15 Energy–economy–environment modelling: a survey

Claudia Kemfert and Truong Truong

1 Introduction

Concern about fossil-fuel resource depletion in the early 1970s has led to the development of theoretical and applied economic models of energy–economy linkages with a detailed representation of the energy market. Pioneering energy–economy modelling efforts focused primarily on the representation of scarce resources such as oil and its impact on world economies. More recently, not only the scarcity of energy resources, but also other natural resources in the environment played a major role in economic modelling. The complexity of models has increased considerably, especially in areas relating to global environmental issues such as acid rain, ozone depletion and climate change. Take the issue of climate change as an example. Here, it is generally agreed (or assumed) that one of the important cause of this likely phenomenon is anthropogenic greenhouse gas (GHG) emissions which originate mainly from fossil-fuel consumption. To prevent or mitigate against this likely event, integrated energy–environmental strategies and policies are required which need to take into account the complex interactions between climate, ecological and economic systems. Such integrated policies and strategies are often studied within the framework of the so-called integrated assessment modelling (IAM) approach.[1] Existing literature on IAM focuses mainly on a comparison of modelling results.[2] The aim of this chapter is to provide an overview of the theoretical backgrounds, the methodologies and model designs. Section 2 explains the theories and general methodologies of different models, and Section 3 looks at applied models. Section 4 considers some specific issues such as energy substitutability and the role of energy and environment resources in economic models, as well as providing a brief survey of existing major energy–economy–environment models, and Section 5 concludes.

2 Economic Theories

Economists usually distinguish between two major economic theories: *neoclassical* and *neo-Keynesian*. Neoclassical economic theory covers the microeconomic decisions of individuals and investigates the distribution and allocation of scarce resources towards alternative objectives under the assumption of fixed resource constraints and market clearance. Consumers maximise their utilities subject to budget constraints and firms maximise their profits under costs constraints. At equilibrium, the marginal utilities of consumption or marginal products of factors are equal to their relative prices. Substitution processes are induced by changes in relative prices. Clearance in all markets is reached by the adjustment of market prices. This is the theory of general equilibrium where the primary focus is on the microeconomic allocation of scarce resources among alternative uses so as to maximise social welfare. There are generally four different markets in which the theory seeks to explain their equilibrium positions: goods market, labour market, capital market and money market. In the labour market, it is assumed that both labour supply and demand are influenced by real wages. Full employment is then reached when the real wage adjusts so as to balance supply and demand. The capital market is governed by investment decisions of firms, and savings decisions of households. The capital market clears when the rate of interest – which influences investment and savings decisions of firms and households – adjusts so as to balance supply (savings) and demand (investment). Finally, equilibrium in the money market is also achieved via the adjustment of the market rate of interest which influences money demand, and given a particular level of money supply which is often assumed to be determined exogenously by the monetary authority. General equilibrium is then defined as the situation when all markets clear. Without government intervention, general equilibrium can be achieved if we assume the working of the so-called 'invisible hands of the markets'. In contrast, in neo-Keynesian theory, it is believed that general market equilibrium cannot always be achieved because of the 'inflexibility' or 'stickiness' of money wages (in the downward direction) in the labour market. This also makes real wages inflexible, and labour demand, therefore, cannot always adjust to the level of labour supply. Unemployment (dis-equilibrium) therefore can exist in the labour market. To represent this dis-equilibrium situation in a 'general equilibrium' model, a 'slack' variable is introduced, which takes on a non-zero value whenever there exists such a dis-equilibrium gap between supply and demand.

Most general equilibrium models are based on neoclassical theory. In some cases, however, elements of neo-Keynesian theory can also be introduced into a general equilibrium model via the use of 'slack' variables as mentioned above. Robinson (2006) describes the mixture of theories used in computable general equilibrium (CGE) models under three headings: (i) the Fundamentalist school, (ii) the Bahá'i school, and (iii) the Ecumenical school. Under the Fundamentalist school, strict neoclassical (or Walrasian) economic theory applies, this means that equilibrium is assumed for the goods, labour, and capital markets. The money market is often not specified in a Walrasian model, which is concerned only with physical flows and relative prices. To determine the money market equilibrium and the absolute level of prices, one has to resort to a separate macroeconomic model. This macroeconomic model specifies the money market variables and their relation to other macroeconomic variables such as aggregate consumption, investment, savings, government spending and taxation. There is the issue of how to relate the levels of these macroeconomic variables to the levels of the microeconomic variables specified in the Walrasian model. Under the Fundamentalist school, this issue does not seem to be addressed. Under the Bahá'i school, the issue is avoided to some extent by the insertion of certain elements of the Keynesian (or other types of) macroeconomic model directly into the Walrasian equilibrium model itself. This, however, decreases the transparency or purity of the Walrasian model. Finally, under the Ecumenical school, where the maxim is 'Render unto Walras the things which are Walras, and unto Keynes the things which are Keynes', a (neoclassical) CGE model can be kept separate and distinct from a Keynesian (or other types of) macroeconomic financial model. An attempt is then made to 'link' the two models together, for example, by allowing for some variables to be specified as exogenous in one model but endogenous in the other (see, for example, Powell 1981; Tyson and Robinson 1983). According to Robinson, in the past decade, the influence of the Fundamentalist school has declined, while that of the Bahá'i school and the Ecumenical school has grown.

General equilibrium models are often static or only 'recursively' dynamic (static results of one time period are fed into the database of the next time period while the behaviours of individual decision makers remain 'myopic'). Intertemporal or truly dynamic general equilibrium models are built only for small models with a limited number of sectors, regions, and/or time periods because of the extra computational burden associated with intertemporal decision. Typically, CGE models assume an infinitely lived consumer (or social planner) who optimises an intertemporal utility (or social welfare) function subject to some resource constraints (such as population growth, energy supply), and under conditions of certainty, competitive markets, and constant returns to scale in production (for example, Ramsey infinite-horizon optimisation model). The model often employs an aggregate production function that includes only a few inputs such as labour, capital and perhaps a natural resource input such as energy. In contrast, there are overlapping generation (OLG) models that allow for different consumers of different generations who have finite lifetimes (see, for example, Stephan et al. 1997; Howarth 1998; Gerlagh and van der Zwaan 2001). Different generations in different time periods can then trade with each other. The results of OLG models do not often coincide with those of the Ramsey models, which also means that Pareto optimality (which is achievable in a Ramsey model) may not necessarily be achieved in an OLG model.

3 Applied Models

Applied models can be classified according to the purpose for which they are constructed. For example, there is a distinction between *forecasting* and *evaluation* (or *simulation*) models. Forecasting models are often built around econometric studies that use historical data and are employed to extrapolate historical trends into the future. Simulation models, on the other hand, are used to address the 'what if' policy question. To do this, a 'business as usual' or reference scenario is first constructed with certain assumptions about major economic variables such as population growth, physical resources growth, substitution elasticities, and rates of technical progress. Next, a particular policy scenario is constructed which allows for certain key economic variables to be varied. The results from both the policy and the reference scenarios are then compared which will help to shed light on the effects of the changes in the key economic variables.

Applied models can also be classified according the geographic or time scale of analysis. For example, global models are those that include information on many regions or nations and used to analyse the economic relations or reactions among them at a highly aggregate level. Regional models focus primarily on a specific region such as Europe or Asia, while national models look at economic relations within particular countries. Many applied models concentrate the analysis on one or only a few sectors within an economy, while others cover many sectors. Single-sector models (or models with a few sectors) are used to analyse macroeconomic issues such as optimal growth or optimal resource extraction while multi-sector models are used for the analysis of microeconomic issues such as structural change or distributional impacts of trade and tax reforms. On the time scale, global climate impact models often cover a long time horizon (at least 50 years), while other economic structural change models cover a medium term of 5 to 10 years. Short-term impact or forecasting models cover a period of 1 to 5 years.

Finally, applied models are also classified according to the level of aggregation and the theoretical approaches being used. For example, 'top-down' models look at the aggregate energy–economy–environmental linkages from the perspective of at the national, regional, or global economy as a whole. In contrast, 'bottom-up' models look at the issues from the perspective of a specific sector (such as transport, or electricity generation) and contain more details on various activities or technologies being used in this sector than top-down models. Bottom-up models often use the mathematical techniques of linear or nonlinear programming for their analysis, whereas top-down models often employ a highly aggregate production function approach. Different approaches or methods of analysis can lead to quite different results (Hourcade et al. 1996). For example, in relation to the issue of energy efficiency and substitution, top-down models tend to produce results which are less optimistic than those from bottom-up models. This can be partly explained by the fact that top-down models often include *general* equilibrium feedbacks (which implies that indirect costs are taken into account) whereas bottom-up models do not (Grubb et al. 1993). The 'partial equilibrium' nature of bottom-up models also constitutes one of their inherent weaknesses, and therefore, to overcome this, bottom-up models are often linked to a top-down model in so-called 'hybrid' approaches. One technique for linking the two types of model is to allow for certain variables to be defined as exogenous in one model but then endogenously determined within the other. The passing of information from one model to the other can be carried out either sequentially and iteratively until some criteria of 'convergence' is achieved within both models (this is called a 'soft link'), or simultaneously – perhaps by 'embedding' the bottom-up model within the top-down model itself (see, for example, Böhringer and Löschel 2006) (which is called a 'hard link'). The hard-link approach has the advantage of guaranteeing full consistency between the results of both models, but it also presents greater difficulty in terms of theory development as well as computational techniques. Hence the technique is not very often employed, especially when the models are large. In practice, modellers are content with just some 'soft links', or even using the results of one model (bottom up) to generate information that is then used to estimate certain key parameters (such as the elasticities of substitution) which will be employed in the other (top-down) model.

Depending on the type of model being constructed, the data used are also different. Forecasting models often employ time-series data, whereas impact studies models use input–output data with parameters (such as elasticities of substitution) estimated from either cross-sectional and/or time-series data. Data reliability and consistency is an important issue for large-scale models. For example, with global economic models requiring data (input–output, trade data) coming from different countries, there is a need to harmonise and reconcile these different databases into a consistent set (see, for example, Hertel 1999). Increasingly, energy–economy–environment modelling also requires the compilation of 'physical flows' information (such as energy usage and emissions data in physical units) in parallel with traditional economic (value flow) data (such as input–output or national account data). The harmonisation and reconciliation of physical (material-balanced) data with economic (value-balanced) data presents a more difficult challenge, conceptually as well as empirically, than does the harmonisation and reconciliation of different databases from different regions but of the same type, that is, either physical, or economic, data.

4 The Role of Energy and the Environment in Economic Models

Traditional energy–economy linkage approach

Mainstream neoclassical economics looks at energy and the environment as 'inputs' into consumption or production activities. Energy is an input produced from natural resources (such as fossil fuels), and the environment is also considered as an 'input' in the sense that it can act as a 'sink' for production activity wastes. The limited supply and non-renewable nature of some of the energy resources can put a limit on the capacity of the economy to sustain growth in the long term. The natural environment also has a limited capacity to absorb 'wastes' from economic activities and therefore this can act as a constraint on long-term sustainable economic growth. One of the objectives of energy–economy–environment modelling is to find out the limits (if any) to economic growth in the long term, stemming from limited energy and environmental resources.

Consider the following aggregate production function typically used in a neoclassical top-down model:

$$X = f(K, L, M, E, N); \tag{15.1}$$

where X is gross output, K is capital, L is labour, M is non-energy intermediate inputs ('materials'), E indicates fuel or energy inputs, and N is the environment input. In most cases E is an aggregate of various fossil and non-fossil fuels. A typical top-down model may also consist of many sectors with each being represented by a production function of the type described by (15.1). For simplicity, we assume here that there is only one sector; hence X can be considered as the gross national output of the economy. To simplify the production function (15.1) further in order to concentrate on the critical issues, we assume that capital, labour, and non-energy material inputs can be combined into a single aggregate factor so that (15.1) is simplified into:

$$X = f(K, E, N; A), \tag{15.2}$$

where K stands for the composite capital–labour–material input, and A is the technological change parameter.

Assume that output X is used for consumption and also for investment. Consumption generates welfare whereas investment is used to add to the stock of human-made capital K (investment for growth) and/or to 'induce' technological change (a change to the parameter A). For simplicity, we consider here only investment for growth,[3] that is,

$$\dot{K}(t) = X(t) - C(t). \tag{15.3}$$

Here, $C(t)$ is consumption, and a dot $(\cdot)$ over a variable denotes the rate of change over time, that is, $\dot{K}(t) = dK/dt$. Constraint on resource extraction is described by the following equations:

$$\dot{R}(t) = -E(t), R(0) = R_0;\ R(t) \geq 0, \tag{15.4}$$

with R being the energy resource stock, which is non-renewable and in fixed supply of R_0 at time $t = 0$. The rate of extraction of the energy resource, that is, $-\dot{R}(t)$, is determined by the rate of energy usage in production activities, that is, $E(t)$.

In the 'traditional' energy–economy (E^2) linkage approach, the environment variable N is not considered explicitly, or equivalently; it is assumed to be a 'free' resource, that is, one with zero cost, hence its presence in the production function (15.2) can in fact be ignored. The objective of the economy then is simply to maximise the following intertemporal welfare function:

$$W = \int_0^\infty \left[\frac{1}{1 - 1/\sigma} C(t)^{1-1/\sigma}\right] e^{-\rho t} dt, \tag{15.5}$$

subject to the production function (15.2) and the constraints (15.3)–(15.4). The parameter σ in equation (15.5) stands for the inter-temporal elasticity of utility substitution, and ρ is the discount rate. In this standard approach, the focus of attention is on the division of output X between consumption and investment activities so as to maximise welfare W. The main issue here is the optimal rate of (energy) resource depletion, to sustain economic growth and consumption in the long term. It turns out that one of the crucial parameters that will determine the answer to this question of sustainable growth for the economy is the elasticity of substitution between K and E. If this substitution elasticity is greater than or equal to one, then sustainable economic growth and consumption is achievable even if the energy resource is in fixed supply. This can be explained as follows: if human-made capital K can be made to replace the use of natural resource E and the process can continue without limit and also without diminishing returns, then so long as part of the current production output is put aside to build up the capital stock K, this can then be used in the future to 'substitute' for part of the natural energy resource stock which is now being depleted. Future economic growth and consumption therefore can be sustained even if the supply of energy resource is limited. When the substitution elasticity is less than one, this implies that there are diminishing returns in the process of substitution of human-made capital K for natural resource E. In this case, sustainable economic growth may still be achievable if technological progress can be made to 'compensate' for the effect of diminishing returns. If, however, both the elasticity of K–E substitution is less than one (diminishing returns) and technological progress is not sufficient to compensate for this effect, then long-term economic growth and consumption will not be sustainable due to the limited supply of E.

Empirical estimation of the *K–E* substitution elasticity

Empirical evidence on the value of the K–E substitution elasticity has been rather mixed (Berndt and Wood 1979; Apostolakis 1990). Estimated values of this parameter have tended to depend not only on the level of aggregation, but also on the type of data used and the specification of the empirical production function. First, on the issue of aggregation, it is now recognised that the estimated value of the K–E substitution elasticity can be highly dependent on the level of aggregation used (for example, whether we look at sectoral or national data). This is partly explained by the fact that the potential for energy substitution is less at the aggregate level of the national economy than at the microeconomic level of a household or a sector. At the microeconomic level, estimation of the potential for energy savings and substitution often does not take into account the 'indirect costs'. For example, home insulation at the household level may directly substitute for heating fuel, but this also involves some indirect (energy) costs (associated with the manufacturing of the insulation materials themselves). These indirect costs are taken into account only at the aggregate national economy level (Stern 1997; Stern and Cleveland 2004). Furthermore, general equilibrium feedback effects (also called the 'rebound' effects; see, for example, Allan et al. 2007; Sorrell 2007) are often not taken into consideration at the microeconomic level. People who save energy in one activity (home insulation) may end up spending the savings on another activity (for example, increased travel) due to the income as well as substitution effects, and these effects are considered only at the aggregate sectoral or national economy levels. In some cases, the rebound effects may even be greater than the initial savings in energy consumption. This is called a 'backfire' which results in a *net increase* in total energy usage rather than a decrease (Khazzoom 1980; Brookes 1990; Allan et al. 2007). To take into account the problem of the variability of the estimated *K–E* substitution elasticity with the level of aggregation, therefore, one solution is to estimate this parameter at a microeconomic level and then use such parameters also at a microeconomic level in a multi-sector general equilibrium model in which important inter-sectoral linkages can be adequately taken account of. This is preferable to the estimation of such elasticities at a highly disaggregate level and then using it in a highly aggregate model, or vice versa.

The next issue is the variability of the empirically estimated *K–E* elasticity of substitution with the type of data used (times series or cross-section). Originally, this was thought to imply that capital and energy are substitutes in the long run (cross-section data) and complements in the short run (time-series data). However, in view of the recent literature on cointegration, this interpretation – that time-series regressions in levels represent short-run results – is now no longer considered to be valid. The empirical estimation method therefore needs to be revaluated and the interpretation of the estimated parameters also needs to be re-examined (Stern and Cleveland 2004).

A third issue is the variability of the empirically estimated elasticity of substitution between *K* and *E* with the form and specification of the production function used (in particular, the question of whether non-energy material is included in the production function as a separate factor or not; see Berndt and Wood 1979; Frondel and Schmidt 2002). From a theoretical as well as empirical viewpoint, it seems that non-energy material needs to be included in any estimation function because it is an important input in most economic activities, and also because it is often explicitly considered in most applied energy–economy models.

A final issue which is more difficult to resolve from both a theoretical as well as empirical viewpoint, is the fact that it is now well recognised that there are not one but several different concepts of 'substitution elasticities' which can be used to refer to the 'ease of substitution' (or otherwise) between a human-made factor of production (*K*) and a natural resource (*E*) (see, for example, Blackorby and Russell 1989; Stern 2004). Theoretically, this issue goes beyond the problem of mere definition and can involve a fundamental debate about the appropriate role of the energy in economic activities (see the discussion on the ecological approach, below). Empirically, this means that the estimated elasticity needs to be clearly defined and accurately identified. An exhaustive study on this issue (Stern 2004, p. 29) has in fact come to the conclusion that 'capital and energy are at best weak substitutes and possibly are complements'. This statement implies that, using the neoclassical approach, sustainable economic growth in the long term for an economy which is dependent on energy as an important input in its activities is at best achievable but only with substantial technological progress regarding energy efficiency and energy substitution.

The addition of an environmental resource constraint

In contrast to the traditional energy–economy linkage approach, where the role of the environment variable N in economic activities is not explicitly taken into account, in more recent energy–economy–environment (E^3) linkage approaches, the role of this variable is now taken explicitly into consideration and given an importance equal to that of the energy resource variable E. The fact that this environmental resource is also in fixed supply is recognised by adding an additional constraint to the list of constraints (previously considered under equation (15.4)):

$$N(t) = eE(t); \dot{S}(t) = N(t); S(T) \leq \overline{S}, \tag{15.6}$$

where e is the pollution or environmental usage coefficient (for example, GHG emission coefficient per unit of energy used), S is the accumulated stock of pollution, that is, of the environmental resource (clean air) used up, and $\overline{S}$ is some kind of limit to the depletion of this environmental resource at some future time $t = T$ so as to avoid irreversible damage to this environment. For simplicity, we have assumed that the environment variable (the flow variable $N(t)$ or the stock variable $S(t)$), does not enter into the welfare function W directly but acts only as a constraint on economic activities. This allows us to ignore the *direct* environmental impacts on human welfare (for example, direct impacts of air pollution or climate change on human health and human properties) and consider only the indirect effects (that is, losses in production activities such as indicated by a slowdown in economic growth, or increased production costs such as due to increased abatement activities). The use of this simplified approach also implies that the problem considered here is not a full benefit–cost analysis (BCA),[4] but only a 'cost-effectiveness' study of the least cost method for achieving a particular environmental objective (such as that represented by the constraint $S(T) \leq \overline{S}$ in equation (15.6) above).[5]

Endogenous (or induced)[6] technological change

So far, the issue of investment is considered only in relation to the question of capital accumulation, and this accumulation is viewed in the neoclassical context of the use of a human-made capital to 'substitute' for the depletion of a natural capital, such as the energy stock. As there may be diminishing returns in this process of substitution, and unless there is sufficient technological improvement to compensate for this effect, long-term economic growth and consumption may not be sustainable (see the traditional linkage approach, above). To 'induce' technological improvement, part of the investment expenditure may be devoted towards the objective of research and development (R&D) to increase the 'stock of human knowledge' H, rather than the stock of physical capital K. This stock of human knowledge can then be utilised to improve on the technology of production (that is, on productivity) which is represented by the parameter A in equation (15.2). For simplicity of exposition, we have described 'technological change' as though it can be captured by a single parameter A. In actual fact, there may be more than one type of technological change. For example, there can be a *Hicks-neutral* technological change that affects the use of all inputs without bias. There can also be an *energy-specific* (or energy-augmented) technological change that affects (improves upon) the use of E only; and finally, there can also be an *environment-specific* technological change that improves upon the use of the environment resource N. Each of these technological change components can be induced by a different 'type' of investment, and therefore, to distinguish between these different types of technological changes and different components of investments relating to these changes, we use a subscript 'i' where $i = \{H, E, N\}$ to indicate the types of technological changes (Hicks-neutral, energy-specific and environment-specific) as well as the types of investment relating to (or 'inducing') these technological changes. Equation (15.3) can now be modified to:

$$\dot{K}(t) = X(t) - C(t) - \sum_{i=\{H,E,N\}} I_i(t). \tag{15.3$'$}$$

The 'induced technological change' equations can then in general be described as:

$$A_i(t) = f_i[I_i(t)] \;\; i = \{H, E, N\}, \tag{15.7}$$

that is, the technological change or 'productivity' parameter A_i is a function $f_i(\cdot)$ of the investment level I_i. For example, if we consider only an energy-augmented (or energy-efficiency) technological improvement, we can assume an 'induced technological change' equation as follows:[7]

$$A_E(t) = E(t)/X(t)$$

$$\dot{A}_E(t)/A_E(t) = \alpha[I_E(t)/E(t)]^{\gamma}. \tag{15.8}$$

Here, the technology parameter A_E stands for the energy intensity of production. The rate of change of this intensity, that is $\dot{A}_E(t)/A_E(t)$, is seen to be related to the level of energy-specific investment I_E (relative to the total level of energy usage E). The parameters α and γ are to be calibrated so that the function (15.8) can fit with empirical data.

Another type of induced technological change can be described as 'learning by doing' (Arrow 1962). The 'doing' here is measured, for example, by the cumulative volume of production, and the technological change is measured in terms of the reduction in unit cost $c(t)$ at time t relative to initial unit cost $c(0)$:

$$c(t)/c(0) = \left[\sum_{t=0}^{t} X(t)/X(0)\right]^{\beta}. \tag{15.9}$$

The parameter β indicates how fast unit cost will decrease as the 'volume' of learning indicated through the cumulative volume of production increases. Typically, the value of β is estimated from empirical studies, and it has been found that the value of 2^{β} (also called the 'progress ratio' because it indicates how much the unit cost will be reduced when the volume of cumulative production is doubled) is in the range of 0.75–0.95, with the smaller value (faster cost reductions) being associated with relatively immature technologies, and larger value with more mature technologies (see Boston Consulting Group 1968; Rivers and Jaccard 2006).

Other more sophisticated approaches to the specification of 'induced technological change' function can also be used. For example, Sue Wing (2006), and Sue Wing and Popp (2006), use the investment I_E to accumulate the stock of human capital H and then use the service of H to induce technological change via a production process where H can be used as an input, just like any other economic inputs. This means that human capital (knowledge) H can be used to replace (that is, substitute for) other *physical* economic or natural inputs, and this implies a reduction in physical inputs per unit of output (that is, improvement in efficiency).

Brief survey of models using induced technological change for climate policy studies

Induced technological change is an important factor in studies that look at the impacts and the cost-effectiveness of climate policy. Given this importance, in this subsection we give a brief survey of the many models that include the use of induced technological change in their studies of climate policy. The survey is not exhaustive as the objective is simply to give a broad overview of the types of models used and their results.

We start with econometric models. These include models such as E3ME (Lee et al. 1990) or WARM (Carraro and Galeotti 1997) which incorporate simple approaches of induced technological change. IAMs such as ICAM3 (Dowlatabadi 1998) use more sophisticated approaches of modelling induced technological changes. Macroeconomic and general equilibrium models such as DICE (R&DICE, ENTICE) (Nordhaus 1999; Popp 2004) and WIAGEM (Kemfert 2002, 2005) also encompass induced technological change that can affect the use of carbon energy. Finally, energy system models such as the newer versions of POLES (Kouvaritakis et al. 2000), MARKAL (Barreto and Kypreos 2000), and MESSAGE (Grübler and Messner 1998) also contain induced technological changes in their approaches, with MESSAGE incorporating some form of learning-by-doing functions into its energy system framework.

In general, it can be said that the exclusion of endogenously determined technological change can lead to results which tend to overestimate the compliance costs of climate policy (Löschel 2002; Sue Wing and Popp 2006). As initial installation of technological innovations is very often expensive, models with a learning-by-doing function can specify how this initial cost will decline over time with increasing experience (Dowlatabadi 1998; Azar and Dowlatabadi 1999; Grübler et al. 1999; Gerlagh and van der Zwaan 2001). The decline in costs over time will help to explain how an early introduction of climate policy can have an overall positive economic impact because it helps to reduce the costs of compliance over time.

One negative aspect of induced technological change is the fact that increased investment for R&D will compete with other types of investment and hence can lead to crowding-out effects which increase the overall opportunity cost of investment funds and can lead to a decrease in overall output (Goulder and Schneider 1999). Nordhaus (2002), Buonanno et al. (2003) and Popp (2004), also find that although induced technological change can lead to significant welfare gains, its climate impacts tend to be small in the long run.

The ecological approach to the role of energy in economic activities

The neoclassical assumption that energy is merely an 'intermediate input' in production activities which can be substituted by human-made capital is challenged by ecological or evolutionary economists[8] who regard energy mostly as a 'necessary' or 'essential' input into economic activities. This essential input is used to produce 'work'[9] an integral part of many economic activities. Seen from this perspective, energy is more of a 'complement' to capital (machineries) rather than a substitute (see, for example, Ayres and Ayres 1996; van den Bergh 1999).

At one level, this difference in perspectives between neoclassical and evolutionary economists can be said to arise from the difference in the level of aggregation used in their respective analyses and hence also in the different concepts of 'capital'. For an ecological economist who looks at the issues from a disaggregate or bottom-up perspective of individual technologies, capital (that is, machinery) and energy are complements rather than substitutes. On the other hand, for a neoclassical economist who views the problem from the top-down perspective of the economy as a whole, capital indicates the aggregate of all technologies and hence the 'substitution' of capital for energy indicates the use of 'more' (that is, more energy efficient and hence more costly) capital to save on energy. Thus, van den Bergh (1999) and Stern and Cleveland (2004) make a distinction between *direct* substitution (or 'replacement') of one factor by another – such as the use of capital (machinery) in place of labour, and *indirect* substitution (or 'saving') of one factor by the use of another, which applies to the case of energy saving by the use of a more fuel-efficient machinery. Müller (2000) also refers to this latter process as the substitution of better-*quality* capital for energy. Here quality of capital is defined in terms of energy efficiency. To take into account this heterogeneous characteristic of capital within the traditional neoclassical framework, Müller suggested that first, an energy 'conservation supply curve' (CSC) can be constructed using engineering data, which shows how increasingly greater amounts of energy can be saved by using increasingly more energy-efficient (and hence more expensive) capital. The curve is upward sloping and can be interpreted as the reverse of the capital–energy substitution isoquant in a traditional neoclassical production function approach. The isoquant is then used to calibrate the substitution elasticity between capital (quality) and energy. Presumably, this substitution applies only to *new* capital where the decision to trade off between higher-quality capital and (saved) energy can only be made at the time of the investment decision. Once the decision has been made, the quality of capital is then fixed, and subsequently (*old*) capital and energy are seen to be complements rather than substitutes. This putty–clay approach therefore requires a capital-vintage method, with at least two types of capital: old and new. Old capital is 'clay', and cannot be changed in its energy efficiency (hence, it is a complement with energy). New capital, on the other hand, is 'putty', that is, its exact energy efficiency level can be decided at the time of investment and this is based on a trade-off between expenditure on capital quality and (expected future) energy running cost. This trade-off is based on relative prices of capital and (future) energy inputs. The heterogeneous treatment of the capital stock is typical of many bottom-up or technology-based approaches (see, for example, Jaccard et al. 2003; Jaccard 2005). However, the ecological approach perhaps goes even further than this simple distinction between top-down and bottom-up approaches and the heterogeneous characteristics of capital. It makes a distinction between energy as an 'intermediate' input (as viewed from the neoclassical approach) and energy as a 'primary' input (as viewed from the ecological perspective). Energy as an intermediate input means that it can be 'created during the production period under consideration' and is 'used up entirely in production', while if it is a 'primary' input, it must exist 'at the beginning of the period under consideration' and is 'not directly used up in production' (but perhaps only 'degraded') (Stern and Cleveland 2004, p. 5). The fact that energy is *not used up* in the production process is consistent with the First Law of thermodynamics which says that energy (and matter) must be conserved. The 'degradation' of the (quality) of energy is then related to the Second Law of thermodynamics which says that for a closed system (such as within the human economic system), the 'ability to do work' – as measured by the so-called 'exergy',[10] or 'quality' of the energy volume contained within this economic system – must decrease rather than increase as more work has been 'extracted' from that volume (during economic activities).

If we consider only the human economic system as a closed system, then the provision of energy primary inputs into this system must come from the available energy resource *stock* which, in each period, is determined *exogenously* of the human economic system (for example, by the geological constraints which fix the rate of energy extraction, see, for example, Gever et al. 1986). The ecological approach then goes further and proposes that energy is the *only* primary factor while capital and labour inputs are in fact 'flows' rather than stocks, which can be measured in terms of the energy 'embodied' or being associated with them, and the entire value added in the economy must then be regarded as rent accruing only to this primary (energy) factor (Costanza 1980; Hall et al. 1986; Gever et al. 1986; or Kaufmann 1987). Energy surplus or rent is then distributed to the owners of fuels, labour, capital, and land, with the actual distribution depending on the relative bargaining power of the different social classes and the suppliers of fuel (Kaufmann 1987; Stern and Cleveland 2004). The implication of this 'energy theory of value' as proposed in this 'fundamentalist' version of ecological economics is that energy is now seen as the only crucial factor determining the growth of production activities in the economy, and any attempt at 'decoupling' energy from economic growth – as attempted in the neoclassical approach via concepts such as substitution elasticity and 'autonomous energy efficiency improvement' (AEEI) (the reduction of energy usage per unit economic activity via exogenous technological progress), is deemed to be theoretically unfounded.

5 Conclusion

In this chapter, we have given a brief survey and overview of the types of models used in the analysis of energy–economy–environment linkages, their theoretical background as well as practical model constructions. Mainstream neoclassical and the more recent ecological approaches to the treatment of energy and environment in economic models are described and contrasted. Although it can be said that perhaps in general, neoclassical approaches tend to be more optimistic than the ecological approaches regarding the issue of whether and how economic activities can be 'decoupled' from energy and environmental exploitation, this also depends to some extent on how energy is specified and modelled within each approach. For example, top-down aggregate neoclassical models tend to be more pessimistic than bottom-up technology-based models regarding the possibility of substituting human-made capital for energy. On the other hand, a bottom-up approach which starts from a position that considers energy as a kind of 'primary' factor, or an 'essential' input into most economic activities (using the ecological approach which tends to view energy from a thermodynamic perspective rather than an economic perspective) will tend to consider the possibility of substituting a human-made factor for energy input as almost impossible. Different theoretical approaches and different model constructions therefore can lead to significantly different results regarding the role of energy and the environment in economic activities. It is the objective of the brief survey in this chapter to give a description of the many components and characteristics of different approaches, so that the results from each can be more clearly understood.

Notes

1. See, for example, Dowlatabadi and Granger (1993), Toth (1995), Rotmans and Dowlatabadi (1998) and Edmonds (1998) for reviews on these models.
2. See Weyant et al. (1996), Bosello et al. (1998), Springer (2003) and Hourcade and Ghersi (2001). Grubb et al. (1993) and Hourcade et al. (1996) give a summary representation of some modelling approaches and classifications.
3. The issue of investment for (induced) technological change will be considered in Section 4 below.
4. Full BCA has to come up with methods for tackling difficult issues such as the quantification of the physical damages caused by the direct environmental impacts (loss of lives, loss of property caused by climate change, for example) and also a valuation of these damages in economic terms (how much value to put on a human life).
5. An example of this environmental target is the limitations on the level of GHG emissions to satisfy the Kyoto Protocol agreements.
6. We use the terms 'endogenous' or 'induced' technological change interchangeably. Endogenous because it is determined within the model, and 'induced' because it is caused by some form of action such as R&D investment or learning by doing.
7. See for example, Edenhofer et al. (2006). For other more comprehensive approaches see, for example, Smulders (2005).
8. It can be said that the ecological approach to environmental economics is concerned with the basic question of 'material (and energy) balance' (conservation of matter, and of energy, as determined by the laws of thermodynamics), in contrast to the neoclassical approach where the issue is 'value balance' (value theory). The ecological approach can perhaps be said to date back to Georgescu-Roegen (1971). For a modern exposition, see, for example, Ayres (1978), Cleveland and Ruth (1997) and van den Bergh (1999).
9. An input is 'necessary' if without it, output also falls to zero. It is furthermore 'essential' if, as in the case of a non-renewable resource, consumption will fall to zero in the long run when this (natural resource) input is completely exhausted. 'Work' implies a higher-quality form of energy, which manifests in the form of mechanical motion. Thus, electricity, for example, is a higher-quality form of energy as it can be used to run electric motors. In contrast, the burning of wood is a lower-quality form of energy because it can be used only to produce heat.
10. For a definition of 'exergy' see, for example, Wall (1977), Cleveland et al. (1984), Ayres (2005), Sciubba and Wall (2007) and Cleveland and Budikova (2007).

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