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Energy system change and external effects in climate change mitigation

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ABSTRACT. Through a dynamic model of energy system change the paper examines the role of innovation in bringing about a low carbon energy system. The processes of innovation and technological substitution are cumulative, dynamic, and highly non-linear processes such that how the energy system evolves in the long term is extraordinarily sensitive to the strength and duration of the initial policies. It is possible, under some policy assumptions, that energy systems would continue to depend on fossil fuels for so long as fossil fuels remain abundant and the least cost resource; and under other assumptions, after allowing for the unavoidable lags associated with investment and the building up of a new capital stock, that fossil fuels would become almost wholly displaced by the non-carbon alternatives. The implication is that the external benefits of innovation, which include the creation of options and the reduction of costs arising directly from innovation itself, and the reduction of environmental damage, are far greater, perhaps by orders of magnitude, than the traditional cost–benefit models used for the analysis of climate change mitigation. The analysis suggests why a focus on discovery and innovation offers a promising way forward for national and international policies on climate change.

1. Introduction

There are by now many studies of the engineering and economic feasibility of a low carbon energy system being achieved over the present century. The possibilities are reviewed in the recent paper by Pacala and Socolow (2004), in all three of the IPCC Assessment Reports (1992, 1995, and 2001), in the Special Report on Emissions Scenarios (Nakicenovic *et al*., 2000), in the World Energy Assessment of the UNDP and World Energy Council (2000), and in numerous studies by industry, governments, and scholars.[1]

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[1] The peer-reviewed literature on the subject is very long, and is substantially covered in the reports and papers just cited.

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Scenarios of global carbon emissions from energy use in the peer-reviewed literature range from ≤ 0 to 60 gigatons per year by 2100, as compared with approximately 6 gigatons per year today, the IPCC scenarios for 2100 themselves ranging from roughly half to six times today's level.[2] Such extraordinary divergences stem from the types of the energy systems assumed for the scenarios, and on the various economic factors and policies that determine technology choice and development.[3]

Although a low carbon energy system would require, by any measure, fundamental changes in energy production and use, such changes have in fact been recurring features of energy supply and use for two centuries. Examples are the emergence of coal as a fuel for homes, industry, electricity generation, and transport in the industrial revolution; its replacement by oil as a fuel for transport in the twentieth century; and its continuing replacement by gas as a fuel for homes, industry, and electricity generation. But there are numerous other examples, almost too numerous to list, in the uses of energy for light, heat, refrigeration, and motive power. Responses to past environmental problems from energy use, by bringing about orders-of-magnitude reductions in the levels of local pollution, provide further examples.[4]

Such changes have many of the features of a threshold effect, which might be described as a cumulative dynamic process beginning with discovery and innovation, investment in demonstration activities, cost reductions, investment in applications induced by cost reductions, and further discoveries, innovations and cost reductions as experience accumulates, and so on, leading to patterns of supply and use that are fundamentally different to the initial situation. The process may take several generations to run its course, on account of the lags involved in replacing an existing capital stock, in retraining and redeploying labour, in developing the supporting infrastructure, and in improving on the original ideas and reducing costs. In many instances the effect has seemingly small beginnings, variously initiated by a discovery or an innovation in response to an external shock, a policy shift, an institutional change, an environmental concern, the shortage of resource or product, a perceived economic need, and sometimes by chance discoveries and innovations arising in laboratories and in the course of everyday economic activity.

The following analysis seeks to show how the process may be simulated using a simple non-linear model with complex dynamics, elements of which are familiar from chaos theory.[5] Such models, which have not so far been applied to the analysis of options for mitigating climate change, show that the process described is exceptionally sensitive to both the initial conditions, which include the stimulus provided by policy in the early phases, and the underlying parameters. It is possible on the one hand for innovations, even those holding much promise, to fail completely if a policy is too tentative

[2] Figure SPM-2 of Nakicenovic *et al.* (2000).
[3] UNDP/WEC World Energy Assessment (2000), and Anderson and Gross (2000).
[4] See Anderson (2001), World Bank (1992).
[5] The core equations of the model have features similar to the equation analysed by May (1976).

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or reversed too early; and on the other hand, if the process takes root, for the innovations to bring about transformations with benefits out of all proportion to the costs of providing the initial stimulus. Both possibilities are often lost in the analysis of climate change policies, which are heavily influenced by marginal analysis and assumptions of exogenous technical progress. The upshot is that the environmental and economic benefits of polices may be understated by orders-of-magnitude; and the error may be compounded by further orders if the possibilities of threshold effects in climate change are also ignored. The aim below is to show why dynamic models of energy system change offer a novel perspective on national and international environmental policies and their social and environmental impact.

Part 2 compares the underlying idea with the standard model of the economics of pollution abatement; it serves to show why the economics analysis of the long-term problems of climate change cannot be dealt with in a comparative static setting but requires a dynamic analysis. Part 3 presents an overview of energy supply options, Part 4 an aggregate model, Part 5 the results, Part 6 a comment on uncertainties and the option value of innovation policy, Part 7 a discussion of technological and regional disaggregation, and Part 8 the conclusions.

2. The external effects of mitigating climate change

The contribution of innovation raises new questions for policies at the national and international levels. For some years, there has been a tension between economists arguing for an almost exclusive focus on a carbon tax, or the alternative of a tradable permit system, and a broader body of professional opinion that has argued for incentives to support innovation directly, *as a complement* to a carbon tax or tradable permit system.[6]

The traditional economic approach assumes a continually declining marginal benefit (MB) curve for pollution abatement, and a continually rising marginal cost (MC) curve. The marginal cost curve may start from a slightly negative value, reflecting a number of commonly discussed 'win–win' options. The intersection of the two curves gives the optimal level of abatement and the optimal carbon tax (or alternatively the equilibrium price of a tradable permit if a tradable permit scheme is introduced), as illustrated in figure 1(A). Technical progress in the pollution abatement technologies is assumed to shift the marginal cost curve exogenously downwards.

The traditional approach is an oversimplification, for two reasons. First, innovation is an endogenous not an exogenous process, and the proposition that the marginal cost curve may shift downwards over time without investment in pollution abatement is misleading. As more experience is gained in pollution abatement, and the more we invest in it, the better we become at it, the greater the benefits of learning, and the greater the possibilities for reducing costs. Furthermore, as discussed later on, the

[6] See the ICEPT report in 2003 for DTI on innovation and the 2001 report by ICEPT 'Innovation and the Environment: Challenges and Policy Options for the UK'.

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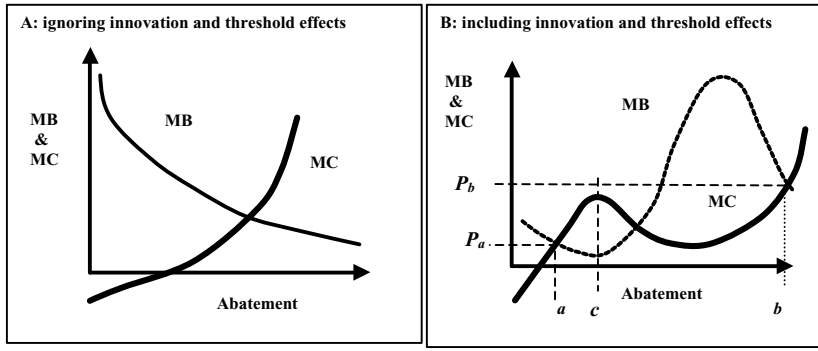


Figure 1. *Economics of pollution abatement*

effects on costs are particularly marked in the early phases of the abatement effort. It is only at very high levels of abatement that the marginal cost curves become steep. The marginal cost curve may rise sharply at first when new technologies are introduced, as we are seeing with many technologies today, peak and then decline over a long period as innovations take root and when the positive externalities are large, and finally rise steeply at high levels of abatement as diminishing returns set in. This is illustrated in figure 1(B). The MC curves of the form shown are readily computed from models such as the one discussed in Section 4 below. It is even possible, depending on the rate of innovation and the extent of changes in world oil and gas prices, for the marginal cost curve to dip below the axis.

Second, given the possibilities of environmental threshold effects associated with climate change,[7] the marginal benefit curve may have significant non-linearities, as also illustrated in figure 1B. The case for an environmental tax or tradable permit remains, but the figure suggests why an innovation policy is also needed, to progress beyond the initial cost hurdle. We now need to apply the methods of energy system modelling on the one hand, and those of integrated assessment on the other, to gain a better quantitative understanding of what is required to move from point '*a*' – the traditional economic position – to '*b*'.

The argument is more than a matter of theory. The Kyoto process has been dominated by emissions targets, where the Accords have been accepted, or by their rejection, most notably by the US and the developing countries, where they have not. Yet even in the US and in major developing countries, such as China, India and Brazil, the importance of innovation is recognized, and all OECD countries have significant policies; it these policies, more than the targets in and of themselves, that seem likely to have the most lasting influence. An international initiative focused on encouraging innovation and the adoption of new energy technologies and practices would offer

[7] See Zickfeld *et al*. (2004), Manabe and Stouffer (1993), Alley *et al*. (2002), Wood *et al*. (1999).

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new opportunities based on already significant national policies in a large number of countries.

The following analysis will concentrate on the costs of mitigation. An effort by economists to model the possibility of threshold effects in climate change is sorely needed, though to our knowledge has not yet been attempted (see the testimonies to the recent House of Lords Inquiry on the Economics of Climate Change, 2005).

3. Energy supply options

Energy supply options vary with the kind of energy demands they are meeting, e.g. with industrial and domestic heating, air conditioning, public, and private transport, electricity generation, and so forth. Most supply options can also meet several demands such as gas, coal, or biofuels for heating and electricity generation, and there is considerable scope for substitution between them.

Partly because of the ways energy statistics are compiled, energy demands, which in principle are best related to particular forms of energy use (heating, lighting etc), are usually aggregated in terms of a number of energy 'carriers', shown in table 1. This table lists the five major energy carriers in demand today, plus the possibility of hydrogen emerging as a new carrier: (1) solid fuels: an aggregate of coal and lignite; (2) oil fuels: an aggregate of heavy, middle and light distillates; (3) natural gas; (4) hydrogen; (5) electricity; (6) biomass used as a 'traditional' fuel, now almost wholly in developing countries. These six categories can be disaggregated further, but are a convenient way of analyzing the demands for energy from historical data since energy statistics are widely gathered and collated according to these classifications, with the exception of statistics on hydrogen, the use of which today is mostly confined to the oil refinery and chemical industries. In the industrial countries (6) is often not reported since the demands for such fuels are now small; in developing countries, however, traditional biomass use represents nearly one-third of their total primary energy consumption, and in energy units is appreciably greater than the oil consumed by Europe.

Supply-side options are shown in the rows of table 1, and are put under two subheadings: carbon and carbon-neutral. The striking feature of the latter is the large number of carbon-neutral substitutes for each of the six energy carriers; all are in use to varying degrees today, and have appreciable potential for further development.[8] The rows could be disaggregated further; for example by classifying marine into tidal streams and wave energy, solar technologies into photovoltaic and thermal devices, or by adding future possibilities such as hydrogen production via photo-electrolysis, and so forth. But this would only serve to strengthen the main point that the list of carbon-neutral substitutes is a long one.

[8] See Pacala and Socolow (2004) and the review of Grubb *et al*. (1993), the technology sections of the IPCC's Third Assessment Report Working Group III (2001), Anderson and Gross (2000), the PCAST reports (1997, 1999), the background studies to the UK Energy White Paper, DTI (2003), UNDP/WEC (2000).

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Table 1. *Options for meeting energy demands*

Energy technologies	*Solid fuels*	*Oil fuels*	*Gas*	*H_2*	*Electricity*	*Biomass traditonal*
Carbon fuels:						
1. Coal – clean	y	y	y	y	y	y
2. Coal – dirty	y		y		y	y
3. Oil fuels – clean		y			y	y
4. Oil fuels – dirty		y			y	y
5. Gas – central	y		y	y	y	y
6. Gas – micro CHP	y		y	y	y	
7. Gas – f-c. vehicle		y				
Carbon neutral						
8. Nuclear electricity				y	y	
9. Hydro electricity					y	
10. Biomass crops	y	y		y	y	y
11. Biomass wastes: CHP	y		y	y	y	y
12. Wind – intermittent				y	y	
13. Wind – with storage					y	
14. Solar PV – intermittent				y	y	
15. Solar PV – with storage					y	
16. Solar Thrml – intermittent				y	y	
17. Solar Thrml – w/gas					y	
18. Solar Thrml – w/storage					y	
19. Marine – intermittent				y	y	
20. Marine – with storage					y	
21. Geothermal					y	
22. Coal – with carbon sequestration						
23. Gas – with carbon sequestration						
24. Hydrogen – central	y		y	y	y	
25. Hydrogen – micro CHP	y		y	y	y	
26. Hydrogen – f-c. vehicles		y				

Possible patterns of substitution are identified by a *y* in the appropriate cells:

Electricity markets: Practically every energy source and every carrier can be used for its generation, depending on costs and availability.

Solid fuel markets: These markets can be supplied by high or low emission ('clean' or 'dirty') coal technologies, with radically differing emissions coefficients for SO_2, NO_x, and PM. Substitutes are gas, to some extent biomass depending on land requirements and supply factors, and, in the longer term, hydrogen.

Oil fuel markets: The history of vehicle emissions in the industrial countries shows that local emission coefficients differ appreciably between the 'clean' and 'dirty' technologies, and further that there are significant downward trends in emissions coefficients. Gas, either compressed or

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converted to methanol for the fuel cell vehicle, is one set of substitutes, electricity (e.g. for railways) is another, and hydrogen another.

Gas markets: Alternatives to gas itself are coal gas, biomass wastes, albeit on a limited scale, and hydrogen.

Hydrogen: This is a versatile energy carrier, which can be generated in a carbon neutral way from coal and gas (with carbon sequestration), biomass, nuclear power and any form of renewable energy, and is capable of being used for electricity generation and as a substitute in the solid, liquid, and gas fuel markets.

Traditional biomass: The big step forward for the 2 billion people depending on these sources for heating and cooking would be a shift toward fossil fuels and more sustainable ways of using biomass, followed subsequently by substitution of carbon neutral forms for fossil fuels.

A distinction is also made in the above table to allow for the possibility of storage for wind, solar and marine technologies. All three primary energy sources are intermittent and, without storage or significant reserve capacity, their use would be limited to modest shares of the electricity markets (e.g. the limit is thought to be around 25 per cent for wind); with storage, for example in the form of hydrogen, their shares would be technically unlimited.

4. An aggregate model

For each type of energy demanded there is usually a technology or 'fuel of choice' – what might be termed a 'marker' technology – against which the alternatives will have to compete. The total capital and operating costs of using this fuel per unit output will be used as a basis or *numeraire* for expressing the relative costs of the alternatives. Let P_t denote the price of the marker relative to that of the alternative. Then

$$P_t = \frac{C_t^N(1 + T_t)}{C_t(1 + G_t)}. \tag{1}$$

C_t^N and C_t denote the expected value of the present worth of the costs of new investments in the technologies per unit of output, the superscript N in the former referring to the fuel of choice. T_t represents taxes (carbon taxes say) on the former and G_t taxes on the latter (either or both may be negative if the energy sources are subsidized).

The costs of both the marker technology and its substitutes are often widely dispersed about the expected values. In electricity generation, the costs of using fossil fuels differ with site conditions, proximity to the coalfields, the quality and calorific value of the coal, whether natural gas is locally available or has to be imported via pipelines or liquefied and shipped, the location of power stations relative to load centres, and so forth. The costs of solar energy vary over a 5:1 range with region depending on the incident of solar energy and its correlation with energy demands; the costs of biomass vary with the fertility of land and the availability of wastes and agricultural and forest residues; the costs of wind vary with region and wind regimes. Even when $C_t^N/C_t \ll 1.0$ there are generally some situations where economic factors favour the alternative over the marker technology,

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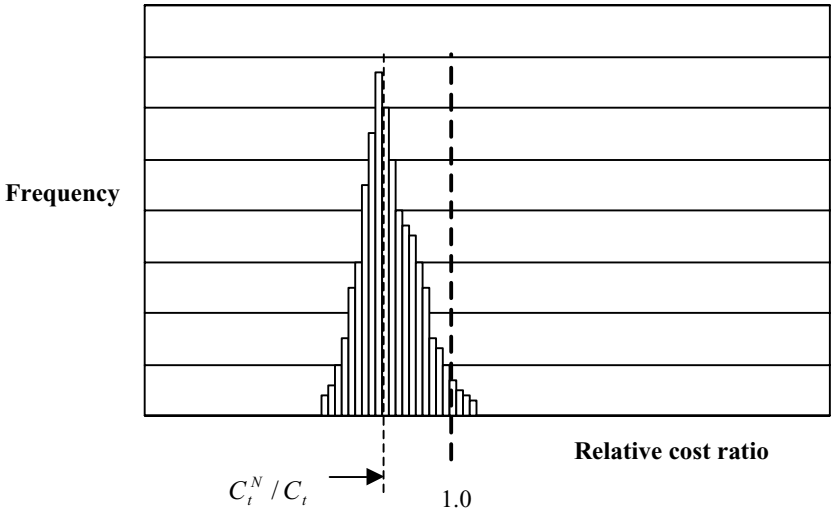


Figure 2. *Distribution of the costs of a marker technology relative to a substitute*

as depicted in figure 2. Examples are off-grid applications of renewable energy, the gasification of agricultural wastes for heat and power, and the use of solar power in regions where there is a good co-incidence between air conditioning demands and the solar peaks.[9]

The equations now discussed can be derived for a full set of energy supply options for the various energy markets, but the underlying structure and dynamics can be shown by considering an aggregate frequency distribution of the costs of the carbon neutral alternatives relative to that for fossil fuels. The distribution is wider in the aggregate model since it represents a wider range of alternatives.

The frequency distribution can be defined to represent the total market for new investment (normalized to unity), such that the area to the right of the line where $C_t^N/C_t = 1.0$ is the share, denoted by S_t, of the (new) alternative to the marker technology in investment in year t. Since market shares are determined by relative prices inclusive of taxes or net of subsidies, several factors can act to shift the distribution to the right and increase S_t: a tax on the marker technology; a subsidy for the substitute; or an innovation, scale economy, a rise in the price of oil, or any other factor acting to reduce the costs of the substitute relative to the marker. (The opposite applies if the tax or subsidy or the innovation etc favours the marker.) Hence, as the relative price ratio (P_t) rises, S_t also rises, slowly at first, then more rapidly, and finally slowly again as market saturation is approached. The effect can be represented by the logistic or 'S-curve' function often used for the analysis

[9] Grubler *et al.* (1999) present data on the standard deviations of the costs of a range of technologies, drawing on the work of Strubegger and Reitgruber (1995). They find that the variance is larger when a technology is in the earlier phases of its development and use.

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of the demand for new durable goods, with the difference that changes in S_t are expressed as a function of changes in relative prices rather than the 'passage of time'[10]

$$dS/dP = a\,S(1 - S), \tag{2a}$$

or in finite difference form

$$S_t = S_{t-1} + a\,S_{t-1}(1 - S_{t-1})(P_t - P_{t-1}). \tag{2}$$

dS/dP is a frequency distribution (S_t being the cumulative distribution) with a mean value of unity, a variance of $\frac{1}{3}(\pi/a)^2$ and fourth moment $\mu_4/\sigma^4 - 3$.[11] The variance is the sum of the variances of the costs of the marker technology and its substitutes.

Above particular values of the product $a(P_t - P_{t-1})$, equation (3) becomes chaotic. A more familiar form, which has received extensive treatment in the literature,[12] is $x_t = \beta x_{t-1}(1 - x_{t-1})$, which is chaotic for values of $\beta \geq 3.57$.[13] For the following variant of this equation $S_t = S_{t-1} + \gamma S_{t-1}(1 - S_{t-1})$, the unstable and chaotic region begins for values of $\gamma > 2.3$. This is the same as equation (3) if $\gamma = a(P_t - P_{t-1})$ and price changes are constant over time. That prices themselves change non-linearly with policies, shocks, and innovations introduces further degrees of complexity to the underlying dynamics.

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 and their changes in previous periods. 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, then boom and bust cycles may appear if investors fail to spot that the market is approaching saturation and assume instead a continuation of 'buoyant' growth – a not uncommon phenomenon. Such effects can be neutralized by shortening the time interval between $t - 1$ and t through the regular feedback of more up-to-date information.

This paper is less concerned with the problem of chaotic behaviour, however, than with another well-known feature of such relationships, which is the extraordinary sensitivity of the trajectories to the initial conditions, parameters, and the exogenous variables (which include the policy variables T_t and G_t). This sensitivity may arise whether or not the equation is chaotic. The effects may be compounded in such models if relative prices P_t vary with innovation and other factors. Consider the effects of innovation.

[10] The more familiar form for the 'S' curve is $dS/dt = a\,S(1 - S)$.

[11] Analysis of the distribution of possibilities is a practical alternative for estimating the parameter *a*. See Anderson and Winne (2004) for a further discussion. The moments of the distribution are to be found in Virtual Laboratories: http://www.ds.unifi.it/VL/VL_EN/special/special13.html and Compendium of Common Probability Distributions: www.causascientia.org/math_stat/Dists/Compendium.pdf

[12] R.M. May (1976).

[13] Ibid, p. 154.

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In studies of innovation, a relationship that is widely fitted to cost data is the 'learning curve'.[14] It has the form $C_t = C_0(X_t/X_0)^{-b}$, where X_t the cumulative investment (taken as a measure of experience) in the technology by time t from the time of its first introduction and b is a parameter. The term 'the learning rate' (given by $1–2^{-b}$) is often used in conjunction with this expression, and refers to the per unit decline in costs with each doubling of cumulative investment. Estimates of this quantity for non-carbon technologies range from 0.06 for nuclear power, to 0.08–0.32 for wind energy, and 0.18–0.32 for photovoltaics; for oil and gas, estimates vary over the range 0.1–0.3. While the effects of learning are apparent in all energy technologies, whether new or mature, they are especially significant in the early phases of development when experience accumulates most rapidly; for example a technology with a 20 per cent learning rate can experience a four-fifths drop in unit costs if its market share in the total market rises from ≈ 0.1 per cent to 10 per cent, whereas it will experience only a one-fifth drop if its market share doubles, say, from 20 per cent to 40 per cent. A finite difference form of the learning curve equation is

$$C_t = C_{t-1} - b(C_{t-1} - C_{\min})(X_t - X_{t-1})/X_{t-1}, \tag{3}$$

where $C_{\min}$ is the estimated minimum value of the possible costs of a technology. A parallel equation applies to the marker technology

$$C_t^N = C_{t-1}^N - b\left(C_{t-1}^N - C_{\min}^N\right)\left(X_t^N - X_{t-1}^N\right)/X_{t-1}^N. \tag{4}$$

To sum up so far, there are four equations to determine the following:

- market shares between the competing technologies, based on relative prices (equation (2));
- relative prices, derived from relative costs adjusted for taxes and subsidies (equation (1));
- the cost of the substitute technology, based on cumulative investment (a learning-by-doing effect – equation (3));
- the cost of the marker technology, also based on cumulative investment (since learning-by-doing is not confined to the substitute technology – equation (4)).

To complete the model, equations are needed to estimate the aggregate energy demand (function of energy prices), aggregate annual investment (equals the change in energy demand plus replacement of retired investments), the cumulative investments in each technology (function of past investment and shares in new investment), and equations to represent carbon emissions and accumulations.

For energy demand, a form commonly found in the economic literature is

$$\frac{D_t}{D_0} = \left(\frac{Y_t}{Y_0}\right)^{\alpha}\left(\frac{Pe_t}{Pe_0}\right)^{\beta}\left(\frac{N_t}{N_0}\right)e^{-\gamma t}, \tag{5}$$

where Y_t denotes per capita income in purchasing power parity prices (here, an exogenous variable), N_t population (also exogenous), Pe_t the price

[14] McDonald and Schrattenholzer (2001) provide estimates for several technologies.

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of energy (a weighted average of the price of the marker and substitute technologies), α per capita income elasticity, β energy price elasticity, and γ the rate of technical progress in energy efficiency.

Turning to investment, opportunities stem directly from the growth of demand and the retirement of old assets

$$I_t = (D_t - D_{t-1}) + \delta D_{t-1}, \tag{6}$$

where δ denotes the retirement rate of assets that have come to the end of their economic lifetime. Cumulative gross investment is given by the recursive relations

$$X_t = X_{t-1} + S_{t-1} I_{t-1}. \tag{7}$$

For the marker technology

$$X_t^N = X_{t-1}^N + (1 - S_{t-1}) I_{t-1}. \tag{8}$$

Carbon emissions and accumulations stem from investments in use. Let U_t^N be the net capital stock or cumulative net investment for the marker technology, θ_t the emissions coefficient, E_t emissions, A_t net accumulations, and r_t the net rate of absorption of carbon accumulations by the environment, then

$$U_t^N = (1 - \delta) U_{t-1}^N + (1 - S_{t-1}) I_{t-1}, \tag{9}$$

$$E_t = \theta_t U_t^N, \tag{10}$$

$$A_t = A_{t-1}(1 - r_t) + E_{t-1}. \tag{11}$$

These 11 equations provide a non-linear dynamic model of an energy system in transition. To recapitulate:

1. The costs of both the marker technology and its substitutes have broad frequency distributions, which imply that, even when the average costs of the substitutes are far greater than those of the marker, there will generally be *some* applications where the substitutes are economically preferable.
2. Tax incentives or regulations in favour of the substitute (equation (1)), a further innovation or perhaps an external shock that increases the price of the marker technology may shift the frequency distribution to the right and increase the size of the market for the substitute (figure 2 and equation (2)). If alternatively the incentives, regulations, or the direction of innovation favour the marker, the opposite will happen, and even 'niche markets' will decline. In the former situation, new investment opportunities in turn create opportunities for further discovery and innovation, and also for scale economies, such that costs may decline further relative to the marker (equations (3) and (4)) giving rise to further investment, and so on.
3. However, investment opportunities crucially depend on either or both of two factors: a growing market and the retirement of old assets (equations (5)–(8)). A slow growth of demand or an extension of the lifetimes of assets in place – a policy often advocated, not surprisingly, by the incumbent industries – may, by stifling opportunities for new

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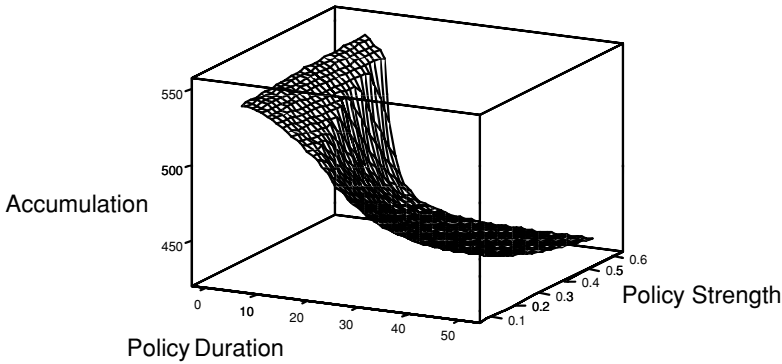


Figure 3. *Effects of the strength and duration of a policy on CO_2 accumulations (ppm) by 2050*

investment, reduce opportunities for innovation and cost reductions in the substitutes. High demand growth rates in contrast are a stimulus for innovation and cost reductions.

5. Results

The results are exceedingly sensitive to costs and prices, and thus to policies, for instance to:

- environmental and other taxes on or subsidies for fossil fuels;
- external factors affecting the prices of fossil fuels;
- taxes or subsidies for the substitutes;
- the duration, as well as the 'strength' of the policy to encourage the substitutes.

The transition from a hydrocarbon energy system to a carbon neutral one may occur within three or four generations even with weak policies if the possibilities for innovation are extensive enough, but would clearly require a more determined effort if the costs of the substitutes were persistently high relative to those of fossil fuels.

Figure 3 shows the effects of alternative assumptions about the strength and duration of a policy on CO_2 accumulations; the strength is measured by percentage effect of the taxes and subsidies on the average price of fossil fuels relative to their substitutes, and duration by the period over which the policies are applied. The parameters are summarized in the Appendix.

At critical points, the contours are very steep in both figures, and a willingness to persist with a policy seems to be as important as its strength. It is possible for policies to have no significant effect if they are too weak or are reversed too soon and conversely to have the precipitous effects shown in the figures with a more persistent effort. There is an initial region, corresponding to the incentives being low or applied over too short a period, where the changes in supply structure and carbon accumulations are negligible. For the parameters underlying these calculations, an effort over at least a generation would seem to be crucial. If, however, there were

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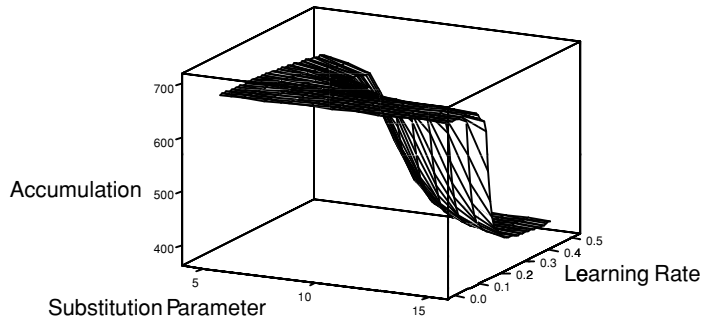


Figure 4. *Effects of the substitution parameter and learning rate on the accumulation of CO_2 (ppm) by 2100*

a willingness to persevere with a policy and the process of innovation and substitution took root, the effects would be far-reaching, giving rise to a fundamental transformation of the energy system and a correspondingly rapid falling off of carbon accumulations.[15]

The results are also very sensitive to the parameters and initial conditions, for instance to:

- the initial costs and market shares, including markets supported by demonstration projects;
- the asymptotic value of the cost parameters ($C_{\min}$)
- the substitution parameter a;
- the learning rates for both the marker and substitute technologies;
- the retirement rates of assets in place and the rate of growth of demand.

The effects of two of the parameters – the substitution parameter and the learning rate for the substitute technology – on long-term carbon accumulations are shown in figure 4. Again, the contours are extremely steep and the threshold effect is clear.

There is a region in the parameter space where policies may have little or no effect. However, an increase in either or both of the strength or duration of the policies shifts the curves toward the origin. If, for instance, the learning rate for the substitute technology relative to that of the marker technology is greater, then a weaker policy will have the desired effect; indeed, when a high learning rate is combined with convincing evidence that the substitutes will be cheaper in the long term ($C_{\min} < C^{N}_{\min}$), no policy may be needed at all. Conversely, if ($C_{\min} > C^{N}_{\min}$) a policy such as a carbon tax might need to be permanently in place. Policies need both to be tailored to the situation and (given that parameters are inevitably uncertain) to evolve as experience is gained.

[15] A similar conclusion as to the importance of perseverance is reached by Hasselman *et al*. (2003). Nor would the effects be likely to be disruptive to economic growth, see the survey by Anderson and Leach (2005) and the study by Azar and Schneider (2002).

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6. Threshold effects, uncertainties, and environmental policy[16]

The possibility of threshold effects or 'tipping points' in technological innovation raises a number of issues for policy, particularly (but not only) when coupled with the possibility of threshold effects in climate change itself as indicated in figure 1. Uncertainties in both the marginal cost and benefit functions add further complications. It is beyond the scope of the present paper to do justice to them, but some points can be made by reference to the preceding analysis and recent studies.

First, consider the differences in carbon accumulations between before and after the threshold effects in technology development, shown in figures 3 (for 2050) and 4 (for 2100). *Without* policies, the accumulations of CO_2 are 550 ppm by 2050 and 700 ppm by 2100. (As these estimates exclude other greenhouse gases, they underestimate accumulations on a CO_2-equivalent basis.) *With* policies of sufficient strength and duration, in contrast, the CO_2 accumulations stabilize at 450 ppm. As the latter corresponds to emissions from energy production and use falling to very low (near zero) levels, as compared with 6 gigatons of carbon per year today, rising to 2–3 times this level in the absence of abatement, there is an order-of-magnitude reduction in annual emissions.

According to the most recent estimates surveyed by the Stern Report on the *Economics of Climate Change* (2006) such levels of abatement may be just sufficient to avoid the most damaging effects of climate change. The latter are probably 'equivalent to [an irreversible] reduction in consumption per head of somewhere between 5 and 20 per cent of world product' and most likely in the 'upper part of this range'[17] on account of the likelihood of a series of much-discussed threshold effects (loss of the glaciers in Asia, thawing of the Greenland ice cap, shifts in the Gulf Stream, positive feedback from the thawing of the permafrost, and several others).

The costs of abatement need more analysis than is provided above, since the preceding cost calculations focus on the relative rather than the absolute costs of using fossil fuels and their low carbon substitutes. In addition, it is necessary to consider the probability distributions of costs, since the costs of low carbon technologies have an uncertainty range of greater than $\pm$ 30 per cent, while those of oil and gas for instance are even greater (oil prices alone have fluctuated over a range of $20–80/barrel in recent years). In a separate analysis for the Stern Review, the average costs of carbon abatement corresponding to the 'with policies' case fall within the range of costs shown in figure 5; the high end of the cost range broadly corresponds to low rates of innovation and low oil and gas prices, the low end to high rates of innovation and high oil and gas prices. Under more buoyant assumptions on innovation (the lower dashed curve) and/or high oil and gas prices, the incentives for carbon abatement could be removed within the next 30 years or so; under less buoyant assumptions and low carbon emissions a permanent carbon pricing incentive would need to be left in place.

What the Stern Review has shown is that when we multiply such estimates as are provided in figure 5, the costs vary between $-1/5$th to

[16] We thank a referee for pinning us down with rather searching questions on the costs of pollution abatement.

[17] Executive Summary, figure 3 and text.

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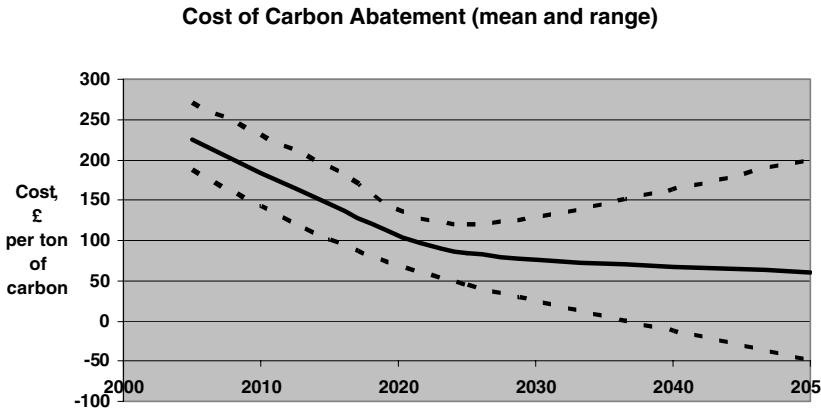


Figure 5. *The costs of carbon abatement of moving to low carbon emissions and accumulations targets*
Source: Anderson (2006).

+1/10th of the costs of climate change. What we have tried to show in the preceding analysis is that the 'technology-tipping point' for moving towards a low carbon trajectory turns on the effects of innovation (and the policies that bear on it), the relative costs and thus the uptake of the low carbon options.

Uncertainties add a further layer of complication. In a deterministic world, a carbon price set at P_b in figure 1 would be sufficient to induce the required investment to move beyond the tipping point at *c*. When uncertainties are large however, the critical price (at or above *c*) is not known accurately, as can be inferred from the range of cost estimates shown in figure 5 above; the required cumulative investment to reach point *c* is also uncertain; and the long time horizon (possibly 50 years or more) before point *b* will also raise questions in industry as to the durability of a carbon pricing policy at such a level. Such uncertainties further argue for an innovation policy to widen and reduce the costs of the options available.[18] It rests on three premises:

(i) The option value of avoiding irreversible consequences of investing is greater than the option value of delaying policies. Option theory[19] tells us that, if the costs and returns to an irreversible investment are uncertain, there is a value to delaying investment until information becomes available that would reduce the uncertainties. Conversely, if the consequences of *not* investing are also irreversible and uncertain, there is a value to bringing investments forward. In terms of uncertainty, the textbook case (Dixit and Pindyck, 1994) for advancing or delaying an investment rests on the net outcome of these opposite effects.

[18] For an excellent discussion, see chapter 16 of the Stern Report, prepared by Chris Taylor.
[19] Dixit and Pindyck (1994).

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(ii) The option value of investments that create options and reduce costs. As Dixit and Pindyck also show however, there can be a further effect to consider, which is that if investment is required to reduce uncertainties as to the costs and returns to an investment, then there is an option value for bringing investments forward based on the value of the experience gained. This is explored by Papathanasiou and Anderson (2001) and more fully by Papathanasiou (2004) in his Ph.D. thesis. Our capacity to address the climate change problem will not be developed without investment to discover, demonstrate, and develop alternative technologies, and the option value of such an investment, as Papathanasiou has shown, can be appreciable.

(iii) The external benefits of reducing costs. Investments in the early phases of pollution abatement have two benefits, not one. The first is their direct contribution to pollution abatement. However, with learning-by-doing each investment contributes to the lowering of costs of future investments, a positive externality identified by Arrow (1962); the magnitude of the externality is the contribution of the investment to the reduction of future costs times the present value of the prospective volume of use. For the estimates shown in figure 5 for example, the costs of pollution abatement over the period 2050 decline as a result of innovation by nearly £200/ton of carbon on average; since we may be looking for carbon abatement levels of perhaps 10 gigatons of abatement per year by then, it is evident that the benefits of innovation are likely to be enormous.

Taken together these points support the case for a climate change policy that would combine carbon pricing with direct support for innovation: the former based on the reduction of negative externalities of pollution; the latter on the positive externalities and the option value of investments in innovation. These results do not directly follow from the preceding model (as a referee rightly observed), but the possibilities of technological tipping points do imply that both the option value and the positive externalities can be appreciable, and far greater than traditional cost–benefit analysis suggests.

7. Regional and technological disaggregation

The equations for the multi-technology, multi-demand case in table 1 have been set out elsewhere, and trial runs have also been made for the case with regional disaggregation.[20] The equation structure remains the same as for equations (1) to (12) above, with the following differences: (a) The demand equations for the output of each technology are defined by the interconnections shown in table 1. (b) The equations for cumulative investment in a technology, which are used to estimate the effects of innovation on costs via equations such as (3) and (4), are now aggregated over all applications and markets. (c) Restrictions on the use of certain energy sources are needed in some cases, for example those arising from the land available for biomass production, the availability of biomass wastes,

[20] Anderson and Winne (2004). The approach has been applied in the large macroeconomic model developed by our colleagues Barker and Koehler. For an earlier version of this model see Barker (1998).

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or the amount of intermittent energy that can be permitted on an electricity grid in the absence of storage technologies. There is still much analysis to be done using more disaggregated models, the details of which will have to be left for a separate paper. But three results are worth highlighting:

(a) Increasing the number of technological options increases the likelihood of a transition to a low carbon economy. However, which ones are likely to become the 'the technologies of choice' is almost impossible to predict, since results change kaleidoscopically with input assumptions on costs, initial market shares, the price assumptions on marker technologies (not least oil and gas prices), and so forth. This argues for policies that support a broad portfolio of possibilities.
(b) The gains from international co-operation, for instance through openness to trade, foreign investment, and technology development, are likely to be immense. High growth energy markets in some regions, for example in developing regions such as East Asia, may offer opportunities for investment, scale economies, and innovation that may be fewer in the more 'mature' energy markets in other regions. Involving developing countries in the development and use of new energy technologies would generate positive externalities for the industrial and the developing countries alike.
(c) Additional economies arise from the aggregation of demands across sectors: hydrogen production for example benefits from the synergies arising from its use in several markets – for heat, gas, transport fuels, and electricity.
(d) When the limits of one technology are reached, for example of biomass or of intermittent renewable energy, there is a shift to alternatives – e.g. for storage technologies and/or hydrogen – to overcome the constraints. This raises costs initially, but once again there is a long-run tendency for costs to decline with innovation and scale economies.

8. Conclusions

The above analysis has sought to explore how 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 policies 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 unavoidable 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 continuing to remain nearly 100 per cent dependent on fossil fuels over very long time periods, to becoming nearly wholly independent of them.

The difference turns on the influence of policies on the rate of innovation and the uptake of carbon-neutral alternatives. But the influence of policy, and its external benefits, may be far larger than marginal analysis might lead us to believe, and it is also possible that the option value of policies to support innovation would be greatly amplified by the existence of tipping

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points or threshold effects in technological innovation. 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 avoided – may be out of all proportion to the strength and duration of the initial impetus. There are two conditions:

- that the policy signal is sufficiently strong.
- that the policy is sufficiently durable.

Otherwise, and depending on the underlying parameters, 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, 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. The only 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, not to mention the hardening of evidence on climate change.

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Appendix: Parameters and a note on units

Parameter	*Value*	*Varied Parameter Run*	*Varied Policy Run*
Substitution parameter (a)		5–15	10
Learning rate for new technology (b)		0.05–0.50	0.3
Policy Strength		30%	10–60%
Policy Duration		20 years	5–50 years
Retirement rate of old technology (δ)	0.03		
Minimum cost of new technology ($C^N_{\min}$)*	2.5		
Initial cost of new technology (C^N_0)*	6.0		
Initial cost of old technology (C_0)*	3.0		
Energy efficiency parameter (γ)	0.005		
Energy price elasticity (β)	−0.2		
Initial per capita income elasticity (α)	0.3		
Initial world population (N_0)	6.3 billion		
Initial per capita income (Y_0)	$8200 ppp		
Initial demand for energy (D_0)	370 exajoules		
Initial demand met by non-carbon tech.	1% of Initial Demand		
Initial working capital stock in place for new tech.	1% of Initial Demand		
Initial working capital stock in place for old tech.	99% Initial Demand		
Initial market shares in new investment (S_0)	0.025		
Initial gross investment, in energy units (X_0)	6% of Initial Demand		
Emissions in 2000 (E_{2000})	6 gigatons		
Accumulation of CO_2 in 2000 (A_{2000})	368 ppm		
Coefficient for converting exajoules to gigatons	0.016 GT/EJ		
Coefficient for converting gigatons to ppm	0.6 ppm/GT		

Note: *Note that it is the relative costs of the technologies that is important such that we can also think of the initial costs of the old technology being 1.0, those of the new being 2.0 and the minimum costs to which the latter can decline being 2.5/6 = 42% of their initial cost. See section 6 for a further discussion of absolute costs.

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