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THE ENERGY OUTLOOK

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Introduction

It is with considerable trepidation that anyone would set about forecasting economic and social change two years ahead. Limited knowledge 1) concerning the flexibility of individuals and national institutions 2) concerning the speed with which governments and society as a whole can recognise that new life styles and economic systems are inevitable, 3) concerning the ecological resilience of the biosphere and the extent and quality of remaining non-renewable material and fuel sources, combined with 4) the fickleness of human nature, regional, national and international kudos and rivalry make it all but impossible to forecast in any sensible format the time-scale and sequence of events in the years ahead. As it is impossible to anticipate the ingenuity with which human operators can devise intriguing ways of misusing complex, 'foolproof' technological systems, so is it impossible to anticipate the evolutionary process. The picture any one person paints of the future will be coloured by personal prejudices. Prejudice is a human condition. A declared unbiased stance is mistaken since each one of us is influenced by a unique environment, education and experience and, above all, by uncertain knowledge.

Economic Growth and Entropy

One of the articles of faith which has guided societies in recent history is the doctrine that all 'economic growth' (whatever this happens to be) is good and beneficial for everyone and that it must and can persist forever (?). This doctrine has been taken up by virtually all modern societies; the creed has been incorporated into the political thinking of communist, capitalist, mixed economy and totalitarian systems. Central to this creed is the notion that due to man's ingenuity and his 'exponentially' increasing knowledge there are no effective material, energy or ecological constraints to his social, economic and cultural development and 'progress'. That is, because of man's ingenuity resources are 'infinite'.

Some observers have difficulty in accepting this dogma as an absolute law. Ecologists, for example, know that all ecological systems attain some 'climax' condition and wonder why this is not also true for the ecosystem of man and nature. There is not universal acceptance of this dogma amongst economists. Notably, Nicholas Georgescu-Roegen has investigated the implication of the Second Law of Thermodynamics (Georgescu-Roegen 1971, 1972, 1975; Wade 1975). The starting point of Georgescu-Roegen's theory is the entropy law. This concerns the notion of irreversibility, that certain processes go in one direction only and can never be repeated except at a far greater cost on the whole. A gallon of oil, for example, can be burned only once; the energy bound up in the combustion products is so dissipated that it is unavailable for use, unlike the 'free' energy in the oil, and the process cannot be reversed. The entropy law says that the entropy of a closed system always increases, the change being from free to bound. All species except man, depend on the sun as their ultimate source of low entropy; man has learned to exploit the terrestrial stores of low entropy, of minerals and fossil fuels. Life feeds on low entropy and so does the economic process. Georgescu-Roegen asserts that the entropy law rules supreme over the economic process. Standard economists teach that the economic process is a closed, circular movement between production and consumption in which the exhaustability of natural resources is not a problem, and undesirable manifestations, such as pollution, can be solved by the pricing mechanism. In the light of the entropy law the economic process can now be viewed as a continuous and irreversible transformation of low entropy into high. The basic inputs are drawn from the solar flow of low entropy and from terrestrial stocks. The material output is high entropy in the form of pollution and dissipated matter and heat.

This view of the economic process differs radically from conventional economic thinking; it emphasises the inputs (energy and natural resources) to the process and the outputs (pollution), aspects which tend to be ignored, or at least considered of lesser import, in conventional analyses. Because the terrestrial dowry of ordered materials (high grade ore bodies) is limited every artefact manufactured now means fewer implements for future generations. If this analysis of the economic system is correct, and it is the only economic framework which incorporates fundamental tenets of modern science, at which point during the process of depleting the earth's finite store of ordered material structures does it become obvious to societies as a whole that they are engaged in a one-way process, with a limited life.

The argument is unlikely to be affected permanently by the advent of large-scale fast-breeder or fusion reactor systems, although its recognition may be delayed some decades, since a progressively increasing proportion of the economic system's production must be used for capital regeneration and capital growth as it becomes necessary to exploit more dilute resource reserves. The essence of Georgescu-Roegen's argument is that if the 'energy crisis' does not catalyse the transition to a new world order, material resource depletion, food scarcity and pollution are waiting in reserve.

The Constraints on Technology Substitution

It is an increasingly recognised fact that all the problems of the world are interacting and interrelated, in a tangled complex of problems. "Dynamics of Growth in a Finite World" (Meadows et al 1975) and "Mankind at the Turning Point" (Mesarovic and Pestel 1975) are highly criticised attempts to take an holistic view of the world system. Desirable though it may appear in theory to develop such integrated total system world models, the practical problems of aggregation accompanied by the mandatory use of correlational relationships does not enhance their abilities to anticipate the proximity and severity of pressing substitution and expansion difficulties.

Theoretically there are many avenues open to mankind in circumventing resource depletion problems; in theory integrated breeder-reactor and high-temperature reactor systems (Hafaele 1974) can satisfy all energy demand; in theory gasification and liquefaction of some of the world's 'enormous' coal reserves can substitute for depleted natural gas and petroleum; in theory the fusion process is a bright hope offering 'unlimited' amounts of 'cheap' energy; in theory uranium can be extracted by crushing granite and in theory the world's food output can be doubled or trebled. However, what should concern society is the practical problems of satisfying the essential and other needs of a world population, which at current rates will double in another 30 years, at a time when high quality energy and material sources are rapidly being depleted. Could the economic development of recent history have been possible in the absence of high quality petroleum? Is it practically possible to derive in time other energy sources which [redacted]

Addendum

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... sources which can sustain the level of economic activity made possible by petroleum? The important comparative properties of substitution resources are quality, capital and labour cost, magnitude and deployment rate. The rate and magnitude problem is succinctly set in context by Amory Loving (1975) in his paper 'World Energy Strategies'.

"The physical resource base, however, is not the whole story. It is hard to think of any thoughtful student of the fossil-fuel industries who believes that as world population doubles, say by the first decade of the next century, world energy conversion will increase 6-x (as current growth rates suggest). Even if the technological, environmental, political and institutional difficulties of such an increase could be mastered, the rate and magnitude problems seem well beyond the capacity of world industry and finance - especially if they are devoted to other problems as well. In the author's view we should be hard pressed to produce half that much growth in the same period, particularly since the world crude-oil production will peak within a generation. A mere doubling of world energy conversion will be hard enough.

Indeed, the exponential growth of energy conversion in any industrialised country (excepting such special cases as Norway) is the sum of a series of overlapping exponential curves representing new energy sources, each introduced as the preceding curve matures or begins to falter, and each in general of a simpler character than those preceding. Thus coal displaced wood, and was in turn displaced by oil and gas (the latter, with its exceptional simplicity, accounting for 66 per cent of US energy growth from 1945 to 1965). In most countries, domestic supplies of oil are in turn being supplemented by imported oil, and in some, gas by imported gas (LNG). Continued exponential growth of total energy conversion requires that each successive source be capable of more rapid growth than that preceding it - possible only if there is a very large existing energy inventory capable of being cheaply and rapidly mobilised, as was historically true of Persian Gulf oil and US natural gas.

Governments have apparently acceded to quick depletion of cheap energy reserves on the tacit assumption that a new source will turn up in time to maintain even faster growth. The latest such innovation, however, is nowhere in sight, and a little ...

and a little reflection about the character such a new source must have, reveals why. Nuclear power, with its complexity and long lead times, is far too slow. Existing energy industries are thus under severe stress to try to make up a growing deficit. (In the USA, for example, gas and oil fields - and the refineries of the major producers - are operating at 100 per cent, or somewhat more, of their nominal maximum capacities). This stress is in a sense due, as is often said, to a temporary shortage (of e.g. refinery capacity) caused by prolonged mismanagement: but the underlying problem is real and will not go away".

Energy Reserves

The gross reserves of non-renewable energy resources are known to an acceptable degree of accuracy (Warman 1972; Hubert 1969; Ion 1975; Thomas 1974). These gross reserves are calculated using a distillation of a variety of approaches - geological, mathematical, probabilistic engineering and pragmatic (Dunham 1976) - and assume, in the case of coal, an approximate 50 per cent extraction efficiency and, in the case of petroleum, an efficiency of between 20 per cent and 50 per cent. A combination of factors, principally prevailing technology and cost of the delivered products, make it uneconomical and therefore impractical to achieve higher extraction efficiences. The reserve estimates include sources which cannot be exploited at the present time due to cost and lack of developed technologies.

A non-controversial estimate for global gross coal reserves is 10,000 Gigatonnes (tonnes x 10^9) (Ion 1975). The current extraction rate is approximately 2.43 Gt (1973) per annum, superficially implying a 4,000 year resource. Such superficial estimates can dramatically shrink under the influence of complex technical and social factors. Gross coal reserves in Britain are estimated to be 162 Gt. In order to achieve high production rates with a moderate labour force, partially to produce an energy product which is competitive with petroleum, it has been necessary to resort to large-scale mechanisation. The equipment used, ROLF (Remotely Operated Long-wall Face) requires generous seam dimensions and good geological conditions, such that only 3.8 Gt of the gross 162 Gt can be mined by this method (Dunham 1976).

At current extraction rates of approximately 140 Megatonnes (tonnes x 10^6) annually the life time of workable reserves is 27 years. Economic considerations aside, the general improvement in living standards in recent years, combined with a heightened awareness of the generally relatively comfortable working conditions outside the mining industry, probably make the adoption of automated mining a cultural necessity. Mechanisation in mining is yet another manifestation of a continuing process which has released labour from manual, if skilled, occupations to catalyse technological advance in mining and other fields.

Coal and its products (synthetic oil and gas) are seen by many observers as medium to long-term alternatives to oil and natural gas. Energetically coal liquefaction and gasification are costly processes, that is, significant amounts of energy are forfeited during the conversion process. Precise conversion efficiency figures are not necessary to illustrate the effect such technologies might have on Britain's coal reserves. As an illustrative example, suppose that in 20 years (1996) a society exists in Britain consuming energy at today's rate of about 300 m.t.c.e. (million tonnes coal equivalent) per annum. Suppose also that all electricity is generated by nuclear power, saving 100 m.t.c.e. per annum; electricity use commanding the same proportion of national energy as today. Suppose, in addition, that of the remaining energy supplies 25 per cent must be in liquid forms and 25 per cent in gaseous forms, for reasons of versatility, control precision, customer acceptance, mobility, etc. Assume also a liquefaction conversion efficiency of 30 per cent and a gasification efficiency of 60 per cent. The implied coal extraction rate is 350 Mt per annum. The lifetime of the 3.8 Gt of accessible coal (using mechanised techniques) would depend on the profile of growth curve for coal extraction, but a mean extraction rate of 200 Mt during the next 20 years would consume the accessible reserves by the close of this period. It seems unlikely, though not impossible, that coal production exceeding by a considerable margin today's output could be produced solely or almost entirely by labour intensive methods; such labour intensive methods would be mandatory to access all of Britain's theoretical gross reserves of 162 Gt.

Should nuclear power not expand beyond 60 GW capacity by 1996 (because of cost, long lead times, uranium constraints, etc.) and should the coal extraction rate not expand beyond 160 Mt per annum (NCB's current target) and if, by 1996, North Sea Oil and Gas are approaching the ends of their depletion cycles (Government estimates) and available Middle East oil is very costly indeed, because it is then recognised by everyone as a dwindling and irreplaceable energy source, then Britain, compared with the present day, will be experiencing an energy short-fall of between one-third and one-half of its present consumption. This eventually would result in dramatic changes in government, industry, social structure and, therefore life styles.

Energy Reserves - Petroleum

Global reserves of petroleum are estimated to be 275 Gt (2000 x 10^9 barrels) (Warman 1972; Hubbert 1969; Ion 1975; Thomas 1974). At the prevailing extraction rate of 20 x 10^9 barrels per annum, this resource would last 100 years. The estimate consists of 30 per cent discovered and 60 per cent presumed reserves, on a world scale. Studies carried out by W. H. Warman, of British Petroleum, indicate that if growth in petroleum consumption is re-established at the pre-1973 rate of 75 per cent per annum then world petroleum production will peak in about 1985. The signs are that all governments are vigorously attempting to steer their economies back onto paths of sustained 'growth' and if they are successful an alternative to petroleum with a production rate capable of rapid increase must be available by the mid-eighties. It is practice for resource analysts to assume a depletion curve with a symmetric profile, with the decline being a mirror image of the climb. Behren's (1971) model of natural resource utilisation gives some indication that these curves can become heavily skewed, declining quite rapidly after attaining a peak. If the model is modified to explore the behaviour of petroleum depletion, where the cost of extraction is a function of cost of the product, very rapid declines in production rates can be induced (writer's experiments). In the case of petroleum one can envisage an expansion of economic activity and expansion of the associated economic superstructure driven by the use of high quality, easily accessed (Middle East) petroleum, followed by a rapid decline when substitution energy technologies prove incapable of rapid proliferation.

Net Energy and Quality

Many forms of energy are low grade because they have to be concentrated, transported, mined from deep in the earth or pumped from remote continental shelf basins. Much energy has to be used directly and indirectly to support the machinery, people, supply systems, etc. to deliver the energy. When one unit of energy is consumed in delivering one unit of energy to the point of use, then there is no net energy. At the present time the consumption of gross energy is increasing, but increasing percentages of energy are being fed back into the energy winning process and therefore the percentage of net energy production is decreasing, e.g. North Sea Oil, Liquefied Natural Gas, coal liquefaction, shale oil, tar sand oil, fission power(?). Many of the proposed alternative energy sources may require more energy feedback than existing sources. There are a number of detailed energy balance studies by analysis mainly outside the industries/technologies being investigated. These analyses, for example, show that coal is less energy intensive than refined oil (but also of lower quality) (Chapman 1973), that Britain's fission reactors appear superior in energy terms in converting fossil fuel into electricity, but are not necessarily net producers of energy in a fission-only economy (Leach and Slesser 1973; Price 1974; Lem et al 1974; Chapman et al 1974) and that North Sea Oil is 10 per cent more energy intensive than delivered Middle East Oil (Chapman et al 1974).

The concept of net energy means that real reserves of energy are less, to a degree which cannot be precisely expressed at present because some of the necessary extracting technologies do not yet exist, than the gross reserves; for any depletion strategy the lifetime of a reserve will be less than an estimate based on the gross reserves. It means that a fission economy founded on uranium extracted from granite is not a practical alternative (Price 1974; Chapman et al 1974; Bupp and Derian 1974), because more useable energy is consumed in the beneficiation of the ore than is produced by the reactors.

Energy is measured in calories, btu's, kilowatt hours but has a scale of quality not indicated by these units (Odum 1973). The ability to do work for man depends on the energy quality and quantity. Although refined petroleum is an energy intensive product compared with coal, it posesses a versatility and convenience that coal cannot approach, other than through liquefaction (which imposes a major energy loss, possibly 70 per cent). In addition coal mining is considerably more labour intensive than petroleum extraction and refining (Chapman 1973). Thus, in order to gauge the relative quality of energy sources we must not only know the energetic efficiency, we must also consider end use, versatility, convenience, labour intensity, capital intensity, resource intensity, skill intensity, stability, reliability, durability, etc. - a truly formidable analysis.

The Nuclear Option

It is conventional wisdom that some manifestation of nuclear power will provide an answer to medium- and long-term energy problems. A close examination of the likely timescales and rates at which nuclear technologies must be designed, developed and engineered on a large scale suggest that the nuclear route is a poor and possibly, improbable option. Nuclear technology is complex and uncompromising and presents technological man with technical management and ethical problems of unprecedented difficulty (Lovins 1974; Rose and Tenaglia 1973). It is not largely subsidised by fossil fuels and it is not possible to know, at the present time, how net yielding nuclear power would be as the primary energy source; we do not know if an economy founded on this energy source is a viable option (Odum 1973; 1970). This is an area which will endure much acrimonious debate between the pro- and anti-nuclear lobbies and is an area the timid commentator should avoid. There are, in any case, much more pressing problems of substituting for rapidly depleting fossil-fuels so as to sustain the level of economic activity necessary for the existence of a nuclear economy.

It is more than 20 years since Britain's first commercial nuclear reactor came on stream. But even now nuclear power supplies a relatively small (about 10 per cent) proportion of national electricity consumption. Although it is frequently said that nuclear power represents a large reservoir of cheap energy capable of rapid mobilisation, experience with a variety of reactor systems up to the present time does not endorse this claim. Not one of the existing available range of developed reactors systems would appear to be a satisfactory design on which to base a large continuing reactor programme. The American Light Water Reactor (LWR) has been rejected by the British Government principally because of safety considerations surrounding the integrity of the reactor pressure vessel. Developments of the quite successful Magnox design are rejected due to poor thermal efficiency and experience to date with the Advanced Gas-Coaled Reactor (AGR) has not generated the degree of confidence necessary to make it the automatic choice for the next round of reactor orders; the search for higher efficiency has encountered what can broadly be described as stress limitations such that not one of the ten-reactor series is expected to meet the original design rating. It seems that the only reactor system which Britain might use in the short- to medium-term is the Steam Generating Heavy Water Reactor (SGHWR) - a brand new design which it is planned to successfully commission by 1982. This is approaching rather closely to the time when petroleum may be a declining resource. The SGHWR generates only electricity (and low grade heat), which is not a total substitute for petroleum, is expensive at about £400 per kilowatt of capacity and, unfortunately, depends on a stock of uranium which has a very limited life indeed. By 1985 the present World reactor programme will have consumed 40 per cent of the non-communist world's 'reasonably assured' uranium resources (Thomas 1974). Another five years operating without further expansion in installed plant would exhaust 'reasonably assured' resources.

A conventional retaliation to this kind of argument is that by this time energy will have become sufficiently expensive to make poorer ores economic. Nuclear fuel cycles utilising existing uranium ore bodies (.3 per cent to .7 per cent U_3O_8) require of the order of 1 per cent of the useful electrical output to be invested in mining and beneficiation the ore (Price 1974; Chapman et al 1974). It is estimated that by mining ores 20 to 30 times less concentrated than today's supply, at least 17 million tons of U_3O_8 would be available (Bupp and Derian 1974) - compared with world 'reasonably assured' and 'estimated additional' reserves of 1.6 million tons at average concentrations down to .15 per cent. Unfortunately the bulk of these ore reserves is at the lower end of the quality range, where between 40 per cent and 50 per cent of the nuclear electricity generated, or some transformations of it, would have to be allocated to mining and beneficiation the ore. It is not possible, at the present time, to determine the ore quality below which nuclear power is not viable, but it could be .02 per cent, limiting the extent of the non-communist world's uranium reserves to about 3 million tons of U_3O_8. The energy industries' projections for the expansion of nuclear power would consume all of this resource by about 1995.

There are in addition other difficulties accompanying the rapid proliferation of nuclear power systems, which can most succinctly be described by quoting from John Price's paper, "Dynamic Energy Analysis and Nuclear Power" (Price 1974).

"This paper presents a conservative assessment of the net energy yields from various thermal reactors, neglecting a number of terms whose inclusion would be likely to make the results worse by a significantly but presently (and to some extent perhaps perpetually) unknown amount. This optimistic assessment shows that reactors fuelled by uranium from high-grade ores typically yield output energy about two or three times as quickly during their lifetime as they consume input energy during their construction. If the uranium is derived from low-grade ores (in particular, Chattanooga Shale, .007 per cent), this power ratio becomes about $\frac{1}{4}$-$1\frac{1}{4}$ and an isolated thermal reactor produces (in most cases) rather little excess energy beyond that required to fuel it.

In the dynamic rather than the static case- that is, if reactors are considered not singly but as part of a multi-reactor nuclear programme whose total inputs and outputs at various times are of interest- the requirements on the output-to-input power ratio of the individual reactors are far more stringent. If the number of reactors increases too quickly, the energy/year that must be continuously invested in new construction is a large fraction of the programme's output. For example, if a nuclear power programme based on the most energy-profitable type of reactor studied (assuming high-grade uranium ores) is to yield to society half of the energy/year that it was expected to yield (the other half being offset against investment in the programme), then the doubling time of the number of reactors cannot exceed 4 years; the corresponding figure for the least energy-profitable reactor studied is 5.5 years. And if the doubling time of the reactor population exceeds 2.6 years for the most energy profitable reactor, or 3.5 years for the least, then the nuclear power programme will continuously consume more energy/year than it produces. For comparison, the doubling time widely proposed for the British nuclear programme is about 4.3 years; for the EEC, about 3 years; for the USA, about 2.5 years; and for France, about 2 years. All these programmes will therefore produce, as output to society, energy/year equivalent to less than about half the demand they were intended to meet, and the output of at least the last two programmes (the US and French) will be negative".

There is considerable scope for indulging in primitive speculative arithmetic so as to acquire a well-rounded appreciation of problems about to be confronted. One could assume that North Sea Oil production behaves according to Department of Energy estimates, and production falls to 30 per cent of its peak by 1990 and the resulting 30 Mt per annum output is reserved for premium uses, e.g. transport, a moderate coal expansion to 180 Mt to substitute for oil's contribution to current electricity production and nuclear power (in the form of the SGHWR) directly replacing the remainder of the oil deficit on the equivalence of 30 Kwh (kilowatt hours) per therm, which is probably somewhat optimistic. The underlying assumption is a level of economic activity similar to 1976. It would be necessary to replace 70 Mt of oil (2.8×10^{10} therms) with 8.6×10^8 Mwh of electricity. This is a mean 99 GW averaged over a complete year and would require 144 GW of nuclear capacity, based on the operating performance of Magnox reactors (HMSO 1973), and implies fifty-five, 4-reactor SGHWR complexes, such as planned for Sizewell B, at an approximate cost of £55,000 million to be spread over a period of 12 years, assuming the programme is started in 1978 (four years prior to the completion of the first SGHWR). This expansion of the electricity supply system to about 3 x its present size would also entail major investment in distribution. The programme here envisaged represents a construction rate at least 20 x greater (in terms of capacity) than has been achieved with AGR's, i.e. a quantum jump in the output and performance of the nuclear power construction industry. The realisation of an investment of this magnitude in buoyant economic conditions would be problematical; it may be extremely difficult in the years of probable shortage ahead. Having achieved such an ambitious objective there would be certain problems in securing adequate supplies of uranium so that the reactors can remain fully operational for their designed life.

The Fast-Breeder Reactor

Concern over the limited reserves of fissionable uranium led to the conception of the 'breeder' reactor as long ago as the early nineteen-fifties. The fast-breeder consists of a core of plutonium fuel elements to raise heat which is removed to a heat exchanger for steam raising by a primary cooling circuit of liquid sodium. Some of the fast neutrons are arranged to be captured by a surrounding blanket of non-fissionable uranium 238, which is converted into Plutonium 239 at a rate dictated by the reactor design and operating point. It is intended that design optimisation will realise plutonium inventory doubling times of 24 years, as claimed for the US breeder, and as little as the 12 years claimed by Britain following its Dounreay experience (some observers consider the burnups and neutron fluxes implied by the latter figure to be rather implausible (Lovins 1974)).

One constraint on the expansion of breeder reactors is the availability of plutonium. A country's plutonium inventory is affected by a number of factors; the reactor types and the number of years they have been operating and access to compatible and functioning fuel reprocessing facilities. The available fuel reprocessing facilities in Britain can handle fuel from Magnox reactors only; plant to process oxide fuels such as are utilised by AGR's, SGHWR's and LWR's will not come on stream until about 1987 and, of course, it will take time to process the backlog of fuel assemblies which will have accumulated. The estimation of the possible doubling times for an expanding breeder system, with the initial reactors being commissioned in 1985, is highly speculative, but times less than about 4 years seem very improbable, limiting a breeder system to 75,000 MW in the year 2000. One has to be something of an optimist to assume that a successful commercial fast-breeder reactor (CFR) will be available by 1985, since the nuclear industry is only now beginning to explore the detailed implications of this concept. It is as well to remember that what was to have been the first AGR will be commissioned not earlier than fourteen years after the commencement of site work and the breeder concept does not have an entirely unblemished history (Fuller 1975).

Fusion power is not an option in combating the very serious energy supply problems of the next twenty-five years. Technological optimists do not consider it a serious proposition until well into the 21st century. It is as Dr. W. Marshall of UKAEA recently said, the most difficult and taxing technological endeavour ever undertaken by man.

Problems of Finance

In addition to technical problems, resource constraints innovatory delays and organisational constraints, it is also going to be very difficult allocating the unprecedented infusions of money necessary for sustaining existing levels of energy use. OECD forecast that between $1,200 bn and $1,600 bn ($\$ \times 10^9$) must be invested in energy between now and 1985.

Recent press reports may be construed as symptoms of the underlying malaise - that resource constraints are hard and not indefinitely malleable under the forces of human ingenuity and that these constraints (manifestations of the entropy law) are already inhibiting the 'natural' evolution of the economic process (e.g. Harris, Financial Times, 15 January 1975; Vogl, Times 25 February 1976; Report, Times 23 October 1975; Newsweek, 8 March 1976; Fishlock, Financial Times 7 November 1974; Thomas, Guardian 2 January 1974).

While GNP (Gross National Product) per capita is not necessarily the best measure of personal well-being, it nevertheless provides a pragmatic indication of the performance of the economic system in the present state of its evolution; it is closely correlated with the per capita consumption of useful energy (Nicholson 1973; Brookes 1972; Meadows et al 1975; Mesarovic and Pestel 1975). One can fairly safely say that energy constraints will either inhibit growth or even produce negative growth, depending on their severity. It is suggested that the evidence documented in this paper is a strong indication that sustained growth is now most unlikely. Ranged before us then is a confusing spectrum of possibilities; from a short-lived business as usual (Chapman 1975) burst, down (or up) to quite severely energy constrained life styles or worse. In the short-term institutional inertia will prevent dramatic changes in direction (barring global conflict, which is not totally incredible) and it is likely that changes in direction will only come about after painful experiences which ultimately lead to the conclusion that traditional responses contribute to, rather than solve, the 'problem'.

In the very long-term it is likely that man will be obliged to sustain his economies and civilisations almost entirely on solar energy and its transformations. In addition to the necessity of adequate and durable food supplies, civilised living will also require some minimum per capita energy subsidy. Preliminary calculations by this writer suggest that a population of about 30 million (cf 56 million now) could survive in healthy self-sufficiency in Britain. The energy self-sufficiency reduces to very roughly 60,000 kilocalories per person per day compared with perhaps 140,000 kcal/person/day at the present time. 60,000 kcal is rather less than the per capita energy subsidy 'enjoyed' by this country in the period 1850-1880, though this is hardly a useful comparison. The energy would be derived from a mixture of sources, solar collectors, windmills (Electrical Research Association claim that wind power can provide 10 per cent of national electricity demand by 1980, the same as that currently generated by nuclear sources), water power (about twice the 1976 hydro capacity) and from various organic sources, waste vegetation (straw, etc.), effluent and energy crops (Evans 1974; Heslop-Harrison 1975; Szego et al 1972; Chedd 1975; Earl 1975; Brown 1976). It is conceivable that a major, though not necessarily dominant energy source would be wood grown on much of the 20 million upland acres. One has to contemplate a certain level of industry, and hence some minimum per capita energy subsidy below which satisfying but constrained life styles are not possible, to provide and maintain the artefacts a stimulating society will need.

After nearly two centuries of unprecedented expansion the prospect of what, in our present wisdom, is seen as contraction is generally viewed with gloom. Mankind, fortunately or unfortunately, has little option but to adapt his life styles to what his 'environment' will allow. There is room for some optimism; man is undoubtedly the most versatile, adaptable and resourceful species this planet has so far seen.

The Uplands

At various times in the past and present the uplands have been essential sources of minerals, food, fibre, energy and water.

The uplands have a considerable potential for providing igneous rock, limestone and sandstone minerals; the production rates of these minerals has been increasing substantially in recent years. Generally sites close to existing developments and those offering good access to major industrial centres will experience most pressure.

Slate production has gradually declined over the years and in 1972 was less than half the peak output of 123,000 tons. The persistence of business-as-usual conditions will probably encourage this trend - slate is very expensive, probably because of a high labour content. Should there come a time when high labour content no longer incurs the economic penalties we have come to associate with it, then there may be a significant revival of this industry.

The uplands were sources of iron, copper, lead, zinc, silver and gold in the past. Upland iron ore deposits are probably unlikely to receive serious attention in the future because of the substantial sources elsewhere in the country which provide one third (9 million tons) of national consumption, however one can never be absolutely certain. Developments which are seen to be in the 'national interest' could see activity in areas which we have recently come to accept as part of the national heritage.

The known world supplies of the following metal ores will be consumed in the time indicated at current extraction rates (Meadows 1972; NAS-NRC 1969; US Bureau of Mines 1970).

Copper - 32 years
Gold - 7 years
Lead - 22 years
Silver - 12 years
Mercury - 9 years
Zinc - 19 years
Tin - 13 years

These metals, which are essential catalysts for the existing industrial system and all of its conceivable developments for some generations to come, will no longer be available for growth priming uses or the replacement of dissipated metals in a time period which is less than that from the beginning of the Second World War. There is some scope for substitution. Aluminium (lifetime at current rates, 100 years) can probably replace copper in an increasing number of applications. "In the long-term however it may be anticipated that aluminium ore, being a thin surface covering of the crust, might be used up before copper reserves in depth have gone" (Thomas S. Lowering, NAS-NRC 1969).

It does not seem possible that conceivable developments of existing technologies can survive at any significant level of economic activity, or for a significant period of time, in the absence of a policy of maximum recycling and one must hope that T. S. Lowering's opinion (NAS-NRC 1969) is pessimistic: "When the time comes for living in a society dependent on scrap for high grade metal and on common rock for commercial ore, the affluent society will be much overworked to maintain a standard of living equal to that of a century ago. Only our best efforts in all phases of resource management and population control can defer that day."

The transition to the new social/industrial order could undoubtedly see pressure to exploit what remains of Britain's non-ferrous ore reserves. The possibility of contributing more than a very small quantity to existing annual consumption of 546,000 tons of copper is doubtful. The total output of the Parys in Anglesey, from start to finish, was 130,000 tons. This is not necessarily a good indicator of kind of yields coming from massive open-pit mining proposals such as surveyed in Snowdonia (Lovins 1973). There still remain deposits of copper, lead and associated metals in many of the upland areas and one wonders how the exploitation of these deposits, using modern methods and machinery, would compare with limestone and slate workings.

Further expansion in the number of reservoirs is unlikely in the long-term, however the combined forces of institutional inertia and project momentum could result in the completion of some current plants which intend doubling volume of impounded water by 2000. It is unlikely that conceivable levels of economic activity will demand more water than is currently available.

Water is also a potential source of energy. It is generally assumed that a very high proportion of potential water power has been developed, however, this is based on an economic criterion where plant opportunities under 250 KW, served by drainage zones under 500 km^2 in area, are disregarded. By tapping the potential of smaller streams with simple and low-cost equipment, it has been estimated that total hydro-electric output could be raised to more than 40×10^9 kwh/year compared with 16×10^9 kwh/year at present. There is a growing interest in the use of small hydro-electric plants, partly precipitated by escalating electricity bills. When the regional water boards tailor down their charges to levels that the market can bear, it is likely we shall see their fairly rapid proliferation.

Farming is inherently a conservative profession, particularly in the uplands where the size of individual holdings and environmental constraints impose a severe limitation on output, and in bad years, can penalise heavily those who over-stretch their resources. Pressure on world food supplies in the immediate future will encourage, through the combined inducement of more expensive food and government incentives, the production for more food from all agricultural areas. Soil conditions in many upland areas do not permit ploughing, although there are a number of elevated areas where arable farming is possible which are suited to growing root crops for winter fodder. There are bound to be at least short-term trends for grassland improvement. Although these improvements tend to be somewhat energy intensive, it is unlikely that energy will be so expensive in the next 10 years so as to exclude this possibility.

There will be attempts to increase the yield from grasslands by manipulating stocking densities, introducing hardier breeds of cattle or reverting to former practices of leaving wethers on the hills to fatten. Only time will tell how successful and sustainable any developments will be. "All the circumstances under which a man lives and acts, and all the laws of nature can never be known to him. He cannot hope to know them all merely in terms of scientific and text-book categorisations, and still less in terms of their manifold interactions. Sympathy, sense, and feeling must necessarily be brought into play to assist to fill the gaps. Thus the man who feels his way into understanding as well as learns his way is the only man competent to deal with the problems of life and therefore the problems of agriculture" (Stapledon, 1942).

There have been a number of experiments recently, which are a little out-of-step with normal practice, and which seem to offer real opportunities of increasing upland yield (Parry 1974; Dalyell 1973). This is the practice of integrating forestry and agriculture and should appeal to ecologists as it runs counter to the trends of increasing monoculture. The advocates suggest it is proper to plant between 25 per cent and 50 per cent of fell land with between 3 and 10 acre blocks of trees. It can entail considerable capital expenditure, fencing, roads to service the wooded areas. The roads have an added bonus in that they improve ease of access for agricultural management. Coupled with grassland reclamation it has been possible to keep more sheep on 500 acres than were formerly kept on 1000 acres (Parry 1974). It is a very long-term enterprise; first can be felled in 50-60 years and the hardwoods require even longer if the crop is sold for its constructional properties. It is possible that different cropping frequencies would be appropriate for crops which are intended as sources of fuel and fibre. For these uses one would be seeking management practice, species selection and species mix which maximise the average annual accumulation of dry matter. The evaluation of optimum strategies could be a long-term endeavour, perhaps as much as 50 years. Recent work in this area however suggests that much shorter timescales may be practicable (Brown 1976).

It is rather difficult anticipating the time when timber might be essential as an energy source. This very much depends on how the economics of coal extraction work out as it becomes increasingly necessary to mine more difficult seams, and, of course, on extraction rates.

Timber has long been a feedstock for the synthetic fibre industry. The recent escalation in the price of petroleum and petroleum products has renewed interest in the use of wood as a feedstock for plastics. The indications are that the existing waste from the harvest of British woodlands and forests could satisfy the feedstock requirements of a plastic industry comparable in size to that now existing (Goldstein 1975). Chemicals from wood are still derived in large quantity.

The total area of conifer high forest, broadleaved high forest and coppice woodland in Britain in 1973 was 1.5 million ha and produced 3.7 million m^3 of wood; when the young plantations reach maturity, the sustained yield from the 1973 forest area will be something of the order of 10 million m^3 (Johnston 1975), implying an average yield of 6.7 m^3/ha. The round wood equivalent of total wood consumption in 1973 was 48 million m^3; therefore for self-sufficiency in wood in that year Britain would have required a productive forest area of about 7 million ha in sustained yield, an additional area of some 5.5 million ha. For the year 2000, home production has been projected on the basis of life styles current in 1973, at 8.7 million m^3 equivalent to a productive forest area of about 12 million ha and assuming the same yield/ha.

The residents of the uplands may soon, in large numbers, re-exercise their turbary rights. Peat is used widely in Shetland for domestic heating and some farmers in the Pennines have recently returned to this practice. The labour entailed in providing for one household for a year does not seem onerous, providing the turbary rights are close to a road and one has access to modern transport. Peat was used industrially in the early days of the industrial revolution in Britain but it is doubtful if there now exist any accumulations compatible with modern industrial requirements. In other countries, Eire, USSR, USA peat is or soon will be a source of fuel for power stations, however the extraction rate of some of these schemes puts peat in the class of a minor non-renewable energy source.

Conclusions

It is going to be said that this is a very unsatisfactory piece of speculation and it has not achieved any of the objectives set. This humble observer has been unable to successfully, or even partially, solve the problem of following through any particular scenario to the detailed implications for upland use in England and Wales. It is always possible to indulge in a highly imaginative look at the future, but does it really mean anything? A study of this nature is hardly an excuse for a novel.

It is relatively easy estimating the lifetime of non-renewable resources at current or anticipated extraction rates and it does not demand intense observational powers to infer that very difficult, resource intensive projects will, assuming they are successful, take longer to perfect and deploy and place a bigger burden on a nation's economy than simpler more parsimonious projects. It is another matter altogether detailing in chronological order the major events and turning points which will take us from the here and now through the inevitably turbulent years ahead. Peter Chapman (1975) in his book "Fuel's Paradise" poses three interesting scenarios, the business-as-usual, the technical-fix and the low-growth, which make entertaining reading. All three scenarios support the general conclusions emerging from this paper, simply because both business-as-usual and technical-fix scenarios are resource intensive and resources are very finite.

But supposing a reasonably reliable and detailed economic scenario could be forthcoming, translating this into the detailed implications for agriculture is extremely difficult.

We do not know the following:

1. The potential of the land for different kinds and degrees of agricultural production.
2. The resilience of practices which achieve maximum output.
3. The direction and rate in which dietary habits will change under pressures of price and shortage.
4. The influence of an evolving EEC agricultural policy.
5. The manner in which the growing world food problem will move and whether our traditional overseas suppliers can continue to support us.
6. The effect of eliminating waste in food distribution, marketing and preparation (some observers estimate that 30 to 35 per cent of all food wasted, implying that the existing national agricultural output could supply 80 per cent of the national diet, as opposed to 55 per cent now).
7. The effect the return to allotment ownership will have on demand in the shops.
8. Is the yield from allotments on average better or worse than that in commercial horticulture and is it more or less energy/labour intensive?
9. Will recent trends where agricultural units have tended to grow considerably in acreage be reversed in response to an awareness that smaller farms have a bigger output per unit area (Walker 1972).
10. Will Britain's population continue the decline of recent years, will the rate of decline change, and what will be the level at which the population stabilises?

The above list is but a selection of a long list of unknowns. The future will always be unknown and unknowable. All the signs indicate that we are about to experience the most rapid transition any culture has been obliged to endure.

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