  $t$  on cumulative experience up to the end of the preceding period,  $U_t^N$  and  $U_t^O$  are defined in 4.6a and 4.6b to include investments only up to  $t - 1$ .) Expressing the costs of old relative to new technologies:

$$C_t = \frac{C_t^O}{C_t^N} = \frac{C_0 (U_t^N / U_0^N)^{b^N}}{(U_t^O / U_0^O)^{b^O}} \quad (4.7)$$

Similar learning rates in the runs reported in the next section are used for both old and new technologies:  $b^N = 0.3$  (for new technology),  $b^O = 0.3$  (for old technology), and  $C_0$  is the initial relative cost at time  $t = 0$ .

When the model is separated into the two world regions, the values for  $U$  are calculated for each region (industrial and developing) and then added to calculate a relative cost function based on world markets. The justification is that with trade, international investment and the sharing of experience and knowledge across countries, the learning-by-doing effect is more closely related to world than to regional market experience:

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<sup>15</sup> For the old technologies, which dominate initial supplies, a reasonable estimate of cumulative investment can be derived from  $U_0^O = D_0 \left( \frac{1}{g^* + \delta} \right)$ , where  $g^*$  is the historical growth rate (we have taken a value of  $g^* = 0.08$ )

$$C_t = \frac{C_t^O}{C_t^N} = \frac{C_0(W_t^N / W_0^N)^{b^N}}{(W_t^O / W_0^O)^{b^O}} \quad (4.8)$$

where  $W_t^N = U_t^N (\text{industrial}) + U_t^N (\text{developing})$  (4.9a)

and  $W_t^O = U_t^O (\text{industrial}) + U_t^O (\text{developing})$  (4.9b)

*4.3 Cost of Old Technology Relative to New: (b) Alternative equation including a minimum value for the cost of new technology*

A shortcoming of such cost equations based on learning curves (though the form in 4.8 is widely used) is that the projected costs can decline to very low levels. In fact, they are asymptotically zero, which is implausible. They may offer good approximations in the early phases of a technology's development, or even over particular periods if refitted to mature technologies, such as has been done for gas turbines; but a relationship which holds well over say the first 5% of a technology's ultimate market cannot be assumed to hold over say the entire following 95%. It is more appropriate have them converge toward some non-zero value, which for many technologies can be estimated separately from engineering studies. To do this, first re-express the relationship for  $C_t^N$  in a finite difference form to make the underlying dynamics more apparent. Above, the cost of new technology was given by

$$C_t^N = C_0^N \left( \frac{W_t^N}{W_0^N} \right)^{-b^N}$$

Differentiating with respect to  $W_t^N$  :

$$\begin{aligned} \frac{dC_t^N}{dW_t^N} &= C_0^N (W_0^N)^{b^N} (-b^N) (W_t^N)^{-b^N-1} \\ \Rightarrow \Delta C_t^N &= \Delta W_t^N C_0^N (W_0^N)^{b^N} (-b^N) (W_t^N)^{-b^N-1} \end{aligned}$$

Or  $C_t^N = (W_t^N - W_{t-1}^N) C_0^N (W_0^N)^{b^N} (-b^N) (W_t^N)^{-b^N-1} + C_{t-1}^N$

Rearranging:

$$C_t^N = (W_t^N - W_{t-1}^N) (C_t^N) (-b^N) (W_t^N)^{-1} + (C_{t-1}^N)$$

To incorporate a minimum value into the equation, replace the term  $C_t^N$  with  $C_{t-1}^N - C_{\min}$ . ( $C_t^N$  is lagged one period to facilitate solving the equations of the model.) This gives:

$$C_t^N = \left( \frac{-b^N}{W_t^N} \right) (W_t^N - W_{t-1}^N) (C_{t-1}^N - C_{\min}) + C_{t-1}^N \quad (4.10a)$$

An equation for  $C_t^O$ , the cost of old technology, can be derived in the same way:

$$C_t^O = \left( \frac{-b^O}{W_t^O} \right) (W_t^O - W_{t-1}^O) (C_{t-1}^O - C_{\min}) + C_{t-1}^O. \quad (4.10b)$$

As before,  $b^N$  is set at 0.3 and  $b^O$  is set at 0.3. Estimates of  $C_{\min}$  can be derived from engineering studies (see Chapter 7).

#### 4.4 Relative Prices

Let  $P_t$  represent the price ratio of energy derived from old to new technologies in the industrial countries and  $P_t^D$  the corresponding ratio for the developing countries. These ratios will be determined by the ratio of costs, the environmental taxes placed on the old (polluting) technologies, and the subsidies for innovation provided for new technologies. In addition, it is necessary to allow for differing natural resource endowments on the useful energy yield of the technologies. As noted earlier, the capital costs per unit of capacity of the technologies used for energy extraction and conversion tend to converge across countries with the influence of trade and foreign investment—for example, the capital costs of oil and gas exploration, of electricity generation from combined-cycle gas turbine plant, or the costs per kW of peak capacity of a solar or wind plant. But the *useful* energy delivered by the plant may differ appreciably between regions on account of differences in resource endowments, especially in the case of renewable energy—wind, tidal streams, geothermal and solar energy are all cases in point. The following expression makes an allowance for this through the factors  $F$  and  $F^D$  by adjusting the effective price paid per unit of energy delivered by an energy resource. In the model runs reported below,  $F$  has been put to unity for the industrial countries, with  $F^D$  for the developing countries thus being expressed relative to that of the industrial countries.

$$P_t = \frac{C_t^O}{C_t^N} \cdot \frac{1+T_t}{1-G_t} \cdot \frac{1}{F} \quad (4.13a)$$

and 
$$P_t^D = \frac{C_t^O}{C_t^N} \cdot \frac{1+T_t^D}{1-G_t^D} \cdot \frac{1}{F^D} \quad (4.13b)$$

$T_t$  and  $T_t^D$  = Tax rates (e.g. carbon tax) on old technology at time t, as a per unit of costs for industrial and developing countries respectively

$G_t$  and  $G_t^D$  = Subsidies for innovation

$F$  and  $F_t^D$  = Resource endowment factors.

#### 4.5 Market Shares

The market shares equation is of the same form as that presented in the previous chapter. There is a separate equation for industrial and developing countries, linked to the price variables for each region. Again letting  $S_t$  and  $S_t^D$  respectively denote market shares of low carbon technology in investment for the industrial and developing countries:

$$S_t = S_{t-1} + aS_{t-1}(1 - S_{t-1})(P_t - P_{t-1}) \quad (4.12a)$$

and 
$$S_{t-1}^D = S_{t-1}^D + aS_{t-1}^D(1 - S_{t-1}^D)(P_t^D - P_{t-1}^D) \quad (4.12b)$$

As discussed earlier, these equations can introduce chaotic behaviour in the variable  $S_t$ , depending on the product of the parameter  $a$  and the change in prices. A significant price shock, for example can lead to values of  $S_t$  fluctuating chaotically above and below unity and above and below zero. The equations are not structurally subtle enough to capture how markets might respond to the

overshooting and undershooting of investment, e.g. through more regular feedback of information or by introducing additional feedbacks to neutralise the effects of high rates of change of prices. But the problem can be circumvented by introducing the condition:

$$S_0 \leq S_t \leq 1.0 \quad (4.13)$$

This is the approach used below.

#### 4.6 Price of Energy (weighted average for energy prices)

The energy prices for each region ( $Pe_t$  and  $Pe_t^D$  for the industrial and developing countries respectively) are taken to be a weighted average of the new and the old technologies. For the industrial countries:

$$\frac{Pe_t}{Pe_0} = \frac{C_0^O \left(\frac{W_t^O}{W_0^O}\right)^{-B^O} (1+T_t)(1-(R_{t-1}/D_{t-1})) + C_0^N \left(\frac{W_t^N}{W_0^N}\right)^{-B^N} (1-G_t)(R_{t-1}/D_{t-1})}{C_0^N (1-G_0)(R_0/D_0) + C_0^O (1+T_0)(1-(R_0/D_0))} \quad (4.14a)$$

$$\frac{Pe_t^D}{Pe_0^D} = \frac{C_0^O \left(\frac{W_t^O}{W_0^O}\right)^{-B^O} (1+T_t^D)(1-(R_{t-1}^D/D_{t-1}^D)) + C_0^N \left(\frac{W_t^N}{W_0^N}\right)^{-B^N} (1-G_t^D)\left(\frac{R_{t-1}^D}{D_{t-1}^D}\right)}{C_0^N (1-G_0^D)(R_0^D/D_0^D) + C_0^O (1+T_0^D)(1-(R_0^D/D_0^D))} \quad (4.14b)$$

These equations enable us to close the loop and solve the energy demand equations 4.1 (for industrial and developing countries) above.

#### 4.7 Demand Met by Non-Carbon Technologies

Another useful term is  $R_t$ , the demand met by non-carbon technologies. This term is defined for industrial and developing countries as:

$$R_t = R_{t-1}(1-\delta) + (S_t I_{t-1}) \quad (4.15a)$$

$$R_t^D = R_{t-1}^D(1-\delta) + (S_t^D I_{t-1}^D) \quad (4.15b)$$

Comparing  $R_t$  to  $D_t$  at any point in time allows us to determine how much of the demand for energy is met by non-carbon technologies and how that demand is influenced by changing policies and initial conditions.

## 5. Results

### 5.1 Model Runs

This chapter summarises the nine runs conducted. Table 1 shows the assumptions made for each of the runs; the blank spaces for run 8 indicate that the level and duration of the carbon tax on fossil fuels are being varied in the model. Unless specified, it is assumed that the other parameter values are the same as in the base run, and that the parameter values are the same for both developing and industrial countries. A full list of all the initial conditions and parameter values for the base case is given in Appendix 1.

**Table 1: Assumptions for the Nine Runs**

Run	Policy (incentive & duration)				Parameter changes from base case
	T	Yrs	G	Yrs	
<b>1. Base case (all regions)</b>	0.3	100	0.3	20	
<b>2. No policy case (all regions)</b>	0.0	0	0.0	0	
<b>3. Base case with policy reversal: a</b>	0.3	10	0.3	10	
<b>4. No policy case + techn'gy surprise or a permanent fossil fuel price shock</b>	0.0	0	0.0	0	$C_{\min\text{-new}} = 0.75 C_{\min\text{-old}}$
<b>5. Sensitivity to the minimum cost of new technology</b>	0.3	100	0.3	20	$C_{\min(\text{new})}=1.25$ $C_{\min(\text{old})}$
<b>6. Sensitivity to initial conditions</b>	0.3	100	0.3	20	$C(0) = 0.3$
<b>7. Parameter space runs</b>	0.3	100	0.3	20	$0.1 \leq b \leq 0.4; 3 \leq a \leq 15$
<b>8. Policy space runs</b>			0.3	20	$5 \leq \text{Policy Duration} \leq 50$ years; $0.1 \leq T \leq 0.6$
<b>9. No policies in developing countries</b>	0.3	100	0.3	20	<i>Industrial countries only</i>

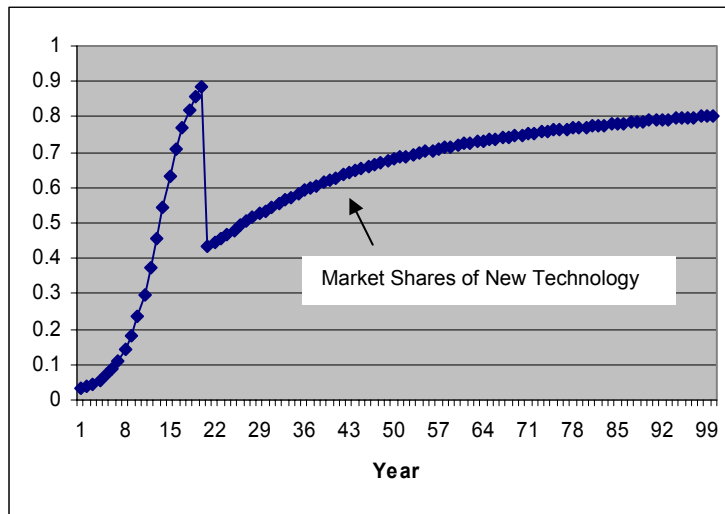
#### Run 1 (the base case)

The following figures show the model results when the initial cost ratio of fossil fuels relative to the non-carbon alternative is 0.5. An innovation incentive of 30% reduces the prices of the non-carbon alternatives for the first twenty years of the model run; a carbon tax increases the price of fossil fuels by 30% for the entire 100 year period. Because the minimum cost of fossil fuels and the minimum cost of non-carbon technology are both set at 0.8, the cost ratio decreases over the 100 year period to 1.0.

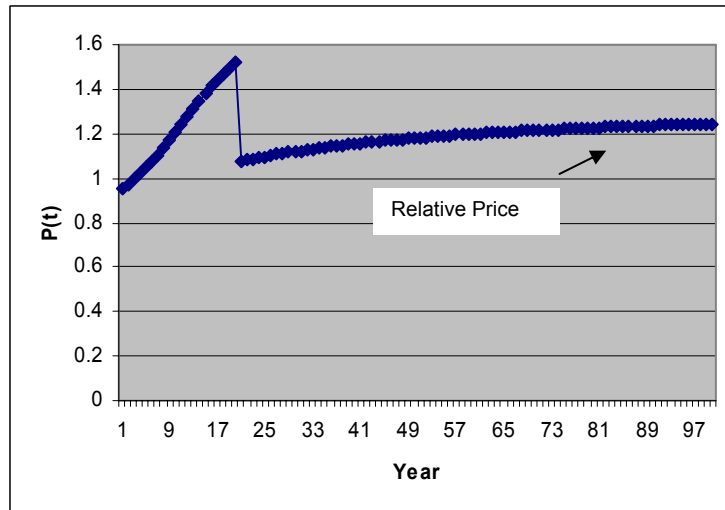
The removal of the innovation subsidy after 20 years is disruptive, but not fatal, to growth, since the non-carbon technology has taken root by then, capable of surviving the shock.

The growth of demand for non-carbon technologies corresponds roughly with the mid range of the IPCC scenarios.

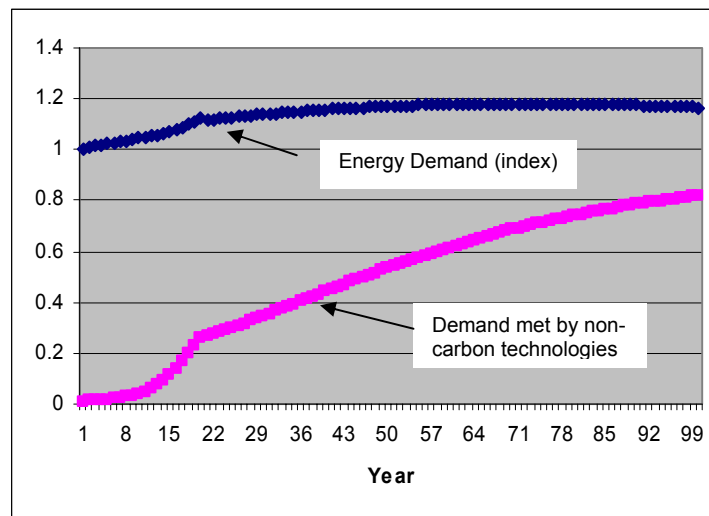
**Figure 5.1:** Market Shares of the New (Non-Carbon) Technology



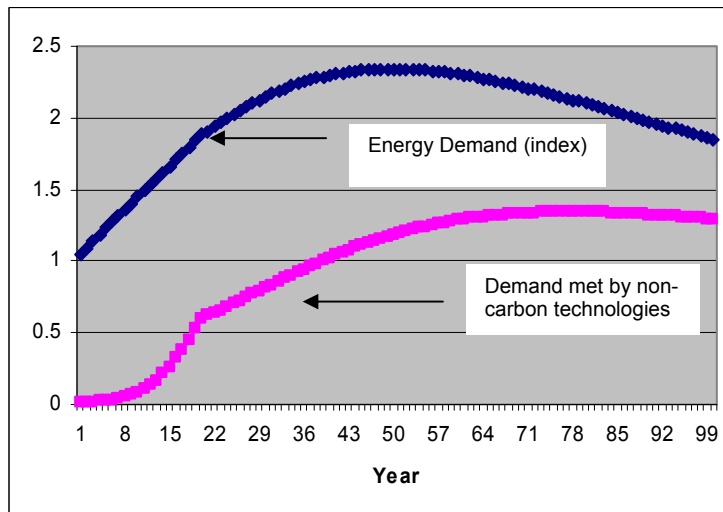
**Figure 5.2:** Relative Price of Fossil Fuels to Non Carbon Energy Sources



**Figure 5.3:** Energy Demand Index (Industrial Countries)



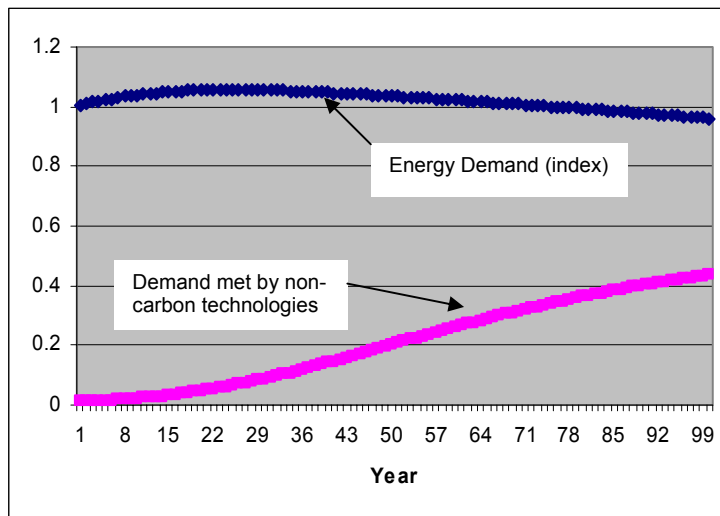
**Figure 5.4:** Energy Demand Index (Developing Countries)



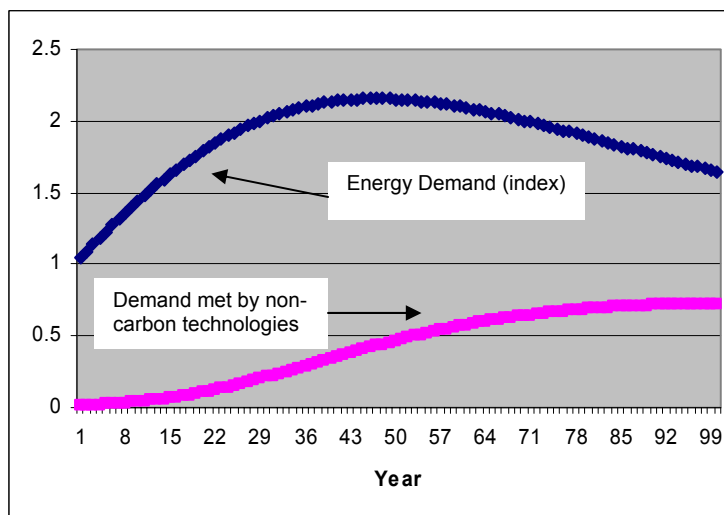
*Run 2 (the no-policy run)*

There are no taxes or incentives implemented in this run. That is,  $T$  and  $G$  are set equal to zero for the entire 100 year period. The non-carbon alternatives emerge endogenously, albeit very slowly, driven by the steady effects of learning by doing and building on the initially small markets for non-carbon technologies that exist today. As can be inferred from later runs (e.g. run 9) it is the higher growth markets of developing countries that provide the main spur for continued innovation when supportive policies are absent.

**Figure 5.5:** Energy Demand Index (Industrial Countries)



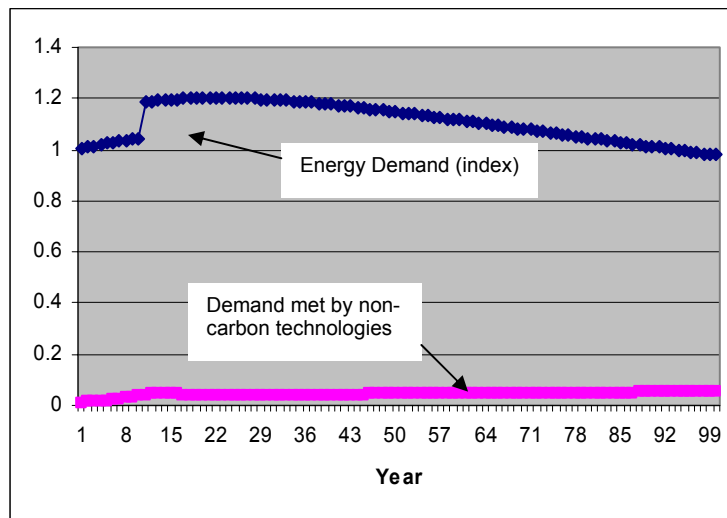
**Figure 5.6:** Energy Demand Index (Developing Countries)



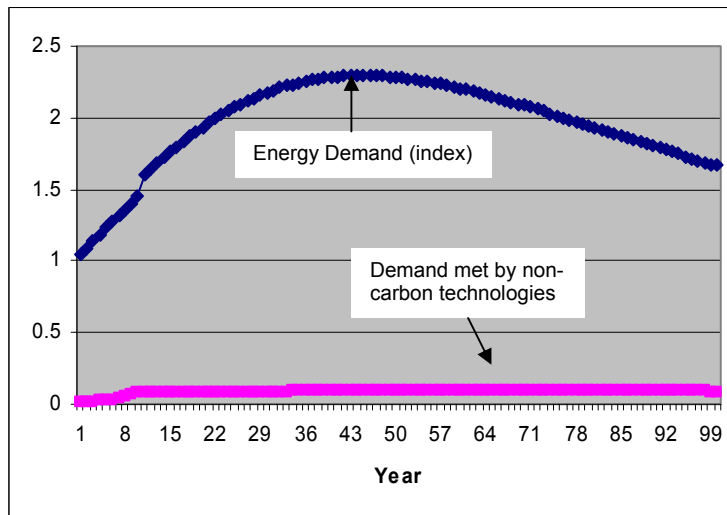
*Run 3 (policy cut after 10 years)*

This run shows the results if there is a 30% policy in place for 10 years only, the alternatives do not emerge at all. Once the policy is taken away after 10 years, the drop in the relative price is too sharp for the non-carbon market to recover. Comparing these results to Run 1 shows that ‘copping’ a policy too soon can be fatal, whatever the promise of the new technology (see also the results reported in Figure 3.3 with the simplified model).

**Figure 5.7:** Energy Demand Index (Industrial Countries)



**Figure 5.8:** Energy Demand Index (Developing Countries)



Run 4 (no policy + technology surprise, or alternatively a permanent shock to fossil fuel prices)

In this case, the possibilities of lower long-run costs for the non-carbon technology, relative to those are explored. Alternatively, since  $C_{min}$  is the costs of the non-carbon relative to those of fossil fuel technologies, it can be considered as the case of a permanent rise in the latter. This run shows the sensitivity of the model to the relative value of long run costs – even though there is no policy, the non-carbon alternatives eventually emerge.

Figure 5.9: Energy Demand Index (Industrial Countries)

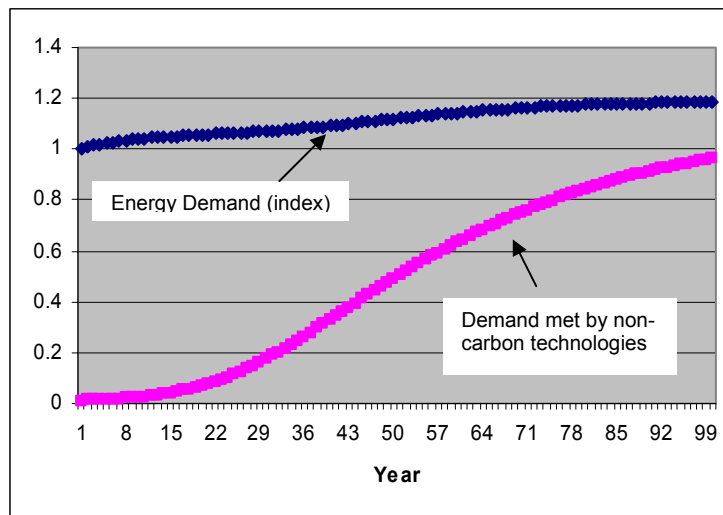
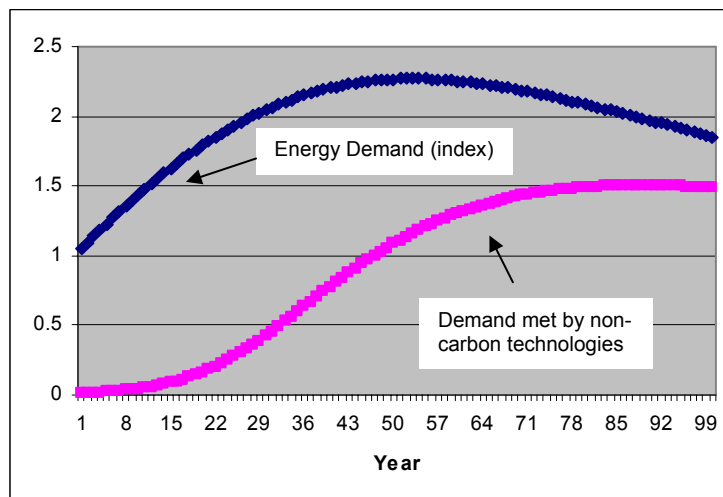


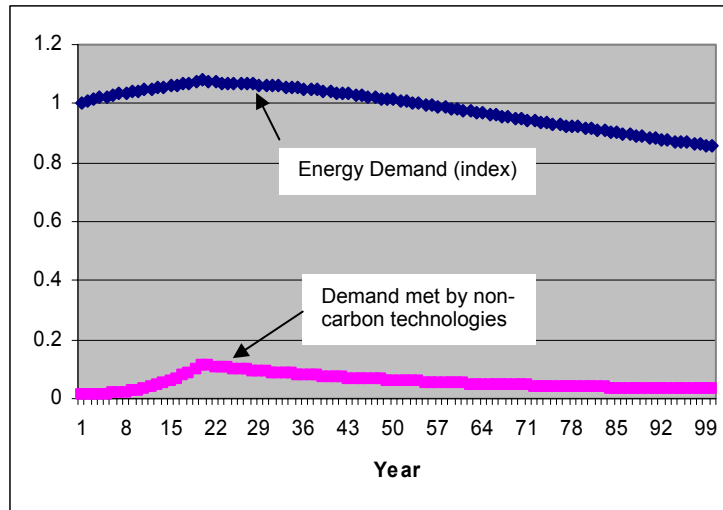
Figure 5.10: Energy Demand Index (Developing Countries)



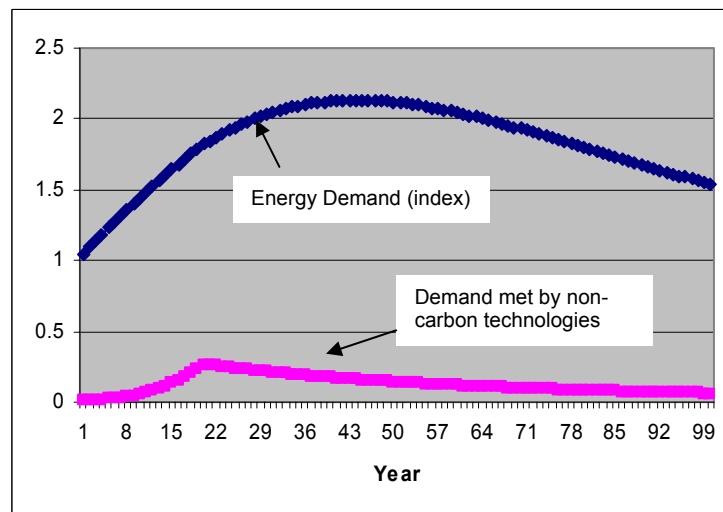
*Run 5* (sensitivity to minimum cost ratio)

To further examine the sensitivity of the model to the minimum cost ratio, this run specifies  $C_{\min}(\text{new}) = 1.25C_{\min}(\text{old})$ . Even with a 30% carbon tax and a 30% innovation incentive for new technology, the alternatives never emerge.

**Figure 5.11:** Energy Demand Index (Industrial Countries)



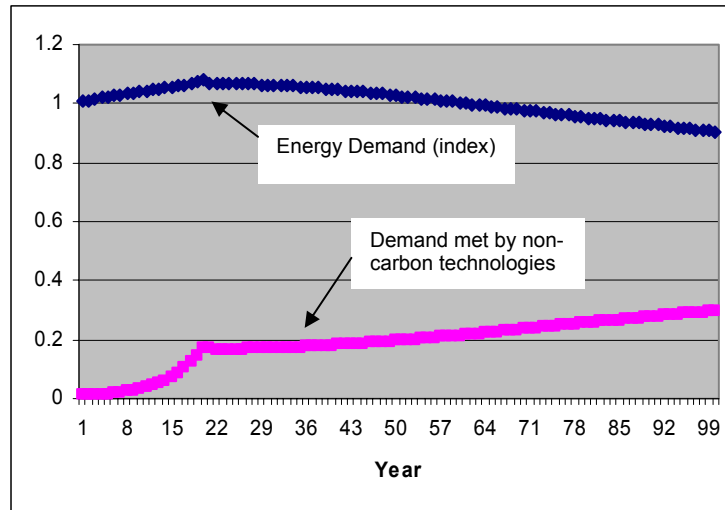
**Figure 5.12:** Energy Demand Index (Developing Countries)



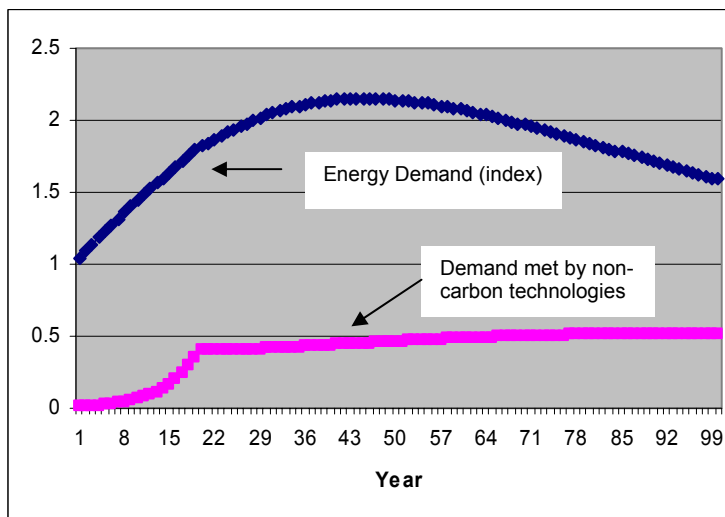
*Run 6 (sensitivity to initial cost ratio)*

In this run, the initial cost of new technology is three times that of the initial cost of fossil fuels, as compared with an initial ratio of two in the base run. As a result, the new technology does not emerge as quickly because it is more difficult to overcome this greater initial difference in cost.

**Figure 5.13:** Energy Demand Index (Industrial Countries)



**Figure 5.14:** Energy Demand Index (Developing Countries)

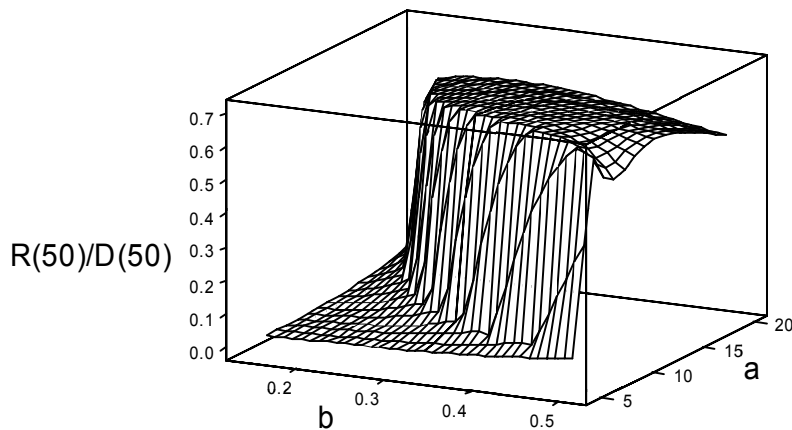


### Run 7 (Parameter Space Runs)

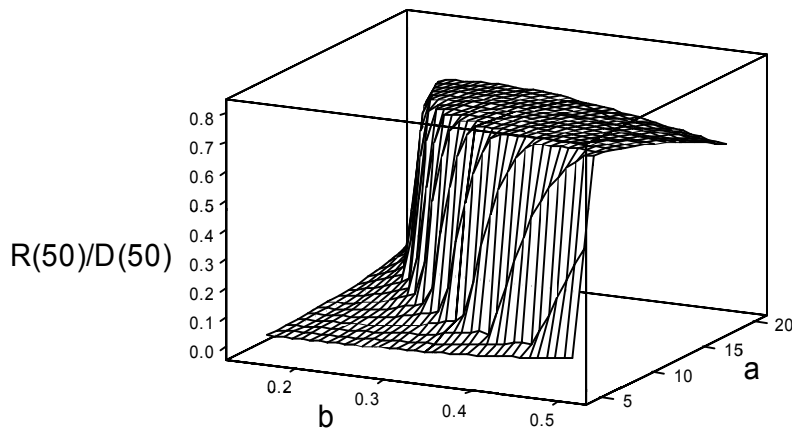
As discussed earlier, the model results are very sensitive to certain parameter values, most notably the substitution parameter,  $a$ , and the learning rate for new technology,  $b$ . This run focuses on the effect of varying both the learning rate and the substitution parameter on  $R(50)/D(50)$ , which is the percentage of the demand for energy that is met by non-carbon technologies at year 2050. Low rates of learning in combination with low values of substitution parameter  $a$ , yield a lower percentage of energy demand being met by non-carbon technologies.

The parameters themselves have threshold values for any particular set of policy assumptions. However, as can be inferred from the next run on the policy space, the ‘cliff’ shown in Figure 5.15 can be shifted toward the origin by stronger and more durable policies; the general *directions* of a policy are thus unaffected by the admittedly large uncertainties as to the parameters  $a$  and  $b$ . A weaker substitution effect (lower  $a$ ) or a lower learning rate (lower  $b$ ) simply argue for a more determined effort. Policies themselves need to include for a margin for error.

**Figure 5.15:** Effects of Parameters  $a$  and  $b$  on Long-Run Energy Options: Industrial Countries



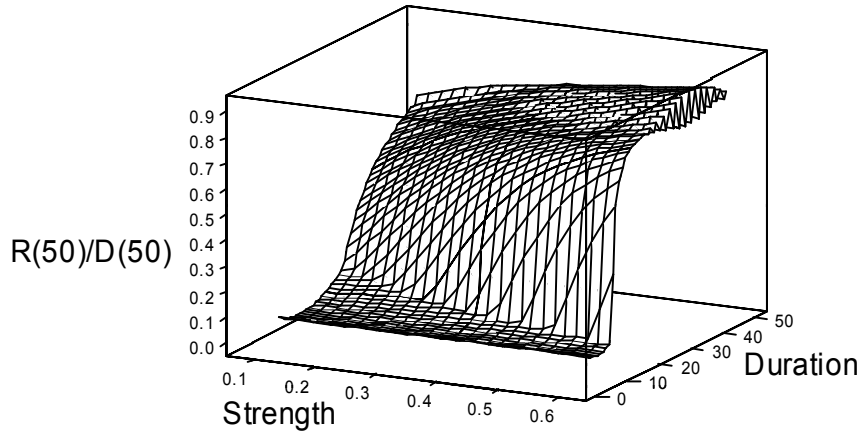
**Figure 5.16:** Effects of Parameters  $a$  and  $b$  on Long-Run Energy Options Developing Countries



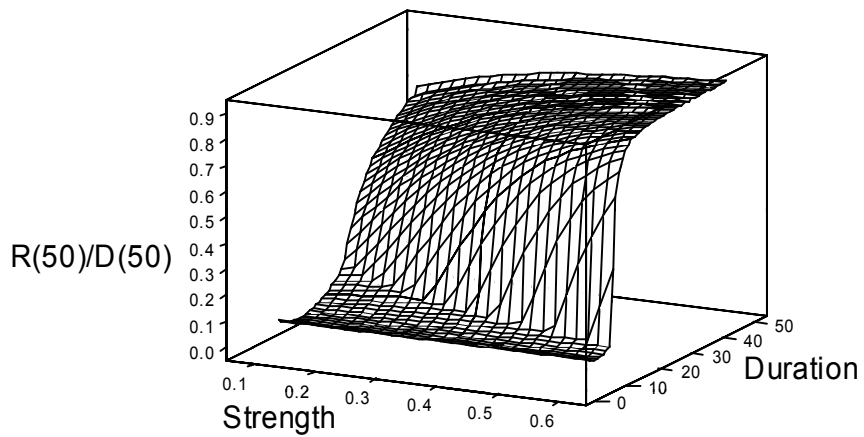
*Run 8 (Policy Space Run)*

The preceding runs have already shown that if a policy is too weak, or is not implemented for a sufficiently long time period, then, barring an economic surprise or a permanent shock to fossil fuel prices, new technologies are unlikely take root. In this run, both the strength of the tax and the duration of the policy are varied in order to show the extent to which policy determines whether new technology catches on in the market. The duration (that is, the number of years both the incentive and the tax are in place before being removed) varies from between 5 and 50 years. The strength of the tax varies from between 10% and 60%. Figure 5.17 and 5.18 show estimates of  $R(50)/D(50)$  over this policy space. The threshold effects of policy are again apparent. Whatever the long term promise of the alternatives might be, they do not emerge when the policies are too weak and/or if they are reversed too soon. The general message is that weakness, equivocation and dithering on the policy front is no better—and is perhaps worse—than no policy at all.

**Figure 5.17:** Effect of Policy Strength and Duration on Long-run Energy Options Industrial Countries



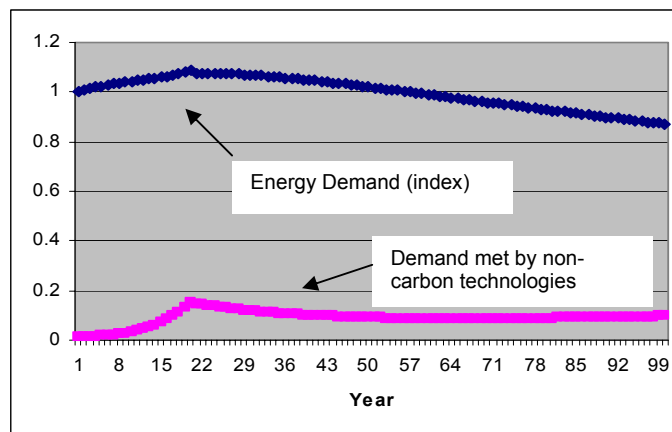
**Figure 5.18:** Effect of Policy Strength and Duration on Long-run Energy Options Developing Countries



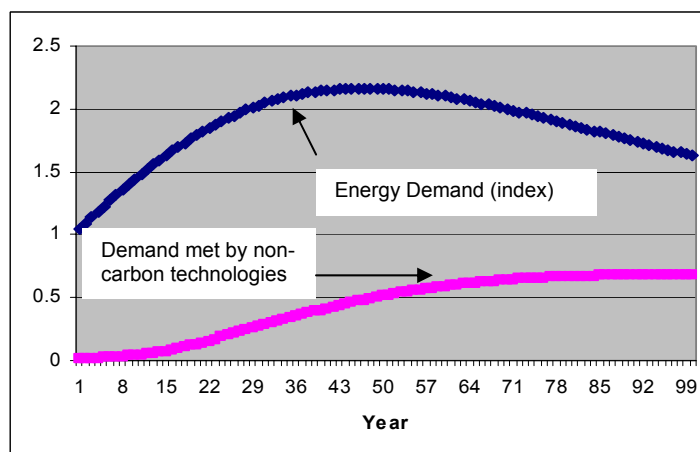
*Run 9 (Separate Policies for Industrial and Developing Countries)*

This run simulates the effect of implementing a 30% carbon tax and a 30% incentive for new technology in just industrial countries, while developing countries are not subject to any policy. In this situation, non-carbon technologies are not able to catch on even in industrial countries because of the absence of policies in developing countries, which undercut investment opportunities and the rate of innovation. There is some growth for the non-carbon technologies in the developing countries, but it is generally low (the result is similar to that in the second run). The results serve to show how important the participation of developing countries in climate change policies will be—and especially the importance of market growth in these regions as a stimulus for innovation.

**Figure 5.19:** Energy Demand Index (Industrial Countries)



**Figure 5.20:** Energy Demand Index (Developing Countries)



## **6. Threshold Effects and the External Benefits and Option Value of Innovation.**

This section discusses some implications arising from the preceding analysis for the cost-benefit analysis of pollution abatement policies. The three main questions it addresses are:

- How do non-linearities and threshold effects in technology development and substitution affect estimates of the external benefits of innovation?
- What are the implications for the cost-benefit analysis of pollution abatement policies? (The discussion also takes account of threshold effects in environmental damage functions.)
- How might estimates of option values of alternative policies be affected?

The intention is to lay the analytical basis for further computations using the preceding model, which will be reported in a future paper.

### *6.1 Externalities*

Let  $p_t$  denote the price of the energy produced,  $k_t$  the marginal private costs of production, and  $e_t$  the present value of the marginal environmental benefits arising from an investment, and  $B_t$  total social benefits.  $I_t$  is total investment. If an investment has no effects on the costs of others, then the marginal social benefits of the investment are simply the marginal private benefits plus the marginal environmental benefits:

$$dB_t / dI_t = (p_t - k_t) + e_t$$

However, this is to assume that investments today have no influence on the costs and benefits of future investments. When future costs change with investment actual social marginal benefits of an investment  $I_0$  in period 0 consists of five terms, not two:

- (i) The marginal private benefits as above  $(p_t - k_t)$
- (ii) *Plus* the marginal environmental benefit arising *directly* from the investment ( $e_0$ ), also as above.
- (iii) *Plus* the present value of the marginal reductions in future costs of investments, weighted by the prospective volume of use.
- (iv) *Plus* the present value of the increase in marginal private benefit of future increases in investments induced by the reductions in future costs.
- (v) *Plus* the present value of the marginal environmental benefits of future investments also induced by the reductions in future costs.

The third term is sometimes known as the ‘learning externalities’ term; it is the cost savings arising from the reductions in future costs brought about by the current investment.

More formally, let  $B_0$  represent the net present value of a time stream of investments with environmental benefits, such that:

$$B_0 = a_0(p_0 - k_0 + e_0)I_0 + a_1(p_1 - k_1 + e_1)I_1 + \dots \quad (6.1)$$

Consider the case where a change  $\Delta I_0$  leads to changes in both the unit costs of future investments and, on account of this, to changes  $\Delta I_1, \Delta I_2, \dots$ . Then:

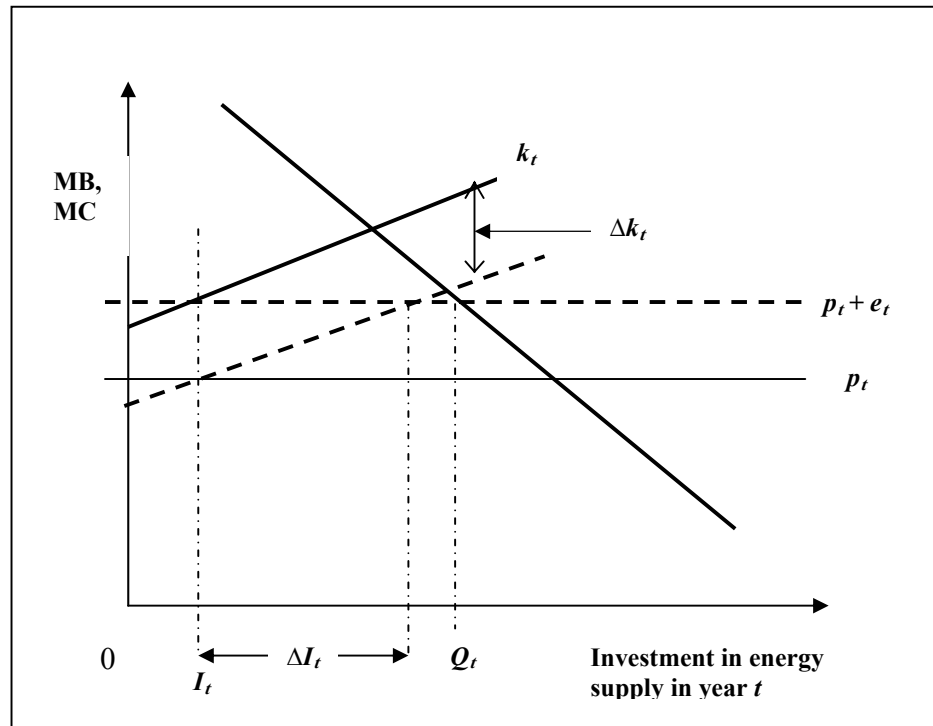
$$\Delta k_t = \frac{dk_t}{dI_0} \cdot \Delta I_0, \text{ which is negative, and } \Delta I_t = \frac{dI_t}{dk_t} \cdot \Delta k_t$$

Then, with  $a_t$  being the discount factor:

$$\frac{\Delta B_0}{\Delta I_0} \approx a_0(p_0 - k_0 + e_0) + \sum_{t \geq 1} a_t \left\{ \Delta k_t | I_t + (p_t - \overline{\{k_t - \Delta k_t\}} + e_t) \Delta I_t \right\} \quad (6.2)$$

The term in the summation sign represents the external benefits of innovation, and corresponds to (iii), (iv) and (v) above.<sup>16</sup> With threshold effects this component of external benefits induced by investments  $\Delta I_0$  may be very large—far larger than the term  $e_0 \Delta I_0$ , which dominates (almost to a fault) traditional economic thinking on environmental policy.

Figure 6.1 Graphical illustration of the terms in equation 6.2



<sup>16</sup> That the term  $k_t - \Delta k_t$  is an average value over the interval  $I_t$  to  $I_t + \Delta I_t$  is explained below in relation to Figure 6.1.

Figure 6.1 illustrates the result graphically. The downward sloping line represents the demand curve for new investment, which is taken to be the marginal benefit curve. The energy price before environmental taxes is  $p_t$  (the pre-tax price of fossil fuels say) and rises to  $p_t + e_t$  if environmental taxes are set equal to the marginal costs of environmental damage. Investment in energy supply in year  $t$  is  $Q_t$  of which the portion supplied by the low carbon technology would be  $I_t$  (if costs remained at  $k_t$ ) the balance  $Q_t - I_t$  being provided by fossil fuels. The marginal cost of supply from the non-carbon alternative is  $k_t$ . If this falls by  $\Delta k_t$  on account of innovation and the learning effects of earlier investments, the cost savings to investment in period  $t$ , all else constant, is approximately equal to  $I_t \Delta k_t$ , the first term in the summation sign in equation 6.2, or item (iii) in the paragraph which preceded it. If however the elasticity of substitution between the alternative technologies is large, as is implied in the figure, small shifts in relative costs will lead to large substitution effects, leading to large environmental benefits, approximately equal to  $e_t \cdot \Delta I_t$ , and to an overall economic benefit in year  $t$  of  $(p_t - \overline{\{k_t - \Delta k_t\}} + e_t) \Delta I_t$ , where  $\overline{\{k_t - \Delta k_t\}}$  denotes the average value of this quantity over the total supply; this corresponds to the remaining terms within the summation sign of 6.2 or items (iv) and (v).

The quantitative importance of the externalities term within the summation sign on the right hand side of 6.2 is commonly neglected in economic studies. Yet there is evidence from engineering studies of pollution abatement technologies to suggest that for a number of environmental problems in the past the elasticities of substitution are indeed large once the technologies have been developed, such that it is the term just noted that has been the dominant effect in practice.<sup>17</sup>

### 6.2 Threshold Effects in Marginal Benefit and Cost Curves

Threshold effects are commonly associated in the scientific literature with environmental change, in which large and irreversible damages are thought to occur with low levels of abatement, and are only avoided by high levels of abatement. Pollution standards have rarely called for, say 20-30 percent reductions, or even 50-70%, but for reductions by orders of magnitude, and in a large number of historical cases, e.g. in water and atmospheric pollution, this is what has been achieved in practice.<sup>18</sup> In its recommendations on how the UK might show leadership by responding to the problem of climate change, the Royal Commission on Environmental Pollution (2000) argued for 60% reductions in CO<sub>2</sub> emissions by 2050; but it is widely conceded that there is a non-trivial possibility of threshold effects occurring, e.g. in the thermohaline circulation and glacial climates, in which case very high levels of abatement might be needed.<sup>19</sup>

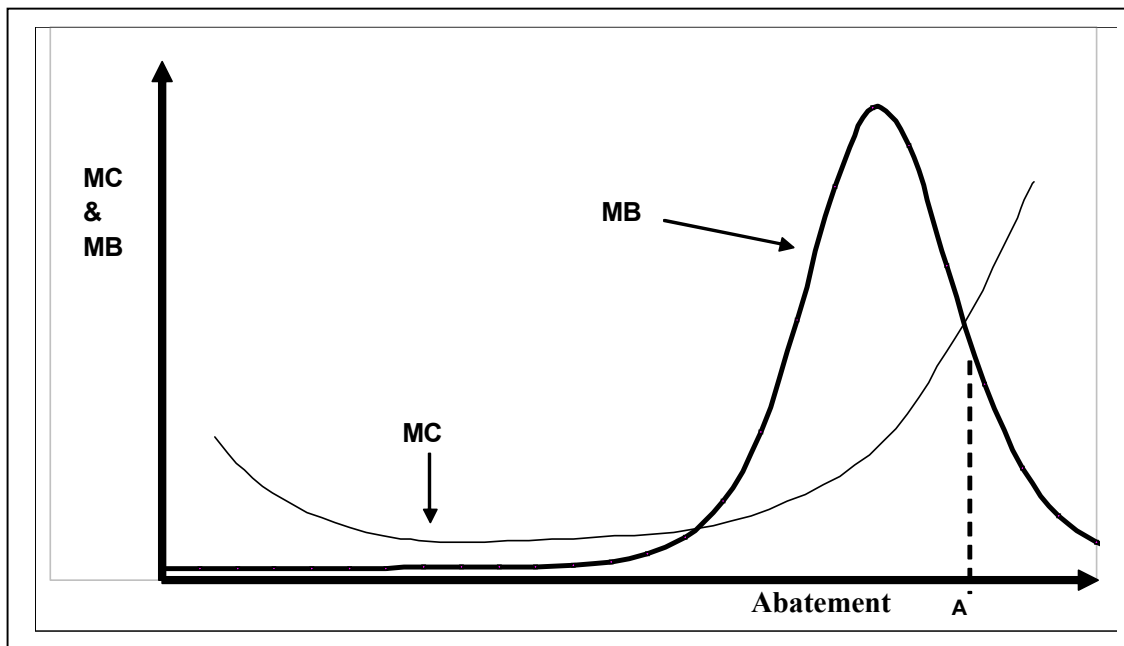
When environmental threshold effects arise, the total damage function may take the form of a sharp S-curve of the form discussed earlier (see Figure 2.1), and the total benefits of abating a reversed S-curve. The marginal benefit curve of pollution abatement is then not the steadily declining function with diminishing returns, so often depicted in economic texts and papers, but a peaky function of the form shown in Figure 6.2. Included is a schematic representation of the marginal costs of abatement, discussed in Chapter 3. The total costs of abatement are the area under the marginal cost curve, while the total costs of environmental damage equal the area under the marginal benefit curve *plus* the irreversible fixed costs of environmental damage at low levels of abatement.

<sup>17</sup> A review and analysis is provided in D. Anderson (2001) "Technical Progress and Pollution Abatement: an economic view of selected technologies and practices." *Journal of Environment and Development Economics*. 6: 283-311

<sup>18</sup> Anderson (2001).

<sup>19</sup> Mastrandrea and Schneider (2001), Ganopolski and Rahmstorf (1999, 2001).

**Figure 6.2: Marginal Benefits and Costs of Abatement with Threshold Effects**



It can be seen why the debate on climate change (and on a good many other environmental policies) is often so polarised. If the view is that irreversible damages are unlikely or are small, then the optimum policy is for no abatement, beyond that which can be achieved by the so-called ‘no regrets’ or ‘win-win’ options such as are often thought possible through energy efficiency.<sup>20</sup> If on the other hand the view is that the irreversible damages would be large in the absence of abatement, then the optimum level of abatement would be at the other extreme, point A in the above figure. In this case is it desirable to pass through a (perhaps long) phase of policy in which the marginal costs exceed the marginal benefits of abatement, a possibility that is often ignored.

### *6.3 Uncertainties and the Economic Value of Exploring Options*

The complexities deepen when uncertainties are taken into account. There are two major uncertainties, concerning the costs of environmental damage, and the costs of avoiding it. It is well known that:<sup>21</sup>

- (a) There is a value, termed the *option value*, to delaying a decision on an irreversible investment until the uncertainties are reduced. This may (depending on probabilities and the estimated cost and benefit streams) argue for delay;
- (b) When, on the other hand, a delay may lead to irreversible damages, the case for avoiding delay and bringing forward a policy is increased.

<sup>20</sup> A discussion of this topic requires separate analysis, and is beyond the scope of this paper.

<sup>21</sup> AK Dixit and RS Pindyck (1994). *Investment Under Uncertainty*. Princeton NJ: Princeton University Press.

(c) If the costs of abating damage are such that they cannot be ascertained reliably without investment, then this too will argue for avoiding delay and for investments aimed at exploring options.

These results are summarised for a simplified case in Table 6.1 in order to arrive at an elementary point for policy. Let  $q$  denote the probability of one estimate of the annual damages arising from climate change and  $(1-q)$  the probability of another estimate. The net annual benefits of avoiding these damages are denoted by  $B_1$  and  $B_2$  respectively, and to simplify analysis they are assumed constant over time. The costs of the investments are annualised and deducted from the net benefit streams.  $B_1$  is taken to be  $> 0$  and  $B_2$ , which if we had more information we would avoid incurring altogether, is  $< 0$  in the first four cases.

In case 1, there is no delay in policy; in case 2, the decision is delayed until better information is available such that the possible economic losses ( $B_2$ ) are avoided. A comparison of the benefits between the two cases suggests that it would always pay to delay in this situation. The situation is different when irreversible losses arise, as can be seen from Case 3; investing now (Case 1) might be the better option, depending on the balance of probabilities and net benefits.

**Table 6.1.**

Probability	Net benefits per period:				Expected net benefits <sup>a/</sup>
	0	1	2	3,.....	
<b>Case 1</b> —Invest now, with downside benefits $B_2 < 0$ :					
$q$	$B_1$	$B_1$	$B_1$	$B_1, \dots$	$qB_1 / r + (1-q)B_2 / r$
$1-q$	$B_2$	$B_2$	$B_2$	$B_2, \dots$	
<b>Case 2</b> —Delay one period (with no irreversible damages):					
$q$	0	$B_1$	$B_1$	$B_1, \dots$	Losses $B_2$ are avoided: $qB_1 / r(1+r) \approx qB_1 / r$
$1-q$	0	0	0	$0, \dots$	
<b>Case 3</b> —Delay one period (with irreversible damages):					
$q$	$-B_1$	$B_1$	$B_1$	$B_1, \dots$	Losses $B_2$ also avoided: $qB_1 / r(1+r) - qB_1 \approx qB_1 / r - qB_1$
$1-q$	0	0	0	$0, \dots$	
<b>Case 4</b> —Invest $I$ to explore options (irreversible damages):					
$q$	$-I - B_1^*$	$B_1^*$	$B_1^*$	$B_1^*, \dots$	$qB_1^* / r(1+r) - qB_1^* - I$
$1-q$	$-I$	0	0	$0, \dots$	
<b>Case 5</b> —As for 4, but with net benefits $B_2^* > 0$					
$q$	$-I - B_1^*$	$B_1^*$	$B_1^*$	$B_1^*, \dots$	As in Case 4 plus: $(1-q)B_2^* / r(1+r) - (1-q)B_2^*$
$1-q$	$-I - B_2^*$	$B_2^*$	$B_2^*$	$B_2^*, \dots$	

a/ The formulae assume long time horizons such that the present value of the benefit streams is approximately  $1/r$  times the annual benefit stream.

However, there is the further possibility of investing in the first period to explore options, the point of which is to find novel and lower cost ways of addressing the problem; the effect is to raise the net benefit stream from  $B_1$  to a higher level  $B_1^*$  and, by the same token, the lower estimate of net benefits from  $B_2$  to a higher level  $B_2^*$ . This is summarised in case 4, in which irreversible damage arises while options are being explored. Again, depending on probabilities and the changes in the net benefit stream, this might be preferable to all other possibilities—and it

certainly would if, in addition, as illustrated in Case 5, it turned even the previously negative net benefit stream  $B_2$  into a positive one.

It is apparent that virtually any policy position might be defended depending on assumptions as to both the net benefit streams and the probabilities to be attached to them. Estimates of the net benefits vary enormously in the case of climate change, from under \$5 per ton of carbon emitted to several hundred dollars per ton, and even these ignore the possibility of extreme threshold events.<sup>22</sup>

However, it does seem that the policy of exploring options is likely remain robust under reasonable assumptions, and may well be justified by reference to the benefits of innovation alone. Let  $\Delta C$  denote the present value of the annual cost savings benefits arising from the exploration of options to address climate change. The net cost savings benefits of exploring options would then lie somewhere in between  $q\Delta C - I$  and  $q\Delta C + (1 - q)\Delta C - I = \Delta C - I$ .

## **7. The Costs of Non-Carbon Technologies Relative to Fossil Fuels**

The cost equations require estimates of initial costs, the sizes of the market or market shares with which these estimates are associated, learning rates, and an estimate of long-term costs ( $C_{min}$ ) from engineering studies. For non-carbon alternatives to fossil fuels, all these quantities vary appreciably between technologies.

Table 7.1 provides estimates of near and long term costs for a range of renewable energy technologies, nuclear power, of hydrogen derived from these sources, and the costs of electricity using fuel cells supplied by hydrogen.<sup>23</sup> The table compares these costs with those of natural gas, transport fuels and the generation of electricity from fossil fuels. The main sources of these estimates are the reviews provided in the World Energy Assessment of the UNDP and the World Energy Council (2000), the background studies and reviews commissioned by the PIU (now the Prime Minister's Strategy Unit) and the DTI for the UK Energy White Paper, and the review by Anderson and Leach (forthcoming) on the use of hydrogen to solve the intermittency problem posed by renewable energy. All the estimates shown are based on engineering economic analysis, as opposed to the statistical analysis of costs more familiar to economists.

The last two columns of the table show the ratios of the costs of the non-carbon fuel relative to the appropriate fossil fuel, which is taken to be petrol and diesel for transport fuels, natural gas for electricity generation and the gas markets.<sup>24</sup> Given the uncertainties in cost estimates—even estimates of today's costs vary greatly between studies—the ratios are indicative only. For the purposes of the present study, five points stand out:

1. *Current costs.* These are generally higher, sometimes appreciably higher, than those of the fossil fuel alternative. They vary from being about 50% higher in the case of wind, 70% higher for nuclear power, to 200% higher for biofuels and offshore wind and marine energy, to 200-700% higher for Photovoltaics (the lower figure being for high insolation areas, the lower one for low insolation areas), to being an order of magnitude higher for hydrogen derived from renewable

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<sup>22</sup> A review is provided by Tol R.S. J. (1999), 'The Marginal Costs of Greenhouse Gas Emissions', *The Energy Journal*, 20, 1, p. 61-81

<sup>23</sup> The costs of hydrogen derived from fossil fuels with the carbon being sequestered are to be added in the next draft.

<sup>24</sup> These ratios are of course sensitive to assumptions about the costs of fossil fuels. It is planned to explore these assumptions more fully in the next draft of the paper.

energy of nuclear power. It is clear that significant innovation, ‘learning’ and scale economies will be needed if the costs of moving to a low carbon economy are not to be inordinately high.

2. *Long-term costs.* The engineering estimates shown in the table suggest that costs should decline significantly over time. This assessment is supported independently by the statistical analysis of learning-curves by McDonald and Schrattenholzer (2001), cited earlier, whose estimates are summarized in Table 7.2.<sup>25</sup> Note that the primary energy technology with the highest initial cost (photovoltaics) is the one projected to have the lowest cost in the long-term.

3. *The costs of using the renewable energy alternative vary greatly between countries.* This is most obviously the case for solar energy, but it is also true (though the estimates are not provided in Table 7.1) for energy from wind and biomass and, by implication, hydrogen derived from these resources. Indeed the costs of coal and gas vary appreciably between countries.

4. *Uncertainties in the long-term costs of fossil fuels.* The sensitivity of the cost ratios to assumptions about the costs of fossil fuels is once again emphasized. Many studies assume that the costs of fossil fuels will rise with growing demand and scarcity. The above estimates and the model used in the present paper assume they will decline with resource discovery and technical progress. The sensitivity of the results to these assumptions still needs to be explored.

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<sup>25</sup> Similar estimates of learning curve co-efficients are also to be found in the review by the IEA (2001).

**Table 7.1: The average costs of renewable energy compared with fossil fuels and nuclear power: today and in prospect.**

Technology	Current cost (US c/kWh)	Projected costs as technology matures (US c/kWh)	Indicative ratio, relative to relevant fossil fuel comparator: <sup>a/</sup>	
			Today	Long-term
Biomass Energy: • Electricity • Heat • Ethanol for vehicle fuels • (c.f. petrol and diesel)	5-15 1-5 3-9 (1.5-2.2)	4-10 1-5 2-4 (1.5-2.2)	3.0	1.5
Hydrogen fuelled vehicle	To be added	To be added		
Wind Electricity • onshore • offshore	3 - 5 6 - 10	2-3 2-5	1.5 3.0	1.0 1.5
Solar Thermal Electricity (insolation of 2500kWh/m <sup>2</sup> /yr)	12-18	4-10	5.0	2.0
Geothermal Energy: • Electricity • Heat	2-10 0.5-5.0	1-8 0.5-5.0		
Marine Energy: • Tidal Barrage (e.g. the proposed Severn Barrage) • Tidal Stream • Wave	12 8-15 8-20	12 4 5-7	3.0 1.5	1.3 2.0
Grid connected photovoltaics, according to incident solar energy ('insolation'): • 1000 kWh/m <sup>2</sup> per year (e.g. UK) • 1500kWh/m <sup>2</sup> per year (e.g. southern Europe) • 2500 kWh/m <sup>2</sup> per year (tropics)	50-80 30-50 20-40	~8 ~5 ~4	8.0 4.5 3.0	1.0 0.5 0.4
Nuclear Power	4-6	3-5	1.7	1.3
Electricity Grid supplies from fossil fuels (incl. transmission and distribution): • Off-peak • Peak • Average	2-3 15-25 8-10	Declines in capital costs may be offset by rising fuel costs		
Costs of Central Grid Supplies, excl. transmission and distribution: • Generation from natural gas • Generation from coal	2-4 3-5	Ditto		
Hydrogen from Renewable Energy: • Industrial consumers • Residential consumers	9 12	6 8	18.0 4.0	12.0 3.0
Hydrogen from fossil fuels with carbon sequestration • From coal • From natural gas	To be added	To be added		
Natural gas supplies: • Industrial consumers • Domestic consumers	0.5 3.0	0.5 3.0		
Average costs of electricity with hydrogen as fuel. a. Used for combustion in central generation: • HV supplies • LV supplies b. With fuel cell for decentralized combined heat & power: • In homes • In industry	17 25 28 23	12 14 12 9	6.0 3.0 3.0 8.0	4.0 1.5 1.3 3.0

Sources: World Energy Assessment: Energy and the Challenge of Sustainability. UNDP and World Energy Council (2000) updated and extended based on data gathered for the UK government, PIU (2002), and for the recent simulation studies undertaken for the UK, DTI (2003). The costs of hydrogen production and its use for central and decentralized generation are based on the analysis of Anderson and Leach (forthcoming in Energy Policy). The above estimates are based on a discount rate of 10%.

a/ The comparators are as follows: For ethanol: petrol and diesel fuels. For wind and marine energy: combined cycle gas-fired generation. For grid connected PVs: the domestic price of electricity. For nuclear power: combined cycle gas-fired generation. For hydrogen derived from renewable energy as a fuel: natural gas. For the use of hydrogen (derived from renewable energy) as a combustion fuel for central generation, and for use in fuel cells for decentralized generation: electricity from the grid. The estimates are rounded, are based on the mid-points of ranges when ranges are available, and are intended to be indicative only.

**Table 7.2 Learning Rates for Selected Energy Technologies**

Technology (and source of estimate)	Period	Learning Rate, %
Wind:		
• OECD	1981-95	17
• US	1985-94	32
• California	1980-94	18
• Denmark	1990-94	8
Solar PV:		
• EU	1985-95	32
• World	1976-92	18
Ethanol (Brazil)	1979-95	20
Electrolytic Hydrogen from renewables (engineering studies)	--	18
Compact Florescent Lamps (US)	1992-98	16
Gas Turbine Combined Cycle Power Plants:		
• OECD	1984-94	34
• EU	n.g.	4
Gas Pipelines:		
• Onshore	1984-97	4
• Offshore	1984-97	24
Oil Extraction from the North Sea	n.g.	25
Coal for Electric Utilities	1948-69	25
Nuclear Power (OECD)	1975-93	6
Electric Power Production	1926-70	35

Source: Except for electrolytic hydrogen, which is based on Ogden's review in the 1999 *Annual Review of Energy and the Environment*, the estimates are quoted from A. McDonald and L. Schrattenholzer (2001), "Learning Rates for Energy Technologies", *Energy Policy* 29: 255-261, who give estimates for several other technologies and from other sources.

n.g = not given.

5. *The diversity of non-carbon options.* This is perhaps the most important and robust conclusion to emerge from a plethora of studies by industry, government, the IPCC and the academic community over the past decade. It is that there is an abundance of options for achieving a low carbon economy should the need arise. The list in table 7.2 is already long, but it is far from exhaustive, and does not reveal an often large number of variants within each technological grouping—in photo-conversion for example, in solar thermal technologies, and in devices for

harnessing the offshore resource. The sheer range of options that is being explored gives further ground for the believing that innovation will reduce costs further, as indicated in the table. The range and diversity of possibilities is such that it is almost impossible to “pick winners” from among them.

This last point has an implication for how the process of technology substitution is characterized in large scale economic modeling efforts. It is possible to draw up a model which represents all conceivable alternatives and to use an optimizing algorithm for choosing between them; this is broadly the approach of the IEA’s Markal model, which was used extensively in background studies for the UK Energy White Paper.<sup>26</sup> Given the range of costs and possibilities, it is necessary when using such models to embark on a large number of sensitivity exercises. However, it is impracticable to incorporate such models in the large scale macro-economic modeling exercises, which serve the different purposes of estimating the economic impact of substitution on economic growth and other economic quantities of interest. Clearly some decentralization of responsibilities is necessary. The present authors suggest characterizing the alternatives to fossil fuels under a single, non-carbon option for each economic sector—transport, electricity generation, and the gas markets—without going into detail as to precisely which of the non-carbon options is likely to emerge. Analysis of the latter can properly be delegated to a separate study using such models as Markal.

## **8. Conclusions and Next Steps**

The preceding analysis has sought to explore how threshold effects in substitution, combined with learning and scale economies in technology development, may influence the way energy systems might respond to the problems posed by climate change. It was shown that even seemingly small shifts in the level and duration of policy assumptions may lead from a situation where energy systems would continue to depend on fossil fuels for so long as fossil fuels remain abundant and the least cost resource, to one in which, after allowing for the inevitably long lags associated with the building up of a new capital stock, fossil fuels become almost wholly displaced by the non-carbon alternative. It is not surprising therefore that the more than 150 scenarios of energy futures in the peer-reviewed studies reviewed by the IPCC differ by orders of magnitude—from the world’s economies continue to remain nearly 100 percent dependent on fossil fuels over very long time periods, to becoming nearly wholly independent of them.

The difference, which in and of itself is hardly surprising, turns on policies, and of course the rate of innovation. But the influence of policy may be far larger than marginal analysis might lead us to believe. An initial impetus provided by policy is, under two conditions, capable of initiating a dynamic process of discovery, investment, a rise in market shares, further investment, innovations and reductions in costs through learning-by-doing and scale economies, further investment... and so on. The two conditions are that:

- The policy signal is sufficiently strong, given the cost parameter.
- The policy is sufficiently durable.

Otherwise, the dynamic process may spiral inwards, no matter how promising the technological alternatives might be, and lead to nothing. It was shown that a policy reversal in the early phases, after, say a 5 year experiment, or a policy signal that is too weak or tentative, is no better than no policy at all: a degree of perseverance is required for any innovation-oriented policy to succeed, as it is for innovation itself. In every sense of the term, the future is what we make it. The only

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<sup>26</sup> Department of Trade and Industry (2003).

exception is when a technological surprise is in the offing; this cannot be ruled out, of course, but to gamble on it would not seem to be a wise policy in the light of what we know of costs and technology developments so far (see Chapter 7).

The implications of such effects are that both the positive externalities of innovation and the environmental benefits of a policy are also far larger than marginal analysis might lead us to believe. Instead of being marginal, *if* the effects of a policy take root, the overall social benefits—the sum of the positive externalities of innovation, and the negative externalities of pollution that are avoided—may be out of all proportion to the strength and duration of the initial impetus.

In the presence of threshold and learning effects, the marginal cost curves for pollution abatement take on a form quite different to the rising convex form so often depicted in economic texts; similarly, given the possibility of threshold effects in the climate change damage function, the curve depicting the marginal benefits of abatement takes on quite a different form. (See chapter 6.) The upshot is that polar opposite conclusions may sometimes be drawn on the role of policy and its effects, depending on one's assessment of the scale of the threshold effects and innovation: on the one hand the optimal level of abatement may be near-zero, on the other nearly 100%. Once again, however, the difference between these extremes may be a relatively small step in policy, above all a willingness to explore options thoroughly.

The markets for energy technologies are global markets, and learning experiences are rapidly transferred internationally both through investment and through the transmission of knowledge. It follows that international co-operation through trade and investment, facilitated by international organisations, conveys appreciable positive externalities across countries. It was shown that the rate of technology development and uptake is likely to be far slower—and in some cases may grind to a halt altogether—if policies fail to recognise the opportunities of international co-operation in the area of innovation and technology development. So far, the international policy dialogue on climate change has focussed on the Kyoto Accords, the Global Environment Facility (the financing arm of the UN Framework Convention on Climate Change) and the Clean Development Mechanism. A new and promising dimension would be to put more onus on international co-operation in the area of innovation, as the UK Prime Minister himself has recognised.<sup>27</sup>

The preceding analysis is also intended to provide a framework for thinking about technological change in large-scale economic models—in particular the Cambridge model—for the analysis of the economic implications of responding to climate change. In turn, this will feed into the research on Integrated Assessment by the Tyndall Centre for Climate Change. A number of analytic findings were reported on in the text, e.g. on how to avoid the chaotic features associated with non-linear models (Chapters 2, 3 and 4) and on how to characterise non-carbon options without getting into impossible tangles when handling what is, in fact, a very large number and diverse array of non-carbon options (Chapter 7). There are already a number of ways of studying the latter in depth, e.g. by using the IEA's Markal model; but this entails sacrifices when it comes to analysing the macro-economic impact. There is a natural division of labour between the two approaches, and for the macro-economic analysis it should be sufficient to concentrate on the substitution and costs of non-carbon options in general for each of the key sectors—e.g. for transport, and the gas and electricity markets. Given the huge array non-carbon options, and the variations of costs between countries, the actual task of analysing which ones are likely to emerge, and what kinds of policy support are merited, is best left to country-level analysis using such tools as Markal.

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<sup>27</sup> See ICEPT (2002): "Assessment of Technological Options to Address Climate Change: A Report for the Prime Minister's Strategy Unit." The report is available on the websites of the Strategy Unit and ICEPT.

There is still much analytical work to be done to complete the analysis. (1) Equations to represent carbon emissions and accumulations need to be introduced (a straightforward step). (2) There is further work to be done on costs, as indicated in Chapter 7. (3) The arguments on positive externalities in Chapter 6 need to be quantified. (4) How to handle uncertainties and risk needs to be explored (a big step). Related to this, (5) we plan to look at the option value of policies in light of uncertainties and the analysis in Chapter 6.

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### Appendix 1: Parameter Values for the Base Case Run

Parameter	Base Case Value	Value for Developing Countries	Value for Industrial Countries*
<b>a</b> : substitution parameter	10		
<b>b old</b> : learning rate for old technology	0.3		
<b>b new</b> : learning rate for new technology	0.3		
<b>g*</b> : historical growth rate	0.08		
<b>Gamma</b> : energy efficiency parameter	0.005		
<b>M</b> : stable population value		8.4 billion	2.0 billion
<b>beta</b> : energy price elasticity		-0.3	-0.5
<b>alpha(0)</b> : initial per capita income elasticity		0.78	0.3
<b>k</b> : population growth rate		0.016	0.006
<b>delta</b> : retirement rate	0.03		
<b>v</b> : rate of decrease in income growth	0.01		
<b>T</b> : Carbon Tax		30% for 100 years	30% for 100 years
<b>G</b> : Innovation Subsidy		30% for 20 years	30% for 20 years
<b>Cmin (old)</b> : minimum cost of old technology	0.8		
<b>Cmin (new)</b> : minimum cost of new technology	0.8		
<b>Cnew(0)</b> : initial cost of new technology	2.0		
<b>Cold(0)</b> : initial cost of old technology	1.0		
<b>D(0)</b> : initial demand for energy		160 exajoules	240 exajoules
<b>Pop(0)</b> : initial population		4.95 billion	1.04 billion
<b>Y(0)</b> : initial income		\$3410 ppp	\$24430 ppp
<b>S(0)</b> : initial market shares in new technology	0.025		
<b>g(0)</b> : income growth rate		0.05	0.02
<b>R(0)</b> : demand met by non-carbon technologies	0.0097		
<b>I(0)</b> : initial investment	0.06		

\* The former USSR is included with the industrial countries.

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