A long-term global energy–economic model of carbon dioxide release from fossil fuel use

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In this paper the authors develop a long-term global energy–economic model which is capable of assessing alternative energy evolutions over periods of up to 100 years. The authors have sought to construct the model so that it can perform its assigned task with as simple a modelling system as possible. The model structure is fully documented and a brief summary of results is given.

Keywords: Carbon dioxide; Global model; Energy–economics

Energy, economics, and the environment have long been recognized to be closely intertwined. Nowhere have they been more closely connected than in what has come to be called the 'carbon dioxide question'. Carbon dioxide (CO_2) is a non-toxic gas in the Earth's atmosphere. It exerts a 'greenhouse' effect by allowing incoming sunlight to pass through to the Earth, but traps outgoing heat. CO_2 is a by-product of decaying plants, animal respiration, cement production, some mining, and fossil fuel combustion. At higher levels of atmospheric CO_2 the greenhouse effect is intensified; global temperatures would tend to be higher, causing associated climatic changes. If the present atmospheric concentration of 339 ppm increased to 600 ppm it is generally felt that the mean global temperature would increase by 1.5–4.5 deg C, with an accompanying change in global climate patterns.[1]

The burning of fossil fuels represents the major anthropogenic source of CO_2. As such, fossil fuel use projections are critical to any analysis of atmospheric CO_2 buildup and are essential in determining the likelihood and timing of significant climate change.

The CO_2 question can be broken up into three parts:

(1) Will CO_2 emissions continue to grow at rates which will cause atmospheric concentrations to reach 'critical' levels?
(2) What are the consequences of CO_2 concentrations in the critical range? and
(3) What can or should be done about this problem?

Points 2 and 3 of a CO_2 research programme would seem to hinge on the outcome of point 1. Ironically, the bulk of the research effort has been conducted in the support of points 2 and 3.

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The lack of attention to the economic–energy aspects of CO_2 buildup stems from an early identification of the issue as largely an area of natural science interest. Early emissions forecasts were based on simple time trend analysis of CO_2 release. Based on such forecasts, CO_2 was moved from an issue of basic research and academic interest to one where a large body of scientific evidence indicated potentially large and disruptive effects on society in the not too distant future. The most recent trends in energy consumption have cast doubt on simple time trend analysis of fossil fuel use as a basis for CO_2 emission forecasts.

Economists have similarly focused on the consequence rather than the existence question.[2,3,4,5] However, the existence question has been studied. Nordhaus[6] and Hafele[7] both address the question. Hafele and his fellow researchers at the International Institute for Applied Systems Analysis (IIASA) used a set of detailed process, linear programming, and input–output models linked together by judgment in the development of two reference energy cases. While the reference scenarios have been lauded, the modelling process has been criticized. Meadows[8] contends that the model system is cumbersome to use (taking months to run successfully) and that its outputs have not been independently reproduced. The Nordhaus model is a linear programming model of the world, used to explore optimal energy–CO_2 strategies.

There was obviously a need for a behavioural, long-term, global energy model, which was flexible enough to explore alternative economic, demographic, technical, and policy interactions with energy and CO_2, but which was also simple enough to provide this analysis quickly and inexpensively. The US Department of Energy, Office of Energy Research, Carbon Dioxide Division began funding the development of such a model at the Institute for Energy Analysis, Oak Ridge Associated Universities (IEA/ORAU) in autumn 1980.

The major thrust of this paper is in the systematic development of the formal model used to assess the long-term, global energy–CO_2 interaction. We develop this energy–economic model as an example of a modelling effort which was designed around a specific energy–economic problem. We discuss the criteria which were used to develop model structures as well as the model structures themselves. Finally, we present some results from model runs, although the detailed discussions of model results are presented elsewhere.[9,10]

Minimum modelling

We have sought to develop the modelling framework with some appreciation for the limitations imposed by the nature of the task and the state of the seer's art. There are uncertainties at every turn. Key exogenous variables such as population and levels of economic activity have proved to be extremely illusive forecast targets in the past, and we have no reason to believe that they are any easier to foretell now. Similarly, such model parameters as the price and income elasticities of demand for energy have proved a rich source of disagreement.

In short the future, and particularly the distant future, is impossible to predict. What is hoped for is that conditional scenarios can be constructed to explore alternatives in a logical, orderly, consistent, and reproducible manner. The model is not a crystal ball in which future events are unfolded with certainty, but rather an energy–CO_2 assessment tool, of specific applicability, which can shed insight into the long-term interactions of the economy, energy use, energy policy and CO_2 emissions.

Recognition of the limits of modelling the long term led to adoption of a single overriding design criterion. We have coined the term 'minimum modelling' to refer to this criterion. It is nothing more than a modelling effort aimed at developing the simplest possible framework for analysis given the research question. As such, the model we have developed is task oriented, with much of the levels of detail and disaggregation dictated by the needs of the user community.

We have also sought to make this model as open as possible. Reproducibility of results was viewed as a key reason for developing a formal model. In addition, we have sought to make the model as understandable and transparent as possible. The 'black box' concept of modelling is less useful to the assessment of CO_2 emissions than what Martin Greenberger has termed the 'open box' concept.[11] Needless to say, the construction of a global model requires attention to some detail and the box, while open, may be more or less understandable to observers. We have felt it useful to discuss both overall model design in the context of the design criteria, and the actual model equations.

Minimum requirements

Despite the desire for simplicity, there are several levels of detail which are nonetheless required if reasonable energy–CO_2 scenarios are to be constructed. These form the set of minimum requirements that a CO_2 assessment must meet:

- disaggregation by fuel type;
- very long-term applicability;
- global scale;
- regional detail;
- energy balance;
- CO_2 energy flow accounting.

Disaggregation by fuel type

Energy is unalike in its emission of CO_2. Nuclear, solar and hydroelectric power generation contribute no carbon directly to the atmosphere, while coal and western US shale oil (oil in carbonate rock) are major sources of carbon release. Oil and gas also release carbon in combustion, but are not as important contributors as coal and shale oil (see Table 1).

In light of the wide disparity among carbon release coefficients of various fuel types, an important element in any carbon release assessment is the composition of fuels consumed over the period.

While there are four CO_2 release coefficients there are in fact nine types of primary energy technologies:

Table 1. Carbon release in the production and combustion of fossil fuels.

Fuel	Carbon, g/MJ
Oil	19.2
Gas	13.7
Coal	23.8
Shale oil mining[a]	27.9
Solar	0.0
Nuclear	0.0
Hydro	0.0

[a] Western US shale oil from carbonate rock.
Source: G. Marland, 'The impact of synthetic fuels on global carbon dioxide emissions', W. C. Clark, ed, *Carbon Dioxide Review*, Oxford University Press, New York, 1982.

conventional oil, conventional gas, unconventional oil, unconventional gas, coal, biomass, solar electricity, nuclear electricity, and hydroelectricity. These in turn are aggregated into six primary energy categories: oils, gases, solids (biomass and coal), hydroelectricity, nuclear electricity, and solar electricity. In addition primary solids may be converted into either secondary liquids or secondary gases, while non-electric solar and conservation enter as a reduction in the demands for marketed fuels.

Very long-term applicability

The CO_2 problem is long term. It is unlikely that fossil fuel combustion will culminate in dangerous levels of global warming before 2030, although the policy initiatives necessary to avoid critical accumulations of CO_2 may have to be implemented at much earlier dates. The current terminal analysis date of the IEA/ORAU framework is 2050. The long-term nature of the enterprise argues for simple model specifications. The elegant and powerful advances in economic theory, which have proved so useful in mid-term energy analysis, have been focused on such areas as duality theory, flexible functional forms, *ex ante/ex post* production structures and input–output analysis. The explicit treatment of capital stocks by vintage, endogenous and embodied technological change and other factors of production would seem to give the illusion of a far greater understanding of the long-term future than can possibly be justified. As a consequence, we have chosen to use simple, well behaved functional forms to represent energy, economic, technical, and policy interactions.

Global scale

While some forms of environmental pollution result primarily in local effects, the expected climatic changes associated with major CO_2 accumulations do not. The severity and geographical distribution of climatic changes resulting from carbon accumulation depends on the total amount of fossil fuels combusted by all global energy users. No major energy consumer can be ignored in the process of CO_2 assessment. Thus, an assessment of both the centrally planned economies and developing nations must be included.

Regional detail

From both a scenario building and assessment perspective, it is necessary to identify individually the major CO_2 actors. Some regions are significant because they are important sources of a major global energy source for example the Middle East. On the other hand some regions, such as the European centrally planned economies, are major sources of fossil fuel combustion with uniquely important characteristics. Still other regions, such as North America or the European OECD nations are important potential sources of energy policy initiatives which would affect carbon emissions. Nine distinct regions have been specified (Figure 1).

Energy balance

Despite the fact that carbon release calculations depend directly on the level and composition of global energy combustion, not all energy forecast models can be modified to suit this purpose. For example much early work in the field of international energy analysis can be categorized as 'gap studies'. Gap studies forecast supply and demand for energy based on an exogenously specified world oil price path. The general conclusion reached by such studies was that under the price scenarios investigated, there were likely to be deficiencies of global energy supplies. These conclusions provided useful insights into the energy problem. But neither these studies nor their methodologies were ever intended to address CO_2 issues, as a consequence they are of marginal value in that regard. Such model designs fail to equilibrate global energy supplies and demands across energy use regions. As a result, the global oil market may not be in balance and it is impossible to tell how much carbon is released by fossil fuel combustion if production forecasts fall below consumption forecasts. At the very least, an assessment tool must provide global energy balance to enable consistent CO_2 release scenarios to be generated.

An iterative process of price adjustment combined with a price sensitive formulation of supply and demand insures global energy demand in each fuel market (see Figure 2). It begins with an arbitrary set of international prices for the traded fuel aggregates, liquids, gas and solids. These prices are used to generate a set of supplies and demands by fuel type. In addition to prices, the demand model uses exogenous inputs of regional populations, regional GNPs, regional energy productivity (technological changes) and regional taxes and tariffs. The supply module uses inputs of regional resource bases for resource constrained technologies and production descriptions for backstop technologies. Prices are adjusted in successive iterations until global supplies and demands for each fuel balance within a prespecified bound. The result is regional production and consumption, estimates of international trade flows and world prices consistent with the global equilibrium. It then becomes a relatively straightforward process of applying CO_2 coefficients to energy consumption and production to arrive at global CO_2 emissions.

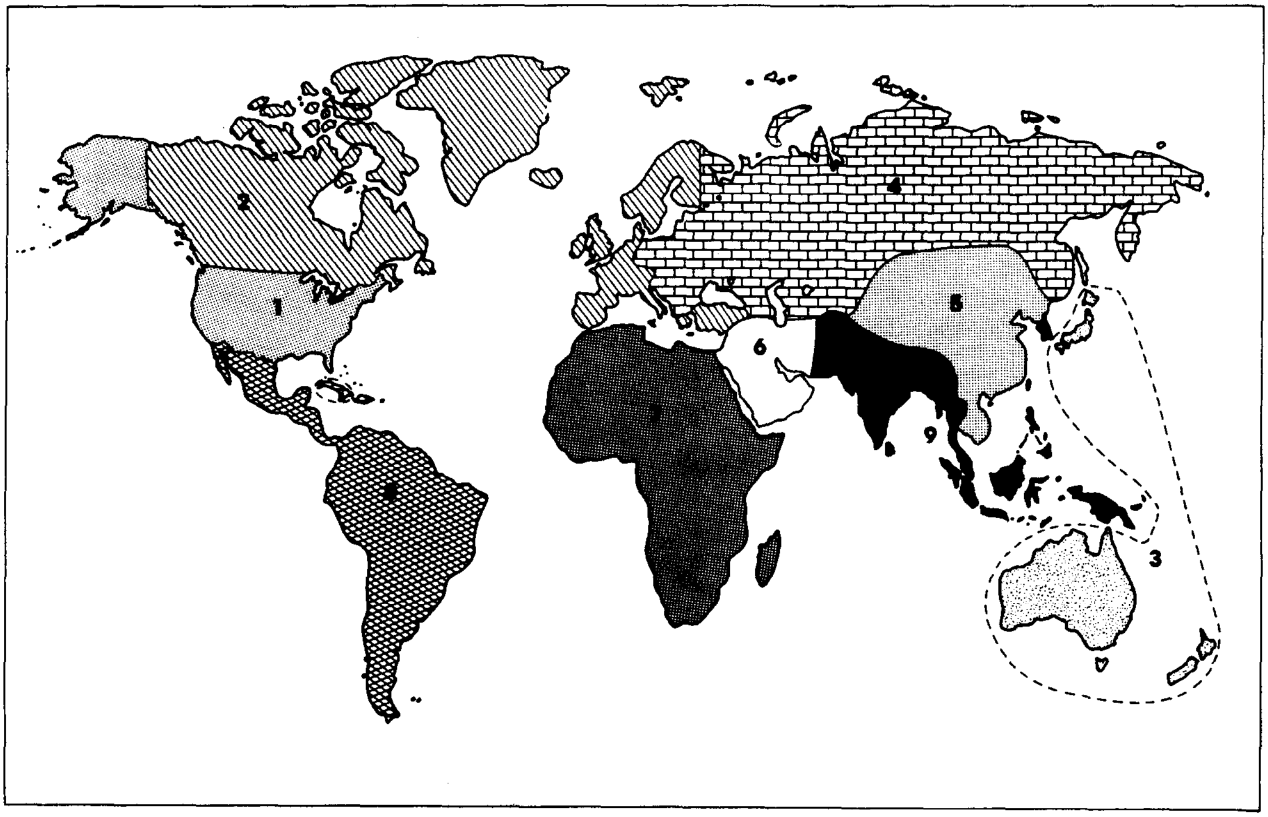

Figure 1. Geopolitical divisions in the IEA/ORAU assessment framework.
Key: 1. USA; 2. OECD West; 3. OECD Asia; 4. Centrally planned Europe; 5. Centrally planned Asia; 6. Middle East; 7. Africa; 8. Latin America; 9. South and East Asia.

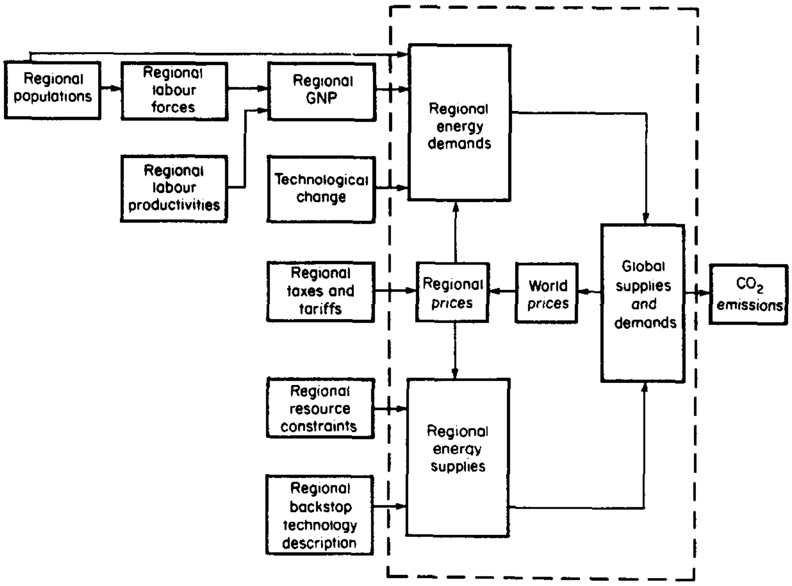

Figure 2. The IEA/ORAU CO_2 emission model.

Energy flow accounting

Carbon is released at the point of energy combustion, which makes it important to distinguish between primary, secondary and tertiary forms of energy and to be able to distinguish non-combustion uses (for example petrochemical feedstocks and asphalt) and flaring. For example the distinction between primary and secondary energy forms would prove important across scenarios if the role of electricity varied between them, and in addition the CO_2 intensity of power plants was either much higher or lower than the economy in general (eg due to either heavy dependence on coal – implying high CO_2 intensity in power generation, or heavy dependence on solar and nuclear – implying low CO_2 intensity in power generation). Similarly, it has proved important to be capable of distinguishing coal which is consumed directly as opposed to coal used for liquefaction and gasification.

The demand for secondary energy types is a derived demand springing from the demand for energy services, tertiary energy. As a consequence, the demand for secondary energy depends not only on the overall demand for energy and the relative cost of that particular energy fuel, but also on the non-energy costs of transforming that fuel into a useful energy form. Thus, coal's low relative cost is frequently more than offset by its associated high capital, labour and material costs, which often make it a more expensive provider of energy services.

The model

Each of the four sections which follows corresponds to a major computational component of the assessment framework: supply, demand, energy balance, and CO_2 emissions. These sections document the actual equations used to calculate regional energy supplies and demands, the techniques used to insure energy market equilibrium, and the computations needed to develop projected CO_2 emissions.

Supply

The supply module forecasts supplies and prices of the six major primary energy categories for a given region in a given period. Its inputs are the prices of the three major traded fuels (oil, gas, and coal), and the energy–GNP demand ratio for the two major renewable resources (nuclear and solar). Prices and outputs for the final primary energy category, hydroelectric generation, are introduced exogenously. There are three generically different technologies considered in the module: 'resource constrained exhaustible energy technologies', 'resource constrained renewable technologies', and unconstrained energy resources or 'backstop' technologies.

The assignment of primary energy technologies to these three categories is given in Table 2.

Table 2. Distribution of supply technologies across supply categories.

	Supply categories		
	Resource constrained conventional energy	**Resource constrained renewable energy**	**Unconstrained energy resources**
Energy technologies	Conventional oil Conventional gas	Hydro	Unconventional oil Unconventional gas Solids Solar Nuclear

Primary and unrefined energy

Each of the three fossil fuels – oil, gases, and solids – forms a primary energy category. A distinction is made between primary energy and a category which, for accounting purposes, has been termed refinable energy. The two categories differ in that the latter includes coal derivative synfuels while the former excludes them.

The primary energy category includes energy at the extraction stage before any processing of the form has occurred. Thus primary oil and gas consist of conventional and unconventional components. Coal used for conversion to liquids and gases is counted as primary coal. In contrast, there are three related categories: refinable liquids, refinable gases and refinable solids. Refinable liquids and gases include both primary energy and the energy content of coal liquids and gases input before the final refining process. Refinable solids include only that coal which is eventually used in the form of solid fuels. It excludes coal production for synfuel conversion. Biomass enters with coal as a solid primary fuel with the potential to be converted to refinable liquids, solids or gases.

Resource constrained exhaustible technologies

Oil and gas resources are disaggregated into two grades of resource, conventional and unconventional. The conventional components of oil and gas supply are resource constrained. By definition all conventional resources are profitable to produce at current price levels. There are, however, real world constraints which prevent this grade of resource from being consumed immediately. The resource must first be found. This requires search procedures and drilling operations. In the short term, drilling equipment is fixed and the ultimate intensity of its use is limited physically. In the longer term, there are costs of building equipment which are minimized by using the equipment over time rather than in one massive search. Even where the oil resources are well known, resource owners have incentives to disburse their product over time so as to maximize profits.

Conventional oil and gas models can be classified into three categories: extrapolation models, econometric models and discovery process models. The first of these classes is simplest. A curve is fitted between production and time or reserve additions and drilling. Such models mete out a fixed resource mechanically over time. They contain no price effects although they are easy to use and have had success as forecasting tools.* Econometric

*See for example Deffeyes and MacGregor,[12] p 70, and Cherniavskey.[13]

models incorporate prices, but typically leave ultimate total production unconstrained. This is a distinct disadvantage in a long-term framework. Discovery process models are the most sophisticated representations of conventional oil and gas supply. They model individually the process of exploration additions to reserves and production from reserves. While these models have performed well as explanatory and forecast models,[14] they are clearly not simple models. Not only must prices, resources and discovery constraints be incorporated, but so also must expected future prices. The latter input is especially important in the formulation of cartel supply models.

Process discovery models are clearly the most intellectually satisfying of the three modelling categories. They yield both insights into the process by which supply is created and are reasonable forecasting tools. They are especially appealing in an economic context since price plays an important endogenous role in the analysis. This is not to say that they are without difficulties. To some extent, the discovery process model pushes all of the interesting questions surrounding production into discovery rate parameters. Thus, 'the discovery process model relies on curve fitting just as heavily as any of the curve fitting extrapolation models'.[15]

In this model, supply is determined by a simple extrapolation model. The theoretical difficulties with such models are well recognized. Such models lack any behavioural insights. They are non-economic in orientation, and the particular function chosen to represent the production time path cannot be justified on physical grounds. Nonetheless, as noted earlier, such models have been successful as forecasting tools. They are simple and sufficiently flexible to accommodate alternative resources-remaining scenarios. Finally, it is worth noting that the alternative real world supply considerations may be implemented exogenously through the various resource and production rate parameters of the supply schedule.

Production of the constrained resource is handled conventionally via a logistics function. The logistics function relates the cumulative fraction of the total resource base which has been exploited, $f(t)$, to time. The relationship is given by

$$\frac{f(t)}{1 - f(t)} = \exp(a + bt) \tag{1}$$

where a and b are parameters, and t denotes time elapsed from an initial period.

This implies that the fraction of the resource exploited by the period t is given by

$$f(t) = \frac{e^{a+bt}}{(1 + e^{a+bt})} \tag{2}$$

The initial resource base to be exploited over all time is denoted by R. The total amount of the resource exploited by time, t, is given by $Rf(t)$. This is different from the rate at which the resource is being produced

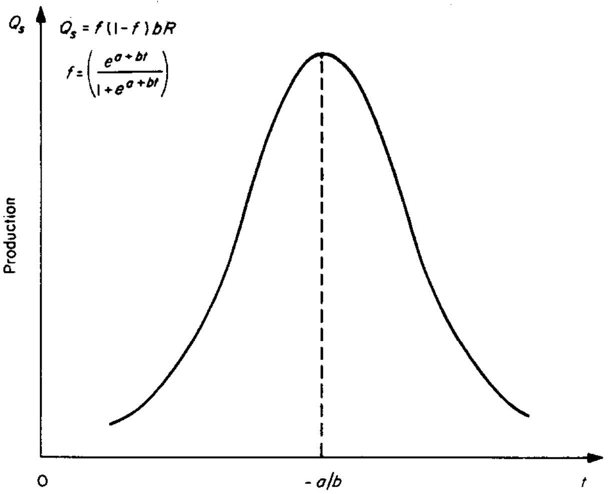

Figure 3. Production over time of an exhaustible resource using a logistics function.

at a given point in time. The rate of production, Q_s, is given by

$$Q_s(t) = f(t)\,[1 - f(t)]bR \tag{3}$$

The time path of production is shown in Figure 3. The initial fraction of resources that were used up in the initial period, $t = 0$, is simply

$$f(0) = \frac{e^a}{1 + e^a} \tag{4}$$

while initial production is

$$Q_s(0) = \frac{e^a}{(1 + e^a)^2}\,bR \tag{5}$$

The maximum production rate occurs where $f(t) = 1/2$, and $t = -a/b$.

For regions other than the Middle East the logistics equation is used to forecast the production of conventional oil and gas. The level of Middle East output is assumed to be determined by OPEC policy, and that policy is an exogenous input to the supply module as is the time profile of the rate of natural gas flaring. For example, a constant level of output is frequently cited as a likely production scenario for this region. Other supply scenarios are also possible.

It is important to point out that while each of the individual regional production time paths may be described by Figure 3, the global production time paths may not be. In fact, the regional pattern of resource distribution is likely to skew the global production time path to the right with a 'fatter' tail and earlier peak than would be obtained from a global logistics representation of production.

For resource constrained technologies, supply does not respond to price. Production rates are assumed to follow the logistics path, and the total supply is offered without regard to market conditions. The same is not true of backstop oil and gas supplies, which are offered to the market on the basis of market prices and overall rate of economic activity.

The one exceptional resource constrained technology is hydroelectric generation. Here the level of resource exploitation is given exogenously along with production costs. Both the price and quantity of this resource are passed on to the electric utility components of the demand module.

Natural gas flaring

Natural gas is a premium fuel frequently found in association with petroleum. Despite its end-use attractiveness, the market for natural gas was slow in developing, due to problems with transport and storage of the fuel. As a consequence, associated natural gas was often flared or vented. As the natural gas market has developed the fraction of gas flared or vented has diminished. In OECD countries the market has developed to the point where most gas is introduced into a natural gas pipeline system for distribution, flaring and reinjection are not important considerations. Some gas is now liquefied, in a more costly process, and transported by sea. However, natural gas markets remain underdeveloped in LDCs.

Economic considerations have been important to the development of gas markets. Prices now offer sufficient incentive to market gas which once would have been flared. As a consequence, the fraction of gas flared, capped, and reinjected is expected to continue to diminish. This has been modelled in the framework as follows: the amount of gas that is flared, f, is expected to continue to decline from a present rate of b, to an ultimate rate of a over a period of T years. The transformation is modelled as an exponential interpolation

$$f(t) = a^s b^{(1-s)}, \; (s = t/T) \qquad (6)$$

where t is the number of years of adjustment already experienced. Note that this equation structure diminished flaring more rapidly in early periods than later periods. If a and b are equal, as they are in the OECD, the flaring fraction is constant. It is also important to point out that while price is the driving motivation for reduced flaring of gas, it is not included specifically, as the magnitude of the gas resource at issue is insufficient to warrant attention to second-order effects which would either hasten or dampen the primary trend.

Backstop technologies

Backstop technologies are, by definition, capable of producing inexhaustible supplies of energy. The term inexhaustible applies strictly to the context of the analysis. Backstop technologies include unconventional oil, unconventional gas, coal, solar, and nuclear energy.

The traditional use of the term 'backstop' implies a resource which can be supplied with an infinitely elastic supply schedule.[16] A backstop technology then is an industrial analogue to the perfectly competitive firm in economic theory. That is, the industry is so small relative to the economy as a whole that its production cannot affect the price of its resources or the long-term price of output.

The methodology chosen for use here is somewhat more sophisticated than that used to model the simple backstop concept, but contains that simplification as a special case. The specification used here departs from the simple backstop concept in that it introduces the concept of a normal rate of growth. For a pure product with no special input requirements this norm might be the growth rate of the economy as a whole. For breeder reactors, this norm might be derived from the breeding ratio. For shale oil it might be some other reference rate. If the backstop energy sector attempts to grow more rapidly than its 'normal' rate, costs are bid up in the short term. If the sector then returns to its normal or base growth rate of expansion, costs of production fall back toward the long-term backstop price, P^*. Backstop supply prices can remain significantly above or below this price only if the sector continues to expand at a rate different from the normal rate.

A relatively simple equation structure is used to relate three parameters: a breakthrough price, a, below which no output will be forthcoming; a 'normal' backstop price, P^*, which is determined by the parameter b; and a short-term price elasticity control parameter, c. The supply equation is specified in terms of production costs, P, and the ratio of output, Q_t, to a base Q^*, $g = Q_t/Q^*$,

$$P = ae^{(g/b)^c} \qquad (7)$$

This equation is depicted graphically in Figure 4. If the long-term rate of expansion of supply matches the normal rate of expansion, then the backstop technology supply schedule, $S(g)$ long term, is infinitely elastic. An infinite amount of supply is available at the price P^*. Over the short run the industry may expand either more rapidly or more slowly than this base rate. If production exceeds the base level, then short-term costs rise, forcing prices up. If on the other hand the industry fails to attain its base production normal rate, prices tend to fall and the industry moves back along its short-

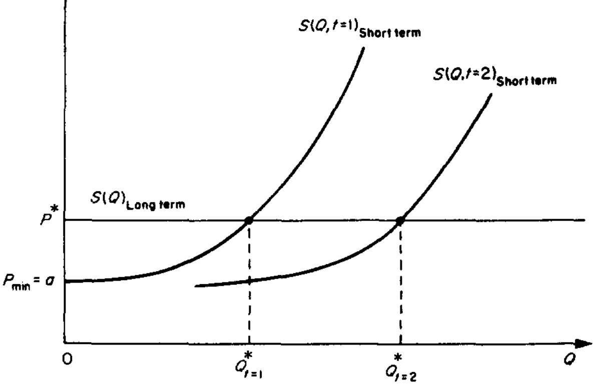

Figure 4. Short-term and long-term supply schedules for backstop technologies.

term supply schedule. There is a limit, however, to how low prices can fall. There is a shutdown price, $P_{\min}$ which is given by a.

Note that the short-term supply schedule shifts over time with the base supply level, Q^* (see Figure 4). Note also that the *marginal* cost, P, of producing a given supply depends only on the rate of growth of output in that period, and that the shut-down price, a, is independent of output and growth rates.

The short-term price elasticity of supply, E, is obtained by logarithmically differentiating Equation (7) which yields

$$E = \frac{\partial \ln Q_i}{\partial \ln P_i} = \frac{(g/b)^{-c}}{c}$$

Note that the elasticity becomes infinite at the shutdown price, $g = 0$, and completely inelastic as g becomes large.

It is also worth pointing out that in the limiting case, where c approaches infinity, the distinction between the short-run and long-run elasticity vanishes, and the two curves merge.

There are three key parameters to be determined, a, b, and c. The first, a, is simply the short-run, shutdown price of the industry. To determine b and c first note that at the reference price, P^*, realized and base production are equal, so that

$$\ln (P^*/a) = b^{-c}$$

The parameter c may then be expressed in terms of the shut-down price, a, the reference backstop price, P^*, and the short-term price elasticity of supply, E, via

$$c = [E \ln (P^*/a)]^{-1}$$

The parameter b then is found by simple substitution:

$$b = [\ln (P^*/a)]^{(-1/c)}$$

It is finally worth pointing out that the supply schedule can be expressed as a function of price, a, Q^*, and supply elasticity at the base price, E^*, by

$$Q_t = Q^* [\ln (P/a)/\ln (P^*/a)]^{E^* \ln (P^*/a)}$$

Another important characteristic of backstop technologies is technological change. This is less important for a fuel such as coal, and extremely important for a technology such as photovoltaic cells. With technological change the entire supply schedule shifts downwards and to the right. There are a number of ways in which this can be represented. In this framework technological change is treated as if it lowered the entry price. Technological change is 'phased in' over a period of length T. This is described as a decrease in the minimum cost of the technology, a, from an initial value of a_1 to an ultimate minimum of a_2. The transition is carried out in T periods using the formula

$$a = a_1^{\left(1 - \frac{t}{T}\right)} a_2^{\left(\frac{t}{T}\right)}$$

Thus in the initial period ($t = 0$) $a = a_1$ and in the final period ($t = T$) $a = a_2$. (Note that the period of transition can begin and end at any chronological time period and that $t = 0$ is used only for expository convenience.)

Resource constrained renewable technologies

Electricity generated from hydropower, geothermal power and wind can best be represented in the period of analysis as a category of primary energy characterized by a permanent flow of energy with an ultimately limited contribution to global supplies. Hydroelectricity is, by far, the dominant technology in the category. The resource has an ultimate limit determined by physical constraint. While economic considerations could elicit a marginal supply response, the overwhelming share of the resource could be available at prices below existing electricity prices. Exploitation of the full resource will be gradually phased in over the period of analysis. The resource, while an important contributor because of the low cost and desirable characteristics, faces an ultimate constraint that is relatively low in terms of future global energy requirements. The resource is modelled as being phased in over time as determined by a logistics curve, described in Equations (1) and (2). Because the resource is renewable, production in period t is simply given by

$$Q_s(t) = \frac{e^{a+bt}}{(1 + e^{a+bt})} R$$

where R is the total resource.

This is not to say that the size of the resource and the rate of exploitation are not dependent on price and profitability. Rather, the sizes of the resources in question are small by world standards, and the quantitative descriptions of price responsiveness are not well-known. Because these economic considerations cannot be expected to add significantly to the degree of accuracy in the estimates of global CO_2 emissions, a first-order approximation of resource constrained renewable supply was adopted.

The path of exploitation described by the logistics curve is shown in Figure 5. The logistics curve describes a path where the share exploited approaches 100% of the total resource.

Unrefined liquids and gases production

While coal, nuclear, and solar are treated as pure backstop technologies and hydro is treated as a pure resource constrained technology, oil and gas are hybrids having elements of both. In addition, unrefined liquids and gases are each made up of three constituents: conventional or resource constrained supplies, unconventional supplies and synfuel derivatives of coal. Synfuel derivatives are an intermediate energy good, representing a transformation from one energy type, coal, to another, oil or gas using energy and resources in the process. Total unrefined supply is the sum of these three elements.

All primary fuels are eventually refined into secondary fuels. Primary oil is refined into the secondary fuel liquids, while all gas is refined into secondary gases. Coal is unique. Some coal is refined into the secondary

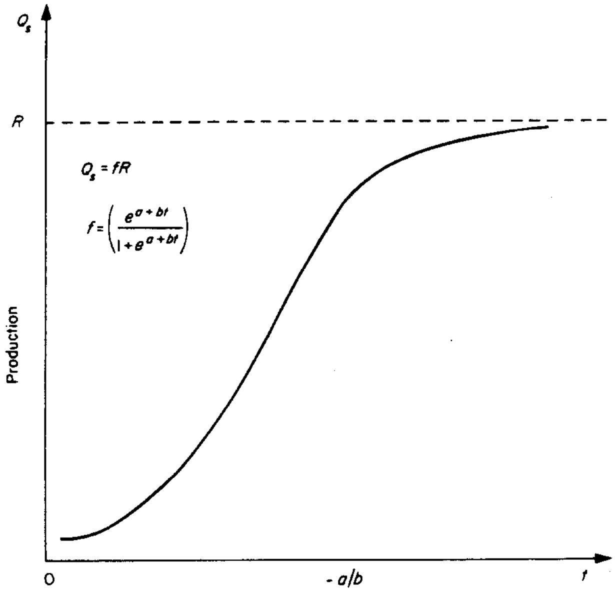

Figure 5. Production over time of a renewable resource using a logistics function.

product, solids, but some is treated as if it were pre-refined into a primary oil or gas equivalent. All three types of oil and gas inputs (conventional, unconventional, and synfuels), are then aggregated and jointly refined into the secondary liquids and gases. While a specific coal conversion process may not be decomposable into these two steps, from an accounting standpoint it is treated as if it were.

The conventional component of oil and gas production is obtained from Equation (3) from the logistics model or via exogenous assumption. The unconventional supply of the resource is obtained from Equation (7). This is accomplished by writing the expression with the energy output ratio as a function of the supply price.

The total supply of coal is determined by Equation (7), but as the previous discussion implies, this supply is trisected. One part is converted into primary oil equivalents, one part into primary gas equivalents and the third part remaining as primary coal. The size of the first two components depends upon the prices of oil, gas, and coal and on the transformation technology.

The cost of producing one unit of synfuel as a substitute for oil or gas depends on the price of coal, the technology, and non-energy costs. That is

$$P_{ic} = g_{ic}P_c + h_{ic} \qquad i = \text{oil, gas} \tag{8}$$

where P_{ic} is the price of a coal substitute for primary fuel i, g_{ic} is the amount of coal required per unit of synfuel production and h_{ic} is the non-energy cost per unit of output.

The share of coal allocated to the production of fuel substitute i, S_{ic}, is given by the logit share equation,

$$S_{ic} = \frac{(P_{ic}/P_i)^{r_i}}{1 + \sum\limits_{j=1,2} (P_{jc}/P_j)^{r_j}} \tag{9}$$

The supply of refinable fuel i derived from coal, Q_{ci}, thus equals

$$Q_{ci} = \begin{cases} S_{ic}Q_{\text{coal}}/g_{ic} & i = \text{oil, gas} \\ (1 - S_{1c} - S_{2c})Q_{\text{coal}} & i = \text{coal} \end{cases} \tag{10}$$

Biomass

As described in Reilly *et al*[17] biomass and coal have much in common. Both can be consumed as solids, or converted to either liquids or gases. The demand for coal and biomass are derived from the same sources, and the price of coal is assumed to govern the price of biomass feedstocks. The supply of biomass depends on the price of biomass and a resource base. Agricultural residue and urban waste are aggregated into a single base which in turn is assumed proportional to the level of economic activity. The share of that base which is exploited is a function of price. The share, S, is given by

$$S = \begin{cases} 0.1 + 0.2{*}P & 0 \leqslant P \leqslant 1 \\ 0.2 + 0.1{*}P & 1 < P \leqslant 4 \\ 0.8 & P > 4 \end{cases}$$

where P is the price of biomass in 1979 constant dollars/million Btu. Note that while biomass waste resource base varies by region and GNP, the rate of exploitation varies only with the price.

In contrast the biomass resource base from biomass farms is invariant with respect to GNP and varies only by region. Again the exploitation rate is assumed to depend only on the price of biomass feedstocks, via

$$S = \begin{cases} 0.0 & 0 \leqslant P \leqslant 1.5 \\ -0.6 + 0.4{*}P & 1.5 < P \leqslant 2 \\ -0.4 + 0.3{*}P & 2 < P \leqslant 4 \\ 0.8 & P > 4 \end{cases}$$

where S is the share of the resource base exploited, and P is the price of biomass feedstocks in 1979 constant dollars/million Btu.

The total amount of biomass supplied is the sum of biomass from waste plus biomass from biomass farms. Since biomass is assumed to compete directly with coal in the solids market, biomass is subtracted from total solids to obtain total coal production.

Demand

The demand module calculates the primary fuel requirements by type for a given region in a given period. The key inputs to the determination of demand are the level of population, level of economic activity (GNP), and prices of primary energy types. (Though prices are exogenous to the demand module, they are endogenous to the analysis framework, a point to be discussed in greater detail in connection with market equilibrium.) The demand for primary energy is established in a two step process which first traces energy from world market prices for primary energy, through transport and refining, to the costs of providing energy services. The demand for primary energy is then derived by tracing the effects of energy prices back through its influence on GNP, end-use energy demands (residential/commercial, industrial and transport), secondary fuel demands (liquids, gases, solids and electricity), through refinery demands for primary equivalent fuels (oil, gas, coal, nuclear, solar and hydro), and, finally, through the derived demand for synfuels to total primary energy demands.

Prices are a key determinant of both the level and composition of demand. The first step is to develop regional primary, secondary and end-use prices for energy. This first step is carried out by the price preprocessor submodule.

The price preprocessor

The price preprocessor submodule determines the regional price for each of the three primary fossil fuels (oil, gas and coal) from the world market prices for each. Next, it calculates regional prices for the four secondary fuels, using the regional prices of all six primary energy types as inputs. Secondary fuel prices are handled in a two step process. First the costs of refined fossil fuels (liquids, gases and solids) are computed. Next the cost of electricity generation is computed using refined (secondary) fossil fuel prices and production costs for nuclear, solar, and hydroelectric facilities as inputs.

The price of traded fuels i in region m, P_{im}, depends on the world market price, P_i, the transport costs associated with that fuel, TR_i, and taxes or subsidies applied to fuels, TX_{im}, in that region. Taxes and subsidies are assumed to be applied proportionately to the landed price of energy so that

$$P_{im} = (P_i + TR_i)TX_{im} \tag{11}$$

Only fossil fuels are assumed to be traded across the regional boundaries. Interregional trade in secondary electricity is almost nonexistent. The cost of producing secondary fossil fuel type j using the associated refinable energy input is given by

$$P_{rj} = P_j g_j + h_j, \qquad j = \text{liquids, gases, solids} \tag{12}$$

where g_j is the unrefined input necessary to produce one unit of secondary fuel j, and h_j is the non-energy refining costs associated with a unit of secondary fuel j.

Electricity is handled separately. Electricity is generated using the three refined fossil fuels and the three primary electricity sources, nuclear, solar and hydro as energy inputs. The cost of producing a unit of electricity using one of these six fuels is denoted, P_{ej}, and is calculated in a manner analogous to that used in Equation (12).

$$P_{ej} = BP_j P_j g_{ej} + h_{ej} \qquad j = 1, \ldots, 6 \tag{13}$$

where j is either refined fossil fuels or primary electricity, g_{ej} is the fuel requirement for a unit of electricity, h_{ej} is the associated non-energy cost of generation, and BP_j is a scale factor relating the average cost of refined fuel j to the price paid by electric utilities.

Five fuels compete via cost for a share of the electricity generating market: secondary liquids, gases, solids, nuclear and solar. Hydroelectricity supply is determined exogenously as is its cost. The market share of the five fuel types is determined by a logit framework. The share of the market captured by the jth supply technology is determined by expected cost and associated probability density function, via

$$S^*_{ej} = \frac{b_{ej}P_{ej}^{r_{ej}}}{Z} \qquad i = 1, \ldots, 5 \tag{14}$$

where

$$Z = \sum_j b_{ej}P_{ej}^{r_{ej}}$$

and the parameter b_{ej} is the base market share of fuel j, and r_{ej} is a measure of the variance of the cost function distribution. The market share for fuel j is related to the market share associated with hydro, S_{eh}, via

$$S_{ej} = (1 - S_{eh})S^*_{ej} \qquad i = 1, \ldots, 5 \tag{15}$$

The cost of generating a unit of electricity depends on the mix of modes used. Denote the electricity cost as P_e, then the relationship between P_e and modal prices is

$$P_e = \sum_{i=i} S_{ej}P_{ej} \tag{16}$$

Equations (12) and (13) define the derivation of prices, while Equations (14) and (15) determine the market shares.

The final function performed by the price preprocessor is the computation of energy service prices. There is one energy service price for each end use sector, and an overall aggregate energy service price. There are two classes of detail considered in the model. OECD regions distinguish three separate end-use sectors: residential/commercial, industrial, and transport. For these regions there are three separate energy service prices. Non-OECD regions are not disaggregated and contain only one end-use sector. The cost of energy services in a sector is given by

$$P_k = \sum_j S_{jk}P_{jk}PK_{jk} \tag{17}$$

where P_{jk} is the cost of providing energy services to end-use sector k using secondary fuel type j (the secondary fuel types are liquids, solids, gases and electric), P_{jk} is the sum of direct energy and non-energy costs divided by a base price, BP_{jk}:

$$P_{jk} = (P_j g_{jk} + h_{jk})/BP_{jk} \tag{18}$$

and PK_{jk} is the relative cost of services provided by fuel j to the overall service price. Again the use of price indices necessitates common units of measure.

The overall aggregate energy service cost, PS, is a weighted sum of individual energy service prices, or

$$PS = \sum_k S_k P_k / BPS \tag{19}$$

where BPS is the base price of aggregate energy services.

Having completed the computation of all secondary and tertiary (energy service) prices, the demand module proceeds to use these in the determination of secondary and tertiary energy demands.

Determining secondary energy demands

The GNP is one of the principal determinants of energy demands, but energy can conversely have an effect on the GNP. To reflect this, the base case GNP is adjusted for the overall level of energy service price to allow for this two-way interaction. This is accomplished through a simple elasticity relationship,

$$Y = \mathrm{GNP} \cdot PS^{r_y} \tag{20}$$

where r_y is the percentage change in the GNP resulting from a 1% increase in the cost of providing energy services, and Y is the adjusted GNP level.

This formulation yields a first-order approximation to the impact of energy on GNP. These effects would be likely to change with both the levels of energy prices and GNP, and these changes in turn would be likely to go on at a non-constant rate. Unfortunately, there are neither clear empirical nor theoretical grounds upon which to determine either the direction or magnitude of second- and third-order GNP feedback effects. Even the magnitude of first-order effects are in question, though for most values of expected energy prices, magnitudes of r_y are expected to be relatively small.† As a consequence, the representation of the energy price feedback given in Equation (20) was deemed to be as accurate as current empirical research can reasonably support.

The total demand for energy services is determined using income and energy service price elasticities, r_{pk} and r_{yk}. The demand for energy services for the residential/commercial and transport sectors in OECD economies is given by

$$E_{sk} = P_k^{r_{pk}} \cdot X^{r_{yk}} \cdot \mathrm{POP} \tag{21}$$

where E_{sk} is the total demand for energy services, X is a per capita GNP index and POP is the population size index. Non-OECD regions and the OECD industrial sector are indexed to the total level of economic activity, Y, so the computation becomes

$$E_{sk} = P_k^{r_{pk}} \cdot X^{r_{yk}} \cdot Y \tag{22}$$

The fraction of energy services provided by each fuel type depends on the relative cost of providing those services, and the level of income. Both income and price effects are considered. These are derived from the logit share structure so that the service share for fuel j in sector S_{jk}, is given by

$$S_{jk} = b_{jk} \cdot P_{jk}^{r_{pjk}} \cdot X^{r_{yjk}} / Z_k \tag{23}$$

$$Z_k = \sum_j b_{jk} \cdot P_{jk}^{r_{pjk}} \cdot X^{r_{yjb}}$$

and where price and income elasticities are determined by the power terms r_{pjk}, and r_{yjk}, and b_{jk} is the base service share captured by the fuel j.

The demand for each secondary fuel in a sector is identically equal to the product of total service demand with the fuel service share and this value is multiplied by the fuel requirement per unit service, divided by the level of technological improvement or

$$F_{jk} = g_{jk} \cdot S_{jk} \cdot E_{sk} / \mathrm{TECH}_{jk} \tag{24}$$

The level of technological progress is added to account for the fact that technological progress has acted to conserve energy even when energy prices fell. Needless to say, this factor may or may not be an important source of energy conservation in the future. This specification allows for both continued progress and stagnation to be explicitly considered.

The region's total demand for the secondary fuel type j is found by simply summing over the sectors:

$$F_j = \sum_k F_{jk} \tag{25}$$

The share of total energy services produced in the region by the kth sector is found by computing

$$S_k = b_{sk} \cdot E_{sk} / Z \tag{26}$$

where

$$Z = \sum_k b_{sk} \cdot E_{sk}$$

and b_{sk} is the base case energy service weight.

The determination of primary energy demand

Primary energy demands may be inferred from the demands for secondary energy sources, and the information on fuel transformations. Fossil fuel demands for primary energy depend on the demands from end-use sectors, the electric utilities and synfuel conversions from coal. The demand for fossil fuels for electric utility generation, in turn, depends on the demand for electricity.

Primary energy demands are calculated in three steps. First the electric utility demand for refinable fossil fuels is calculated by

$$E_{uj} = g_{je} S_{je} F_e g_j \qquad j = 1, \ldots, 6 \tag{27}$$

where E_{uj} is the electric utility demand for secondary fuel j, e denotes the secondary fuel, electricity, g, S, and F having their conventional meanings. This demand in turn must be adjusted for synfuel conversions. There are several alternative accounting procedures that could be adopted to distribute the demand for refinable oil between conventional oil (or gas) and synfuels from coal alternatives. The convention adopted here assumes that all synfuels from coal are consumed domestically, and that all imports of oil (or gas) are of conventional oil (or gas). Refinable energy demand must be adjusted by the share of total demand that cannot be met by domestic synfuel production coal,

†See Hitch.[18] The focus of energy–economy studies has been the USA. The relationship is less well understood elsewhere in the world.

$$\left(1 - \frac{ES_{\text{coal}} \cdot S_{i,c}/g_{ic}}{F_i + E_{ui}}\right) = 1 - S_i$$

Thus, sectoral primary energy demands are given by

$$E_i = (F_{ik} + E_{uik}) \cdot (1 - S_i) \qquad i = \text{oil, gas} \qquad (28)$$

where k is the sectoral index.

Coal demand, of course, is the sum of direct plus indirect demands, the indirect demands coming from both the demand for electricity and the demand for synthetic liquids and gases from coal.

$$E_{\text{coal}} = F_{\text{coal},k} + E_{u,\text{coal},k} \qquad \text{(direct)}$$
$$+ \sum_{j=\text{oil, gas}} S_j \cdot (F_{jk} + E_{ujk}) \cdot g_{ic} \qquad \text{(indirect)}$$
$$(29)$$

The total demand for primary fossil fuels is found by aggregating the primary energy demands for end-use sectors and electric utilities. That is,

$$E_i = E_{ui} + \sum_k E_{ki} \qquad i = 1, 2, 3 \qquad (30)$$

It remains only to compute the fossil fuel equivalent value for primary electricity. This is done by multiplying each of the three benign forms of electric power generation, nuclear, solar, and hydro, by the average primary energy used by fossil fuels to produce energy, C. That is,

$$E_i = C \cdot F_{ei} \qquad i = 4, 5, 6 \qquad (31)$$

The average primary fossil fuel requirement is computed by first summing all fossil fuel inputs to electric power generation, and then dividing it by the total power generated:

$$C = \left(\sum_{i=1}^{3} E_{ui}\right) \Big/ \left(\sum_{i=1} S_{je} \cdot F_e\right) \qquad (32)$$

Energy balance

It is an identity that the quantity consumed must equal production. The framework must accommodate this reality. So-called 'gap studies' take a price as exogenously given and then calculate the resulting supply and demand. These are generally not equal, but there is no mechanism by which equality can be achieved other than by allowing a residual fuel to provide a backstop.

The approach taken here is different. Markets for oil, gas, and coal are international and, as a consequence, there is an interdependency between price and the resulting supply and demand in that market. By assumption, nuclear, solar, and hydro do not trade and are available as specified in the supply and demand modules. There is no problem with markets clearing for these three fuels. They are clear as identities.

The oil, gas, and coal markets are different. They must be cleared by a more complicated mechanism. A set of market prices for these three fuels must be found which brings production and disbursements into agreement. The methodology employed to derive these prices is relatively simple, and involves a search procedure begun at an arbitrary set of prices.

The market equilibrium search procedure

At the initial prices world supplies and demands for the three fossil fuels are calculated. A measure of the disparity between supply and demand is calculated by the difference between the natural logs of both sides,

$$X_i = \ln Q_i^D - \ln Q_i^S \qquad i = \text{oil, gas, coal} \qquad (33)$$

If the gap between supply, Q^S, and demand, Q^D, is sufficiently small, then the market is assumed to clear. If the initial prices were not sufficiently close to equilibrium, then an estimate of the new equilibrium prices is made, based on price elasticities.

Denote the price elasticity of demand by U_{ij}, and the price elasticity of supply by V_{ij}, where

$$U_{ij} = \frac{d \ln Q_i^D}{d \ln P_j} \qquad (34)$$
$$V_{ij} = \frac{d \ln Q_i^S}{d \ln P_j}$$

Now for each fuel

$$dX_i = \sum_j (U_{ij} - V_{ij}) d \ln P_j \qquad j = \text{oil, gas, coal} \qquad (35)$$

An estimate of equilibrium prices can be obtained by calculating exactly how much prices need to change to reduce excess demand to zero. The necessary change in prices is given by setting dx_i equal to $(-x_i)$, and calculating

$$\begin{bmatrix} d \ln P_{\text{oil}} \\ d \ln P_{\text{gas}} \\ d \ln P_{\text{coal}} \end{bmatrix} = \begin{bmatrix} W_{\text{oil, oil}} & W_{\text{oil, gas}} & W_{\text{oil, coal}} \\ W_{\text{gas, oil}} & W_{\text{gas, gas}} & W_{\text{gas, coal}} \\ W_{\text{coal, oil}} & W_{\text{coal, gas}} & W_{\text{coal, coal}} \end{bmatrix}^{-1} \times \begin{bmatrix} -X_{\text{oil}} \\ -X_{\text{gas}} \\ -X_{\text{coal}} \end{bmatrix} \qquad (36)$$

where $W_{ij} = U_{ij} - V_{ij}$.

New prices are calculated by $P_{\text{new}, i} = P_{\text{old}, i}(1 + d \ln P_i)$. These new prices are in turn used to compute a new gap measure, which is tested for closeness to equilibrium.

Calculation of elasticities

The calculation of elasticities can be made either on the basis of numerical or analytical procedures. The latter have the advantage of being faster to calculate once derivatives have been obtained, but possess the disadvantage that calculating the derivative may be a lengthy, intricate, and tedious procedure. Furthermore, derivative procedures make model modifications more difficult since not only must supply or demand changes be instituted in the model core, but in addition the effects of these changes in model structure must be traced through the model derivatives. This makes model transport more difficult as well. As a consequence, model run time has been sacrificed in order to obtain malleability.

The procedure used is a simple one. The computer model has been encoded in double precision Fortran. Derivatives are obtained by sequentially varying each price by a small amount, and noting the resulting difference from the unperturbed run.

CO_2 emissions

Given the solution from the energy balance component of the model, the calculation of CO_2 emission rates is conceptually straightforward. The problem merely requires the application of appropriate carbon coefficients (carbon release per unit of energy) at the points in the energy flow where carbon is released. Carbon release is associated with the consumption of oil, gas, and coal. Significant carbon release is also associated with production of shale oil from carbonate rock. A zero carbon release coefficient is implicitly assigned to nuclear, hydro, solar, and conservation.‡ Actual calculation of CO_2 emissions is made somewhat more complex than indicated by the conceptual simplicity, but primarily because of the need to account appropriately amounts of fossil fuels which are subtracted out before final consumption (see Figure 6).

A considerable literature exists concerning appropriate values for CO_2 coefficients. The coefficients in Table 1 are representative of average global fuel of a given type and are consistent with the model's CO_2 accounting conventions as indicated by Figure 6.

In order to grasp the underlying rationale for the flow diagram in Figure 6, it is necessary to note a few points concerning CO_2 release. Generally CO_2 is not released from fossil fuels used as feedstock (asphalt, lubricants, road tars, and waxes). However, a group of petroleum products are rapidly oxidized (eg paints and solvents). This latter group is not included as part of the feedstock in Figure 6 and, therefore, CO_2 released from oxidation is included as part of calculated emissions.

While non- or very slowly oxidizing feedstock uses are excluded, all energy arriving at the 'refinery gate' is included. In terms of the model's accounts, both

‡ Only direct emissions of carbon from energy consumption are calculated. Indirect emissions are implicitly included. For example, the CO_2 released in the production of steel for solar and nuclear and in the transportation of fossil fuels is accounted for in the industrial and transport sectors respectively.

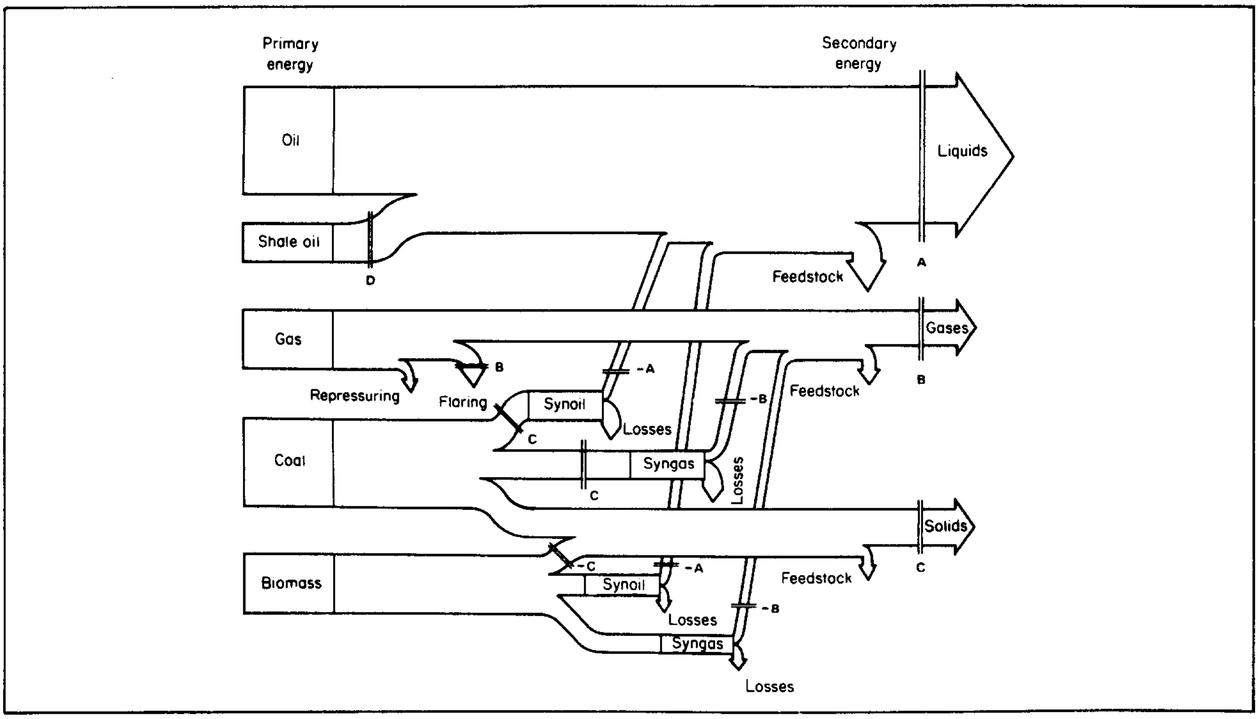

Figure 6. Energy–CO_2 accounting diagram for the IEA/ORAU long-term global energy–CO_2 model.

Application of CO_2 coefficients

A = CO_2 (liquids)
B = CO_2 (gases)
C = CO_2 (solids)
D = CO_2 (shale)
═ indicates point of application
— indicates application of a negative value

conventional and unconventional oil and gas are included as are liquids and gases derived from the production of synfuels (using both coal and biomass as bases). For solids, secondary energy consists of the portions of coal and biomass which were not allocated to the production of synfuels and non-oxidizing feedstocks. This accounting method yields an appropriate estimate of CO_2 releases associated with consumption for any given region.

To get total regional release of CO_2 it is necessary to add releases associated with energy production. These include synfuel production, biomass production and shale oil production. Production of shale oil from carbonate rock has relatively high CO_2 release because the retorting process releases the carbon in the carbonate rock. The total CO_2 release from shale oil includes the carbonate rock mining plus liquids consumption coefficients or 47.6 TG/EJ. Production of synfuels (from coal or biomass) tends to release high amounts of CO_2 because of the tremendous amounts of the energy input consumed in the process. To account for this energy use the full coal coefficient is applied to the coal going into the synfuel plant; the CO_2 remaining in the liquid or gas as it leaves the plant is then subtracted to avoid counting the amount at the production and consumption point. Negative liquid, gas, and solids coefficients are applied to amounts of end-use fuels derived from biomass. Since biomass fuels, at the point of consumption, are implicitly assumed to have carbon release equal to the average of the fuel type, this accounting methodology implies zero net contribution to carbon emissions from biomass.§

Finally, the production of conventional gas from associated wells gives rise to another source of CO_2 release in energy production. Portions of the associated gas which are not marketed are either flared or reinjected in the well to maintain well pressure and aid in the extraction of oil. Flared gas is counted at the end use CO_2 emissions rate; reinjected gas is counted at a zero emissions rate.

Results in brief

The model has been used to develop a long-term global base case for CO_2 emissions. This work is more extensively documented in Edmonds and Reilly.[19] The results of this first stage of work are rather striking, however, and a brief summary is indicative of the model's potential.

We begin by establishing a reference level of CO_2 concentration in the atmosphere at 600 ppm.♦ The doubling date depends on the initial CO_2 concentration, the rate of release, and the fraction of that release which remains in the atmosphere (the airborne fraction, f). We have developed a concept called the 'doubling window'. The doubling window is defined by looking at the date at which the CO_2 concentration reaches 600 ppm under a given scenario assuming that f goes no higher than 0.7 nor lower than 0.4.

Simple time trend extrapolations of the post-war rate of growth of CO_2 release yield a doubling window between 2021 and 2035. Our base case, no surprises scenario yields a doubling window period of 2049–2067. This finding indicates a doubling date as much as three decades later than scientists had originally used as a reference point.

On the other hand, our findings indicate considerable difficulty in postponing the doubling window through the use of CO_2 taxes. Unilateral action by the USA would have little effect on the doubling date. For example, a 100% tax on coal use combined with taxes on oil and gas in proportion to their relative carbon release rates with an export ban on coal moved the doubling window back about five years. Even under a cooperative scenario, where the entire world joins the USA in such a CO_2 tax scheme, the doubling window would be moved back only about a decade.

Among the CO_2 results, was the finding that the globe appears to be heading towards a period in which coal and shale oil become economic ways of providing secondary liquids and gases while coal continues to compete with nuclear to supply electricity. Renewable technologies, particularly biomass and non-electric solar and conservation, will provide a very significant contribution to energy needs by 2050, but continued growth in energy demand spurred by population and economic growth put heavy demands on all fuels. The next 75 years are likely to evolve with a mixture of energy types fuelling the world rather than a transition to a 'sustainable future' based on nuclear, solar, fusion or some combination of these sources. Fuel mode shares will probably change over the next three-quarters of a century, with an initial shift towards primary electric and natural gas, slowing the rate of CO_2 emissions from a historic rate of 4.5% per year to 1.5% per year for the remainder of this century before increasing to over 3% per year by 2050. The pattern emerging from the modelling effort, continued slowing of CO_2 growth in this century followed by a jump in the rate of increase, should caution policy makers and researchers from being lulled into believing the CO_2 problem will 'go away' on the basis of present trends and short-term forecasts.

§ Stock effects of growing or shrinking biomass resources are not computed, though such effects could make biomass either a net source or sink for carbon.

♦ A level of 600 ppm, approximately a doubling of the pre-industrial atmospheric concentration, has become a common benchmark. It is likely to cause a temperature rise of 3 ± 1.5 deg C (see Perry *et al*[20]). Climatic and, in turn, societal impacts of atmospheric CO_2 are not subject in any simple way to a threshold level; the number of different events, continuous temperature change, and uncertainty about specific relationships make it impossible to identify a single critical CO_2 level. Our adoption of 600 ppm as a reference level is based on this understanding.

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