

THE ENERGY FUTURE AND THE CHEMICAL FUELS

J. O'M. BOCKRIS

Institute of Solar and Electrochemical Energy Conversion, Flinders University, Adelaide, Australia

Abstract—An account is first given of the origin of present chemical fuels, with particular reference to the lastingness of coal. Methods of estimation of these fuels are discussed and the greenhouse effect arising from the burning of coal is described. Consideration is then given to methods available for extending the uses of chemical fuels, including interfacing them with new inexhaustible, clean energy sources. Finally, accounts are given of the Hydrogen Economy and of the production of chemical fuels from wind energy in massive wind belts.

1. INTRODUCTION

In considering this paper on chemical fuels, we are concerned with a lively subject which directly determines our standard of life. Thus, in Fig. 1 is shown the relation between the amount of energy per head in the various countries and the corresponding *per capita* income. The factors are linearly coupled.

Two basic questions concern us in considering the future of chemical fuels:

- (1) How long will the present chemical fuels last?
- (2) What will be the new fuels which will produce inexhaustible clean sources of energy?

Before beginning the details of my presentation, I wish to say that the subject has been fraught with optimistic illusions. Until recent times (the early 70's) it had been assumed that there would be no difficulty in the transition between the fossil fuels and the on-coming cheap atomic energy. These classical concepts of the post-war attitude towards energy have now been revealed as fraudulent and we are, in fact, going to have to fight a battle to avoid the exhaustion of the present classical fossil fuels, before the advent of new ones, arising from the inexhaustible energy sources of nuclear, solar and solar-gravitational sources.

2. METHODS OF CALCULATING THE EXHAUSTION TIMES OF A RESOURCE

One of the reasons for the illusionary nature of our former concepts concerning the lastingness of our fuels arose from the lack of understanding of the relation between linear and exponential growth rates. In a general sense, we have constantly miss-estimated growth; and, in earlier times, made the absurd assumption that no further growth of energy need would occur from that of a given year. During the sixties, linear growth rates were taken into account. It had to await the pivotal work of Meadows, Meadows, Randalls and Behrens¹ to show us that the growth of needs in affluent societies was exponential so that calculations made upon a linear basis became inadequate.

Allowance for the change-over from linear to exponential laws, and the growth of affluent societies, is at the root of all our suddenly realised difficulties concerning the exhaustion of our resources, and the chemical energy sources (the most basic resource) in particular.

A method of estimating the time at which a resource passes its usefulness and must begin to be replaced by another, was researched by Hubbert, and then by Elliott and Turner.³

According to Elliott and Turner (cf. Hubbert), the rate of production of a natural resource as a function of time for the resource, and the quantity remaining, may be expressed as:

$$\frac{dP}{dt} = f(D) \cdot f(S) \tag{1}$$

in which P = cumulated production of the resource; t = time, calendar years; dP/dt = annual rate of production; $f(D)$ = function of demand; $f(S)$ = function of remaining supply, but the supply is a function of the fraction of the resource remaining, so that one gets:

$$\frac{dP}{dt} = \frac{b'P}{U} \left\{ 1 - \frac{P}{U} \right\} \tag{2}$$

in which U = ultimate resource and b' = a constant.

Integration of eqn (2) gives:

$$-\ln \left\{ \frac{U}{P} - 1 \right\} = \frac{b't}{U} + n = bt + n \tag{3}$$

in which n = constant of integration and $b = b'/U$.

Thus:

$$P = \frac{U}{1 + \exp(-bt - n)} \tag{4}$$

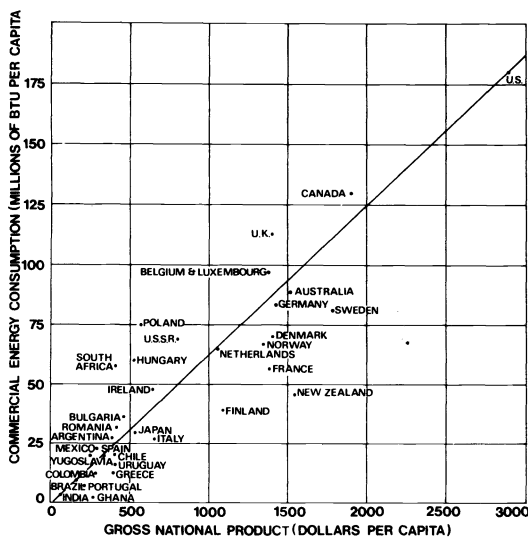


Fig. 1. The relation between energy *per capita* (total energy budget divided by population) and income *per capita* (G.N.P. divided by total population).

One may then take the second derivative of eqn (4), equate it to zero, and let t_m be the time at which the maximum rate of production occurs. The solution is that:

$$n = -bt_m \tag{5}$$

Combining eqns (4) and (5), we have that:

$$P = \frac{u}{1 + \exp[-b(t - t_m)]} \tag{6}$$

This eqn (6) is that derived by Elliott and Turner, and is similar to that of Hubbert, in which:

$$P = \frac{U}{1 + A \exp[-b(t - t_i)]} \tag{7}$$

where t_i = a reference calendar year and A = a constant, when the substitution, $A = \exp b(t_m - t_i)$ is made. The quantity which passes through the maximum is (dP/dt) .

Thus, if one applies the equations derived above to resources of varying kinds, one obtains curves such as those shown in Fig. 2. The resource production rate maximizes and then falls off. It is conventional to call the time of the maximum, that at which the resource is "exhausted". Of course, this term is not to be taken at its face value. It can be seen from the graphs that at the maximum there will be a short-fall of the given chemical fuel which will thereafter have to be supplemented by something else, and then the contribution of the resource will tail off.

The method suggested by Hubbert, and developed by Elliott and Turner, contains several limitations.

(1) One must know the resource base, i.e. the total amount of material in the ground which is expected to be available to a given technology. This is not easy to know and is *estimated*. Thus, the value of the resource used in the results, which I am going to give below, is not that which is known to be available, but that which the history of the rate of discovery of a resource suggests *will* be available on continuation of exploration. Thus, resource experts use several values of the resource base, because it involves some (though a fairly well defined) uncertainty.

(2) Estimates of a resource base cannot be separated from some assumption about the technology available for

extraction or recovery. It is only safe to assume that the technology of the next few decades will be that available now. With this assumption, it is easy to come up with a resource base figure; and, thereafter, one may produce other figures which become more speculative by assuming that technology, e.g. mining at depths too great for economic cooling to be made available to the miner, will become possible, perhaps by the use of automated mining machines, etc. Such assumptions give rise to an increase in the available resource base, and, finally, one can assume that the whole, even that at depths greater than that of any mining conceivable at present, will become available.

(3) Another assumption, which is the Achilles Heel of the resource-estimation field, and the justified butt of criticism, is that one must assume a rate of expansion of an economy. It is easy to point to hypothetical extrapolation of the past, when absurd results are indicated based upon extrapolation. It is difficult to know how to deal with this question, not only because the capitalist world is devoted to growth, but because within the few decades which the present discussion encompasses, much growth is built into the system. Thus, the average age of the population in Western countries is a low one, and many hundreds of millions of young people have still to grow up, become full energy consumers, and produce children who will grow up and consume energy, etc. Barring catastrophes of a magnitude which cannot be accepted into a Plan, great increases of resource use rates are hence bound to occur, before the population growth can be made zero and the living standard (i.e. the energy supply) less unequal.

What shall be the growth rates assumed? It can only be said at present that a *reversal* of the trends (5-8%) assumed would be likely to involve considerable political changes in Society, including in particular Government intervention (taxation, etc.) in the number of children born per family.

3. THE EXHAUSTION TIME OF THE FOSSIL FUELS

This most important question in our present energy considerations has been subject to little published work: it needs more work—and urgently—by Universities and independently-funded Research Institutes. The estimates given spring from the work of one man, King Hubbert,⁴

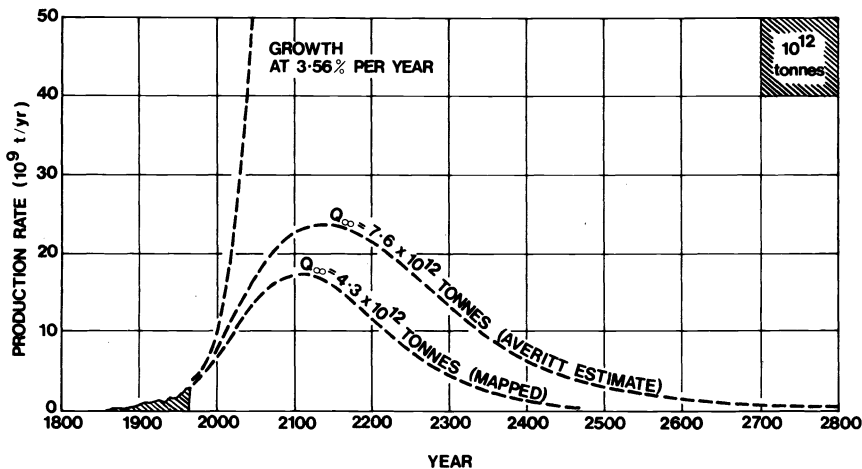


Fig. 2. A typical resource curve showing the maximum production rate referred to as exhaustion.

but they have been verified by the work of Elliott and Turner³ in 1972, and by that of Linden⁵ in 1973-74.

Oil and natural gas

There is not much to say about these resources, for their exhaustion (passing through the maximum) has already happened in terms of decades. Thus, Fig. 3 shows the complete cycle of U.S.A. crude oil production, and Fig. 4 the similar figure for the production of petroleum liquids. Here the growth rates of 5.8 and 5.1% have been used respectively. Therefore, the U.S. is out of oil, but this has to be understood not in the simplistic sense, but in the sense of the resource discussion of this paper. There will from now on be an increasing shortfall of U.S. oil which can only be made up by imports.

In respect to the O.P.E.C. oil, the estimates of what is available here must go much more upon the recent statements of Pahlevi than upon estimates made by independent observers. According to him, the Middle

East resources will last for about 25 yr always assuming, as throughout this paper, that growth rates will continue unchecked.

Coal

As seen below, coal is all we have—it is the only resource which can be called abundant—and the technology of conversion of which is well understood. For this reason the resource exhaustion curve for coal is of particular interest and a famous one, upon which many projections have been made, and is that given in Fig. 4 due to Hubbert.⁴ It is there seen that upon his assumptions there would be a maximisation of the production rate of coal at around 125 yr from the present time, comfortable enough so that one would expect that the inexhaustible resources would be ready and built up. However, the graph due to Hubbert involves an assumption, the removal of which brings a dramatic change to the figure. Hubbert has assumed the basic law of extrapolation,

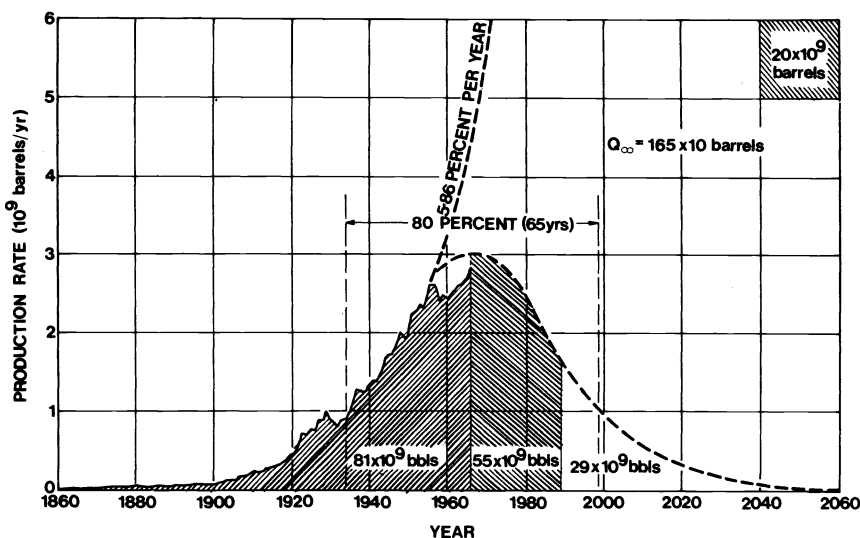


Fig. 3. The production-time curve for U.S. oil.

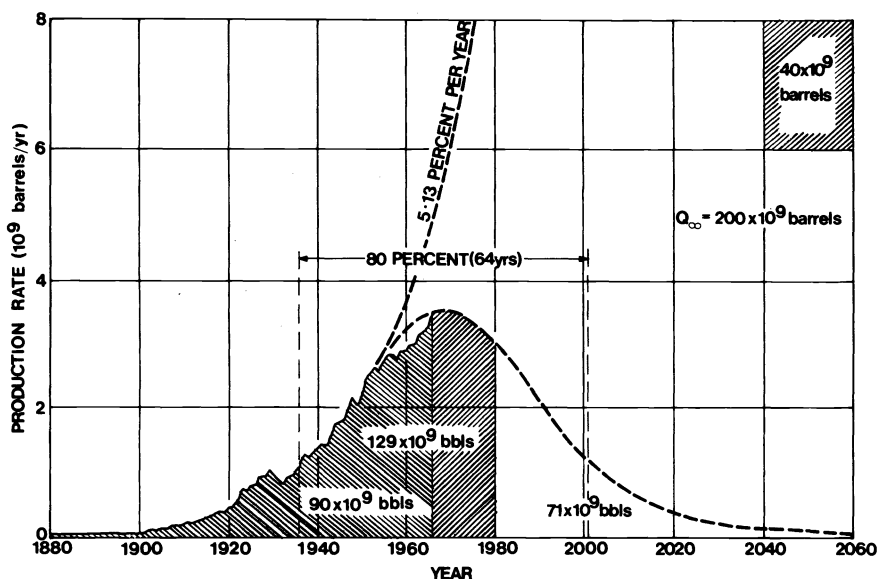


Fig. 4. The production-time curve for U.S. gasoline.

namely that things will be basically the same as before, although growth will occur. In the case of coal, this introduces a gross degree of optimism. Thus, coal supplies less than one-third of our energy needs. Were coal to begin to be used to replace oil and natural gas, there would have to be a multiplication of the rate of its use by about three times. The tuning in of the increased use of coal to take over from oil and natural gas, is not to be done simplistically, e.g. that on the basis that in some given year a changeover will be made. The extra claims on coal have to be carefully fed into the calculation of a resource curve and Elliott and Turner³ have done this, and the result is shown in Fig. 5, where it follows that the most probable time of exhaustion of coal (according to the Elliott and Turner approach, but see also below) is about 2040 or some 65 yr from now. This figure begins to show the cause for some degree of tension on the major question as to whether we shall be ready with the inexhaustible resources (*built up* the world over) in time.

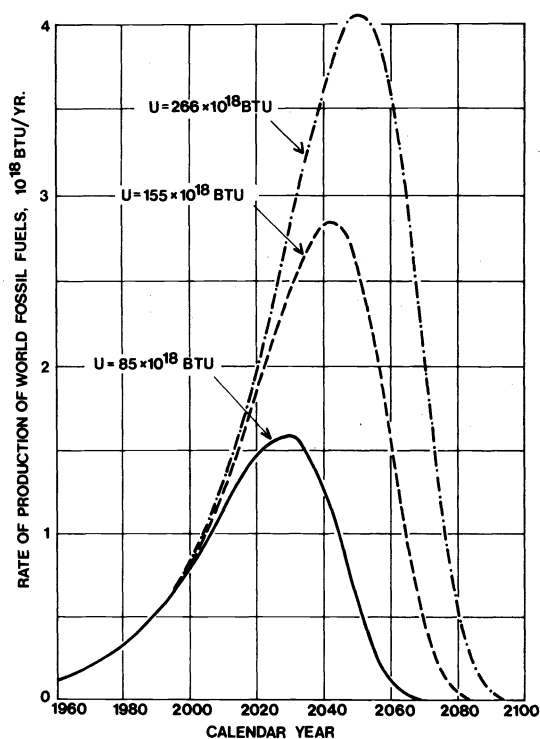


Fig. 5. Elliot and Turner's estimation of the total world fossil fuel production rate as a function of time, taking into account the increasing use of coal to cover the shortfall in petroleum and natural gas.

The Elliott and Turner estimate may be very optimistic for it neglects the difficulties associated with a sufficient rate of removal of the coal from the ground, i.e. the enormous amount of mine building, and this point will be elucidated below.

There are difficulties which inveigh against the foundation of a latter-day coal age, based upon the estimates of Elliott and Turner. Firstly, there are other, and more recent, estimates, and some of these are more pessimistic than those which arise from the work of Elliott and Turner. Thus, Brennan,⁶ basing his working upon the investigations of Starr,⁷ reached the conclusions of Table 1. He uses the unit $Q = 10^{18}$ B.t.u. = approximately 10^{21} J = approx. $3 \cdot 10^{14}$ kWh (1 B.t.u. = 1.05 kJ = 1.05 kWsec). Brennan states that world resources of fossil fuels are about 40Q and thus the amounts used between 1970 and 2000 will be some 20Q. In Brennan's analyses, world energy consumption maximizes at 2000. The most recent values are given by Linden.⁸ He calculates a maximum in the coal curve on the assumption that mining technology does not change, as occurring about 2010. If he then assumes that technology has advanced so that all coal is available, he comes to 2050, an agreement with Elliott and Turner's upper limit. Thus, it is seen that the average of these estimates is about 2025, but it would not be practical to rely upon coal after about 2010. These analyses, therefore, suggest that we have as little as 35 yr, and as much as 50 yr, to change from our present reliance upon the fossil fuels, to the reliance upon other sources (see Table 2). In this time, we should have to accomplish the necessary research and development and then we should have to carry out the colossal task of *building* the new machinery throughout the developed world.

4. LOGISTICAL AND OTHER DIFFICULTIES IN THE RELIANCE UPON COAL

The estimates made above would seem worrying, have regard to the time it takes to develop a new energy technology. Thus, the first atomic reactor was built in 1942, but no country has a significant amount of atomic power.

However, the estimates given may be too optimistic, and the reasons for a less happy view can be stated as follows.

The difficulty is in the rate of *removing the coal from the ground*. Thus, for example, a discussion in "*Industrial Week*" by D. B. Thompson¹⁰ brings up the question of whether it would indeed be possible to build a sufficient number of coal mines by the end of the century so that the U.S. could run entirely on coal. In the U.S. there are some 5600 mines and they produce about 603 million tons of coal per year, so that the output of each mine is about 0.1 million tons. According to Arthur a rate of production of

Table 1. Estimates of the year in which a maximum production rate of coal could occur†

Source	Year	Comment
Chase Manhattan Bank, elucidated	2033	Original report states 1500 yr at 1972 rate of consumption. Elucidation in text.
Brennan	2000	Assumes energy demand stops increasing at 2000.
Elliott and Turner	2040	Takes into account use of coal to replace oil.
Linden	2010	Assumes mining technology not radically improved on 1970's.
Linden	2052	Assumes all coal can be mined.
Linden	2073	Highest credible limit for resource base assumed.

†In general, the assumption is made that the logistical difficulty of mining coal *at a sufficient rate* has been solved.

Table 2. Time development of some energy sources

Source	Electricity	Steam engine	Fission	Fast breeder	Fusion	Solar
Scientific feasibility established	Faraday (1831)	Newcomen (1712) Watt (1765)	1942	1950	1975?	1954
Useful power	Sturgeon (1836)	Many developments	1955	1960	?	?
Economic power	Siemens (1856)	1785	1965	1980-90?	?	?
Time	25 yr	20 yr	23 yr	35 yr†		

†In general, the assumption is made that the logistical difficulty of mining coal at a sufficient rate has been solved.

about 3 billion tons of coal per year will be necessary by 1985 to avoid an energy shortfall. Thus, the number of coal mines would have to be increased at that time by some $3/0.6 = 5$ to avoid the energy shortfall. The manpower would have to increase from about 128,000 to about 1 million according to Arthur.¹¹ It seems reasonable at least to double this figure if one is to rely on coal exclusively by 2000 in the U.S. Thus, conservatively, one would need 56,000 coal mines, and were these to remain the same size as the present ones, one would have to open five new mines per day in the U.S.A. until the end of the century. Supposing the new mines were giants, ten times the present average size, the Americans would have to open a new giant every second day until 2000. Thus, it is not easy to see a reliance upon coal to take up the shortage of oil.¹¹ In fact, the growth of the electricity supply will be such that it will be difficult for the growth of coal mines to be sufficient to keep up with that.¹¹

Other figures of interest are that it takes 3 yr to put a strip mine into operation and 3-5 yr to start a small deep mine. This evidence is strongly against the use of coal as a source of replacement for oil and natural gas, so that evidence about coal and the difficulties of its use, need hardly be given.

Two other points are perhaps worth making briefly.

(1) The pessimistic results of the above considerations would be avoided if we could develop the underground gasification of coal. Unfortunately, we know all too much about this subject, for it has been researched extensively in the U.S., the U.S.S.R. and the U.K. Results are pretty miserable.¹² It is possible to set alight some coal in mines, but the fire only burns along the face which has been exposed and slowly into the interior of the coal bed. To get the gas produced (a mixture of hydrogen and carbon-monoxide) out of the shaft, one has to blow a great deal of air through, and the result is that the gas produced contains an abnormal amount of nitrogen. It is of poor quality and this is illustrated by the fact that its calorific value is about 1000 B.t.u. per S.C.F., whereas that of natural gas is about 1000. (See Table 3.)

(2) Lastly, there is the greenhouse effect. Admittedly, calculations of how long it would take for the extra CO₂ in the atmosphere to cause enough trapping of reflected solar light to cause trouble is fraught with much difficulty.¹³ What would the feed-backs be? How much extra cloud would cover the earth when the temperature rose? How much would the increasing world aerosol concentration reduce the solar heat reaching the earth? These factors are at present somewhat imponderable,¹⁴ although Manabe,¹⁵ and other atmospheric physicists are trying to see what sort of net figures can be obtained. Just

Table 3. Typical composition of underground gasification of coal

	Underground gas (%)
CO ₂	10.5
O ₂	0.9
H ₂	8.4
CO	10.7
CH ₄	1.8
Other hydrocarbons	0.3
N ₂	67.4
B.Th.U./ft ³	86.0

to shut down the last hope of relying upon gasified coal, for a plentiful supply of energy in the longer term future, we show Fig. 6 based upon the work of Plass.¹⁶ It assumes that all fossil fuels have been burnt by 2040; and that there

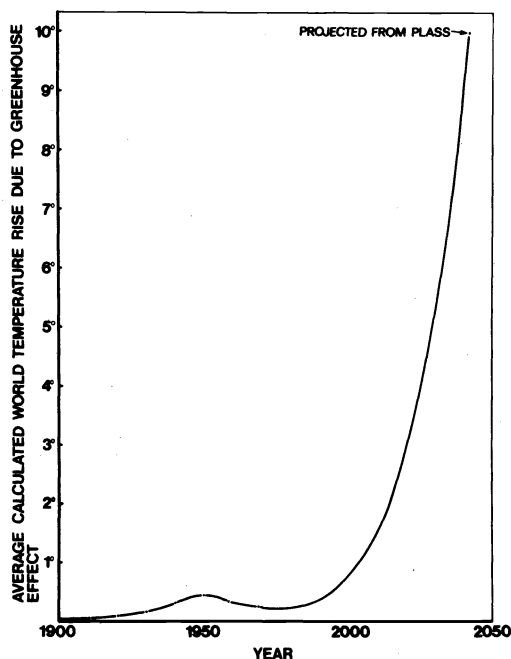


Fig. 6. A "guestimated" curve for temperature as a function of time. Points till ca. 1970 are factual. The downturn from the 50's arises from aerosol production. The point at 2040 is calculated from Plass' estimate of a 12°C rise in world temperature if all fossil fuels were burnt by that date (the mean of Elliott and Turner's exhaustion time). Dissolution in the sea is taken into account but the calculation neglects the effect of increased cloud formation, and changes in the polar albedo.

are no counter effects of aerosols, i.e. it is a worse case. However, it is so dreadful, 12 degrees increase in temperature worldwide, that even a partial application of it should knock out any concepts we have of going ahead towards that latter day coal age.

5. ON EXTENDING THE LIFE-TIME OF THE CHEMICAL FUELS

The evidence given suggests that, in round terms, we can rely on oil and natural gas to 2000; and that reliance upon coal to replace them is doubtful, but that reliance on it beyond 2010 would be a gamble with a number of adverse consequences.

In this circumstance, and knowing (see below) that the achievement of possible energy utopias are beyond these dates, the best thing we could do would be to attempt to change our methods of conversion of fossil fuel to energy so that instead of throwing away between two-thirds and four-fifths of the chemical energy of the reaction between a fuel and oxygen in the form of heat, we convert a greater proportion (50–60%) to mechanical energy. If such an aim could be achieved, we have the chance of doubling the time over which we could use our remaining fossil fuels, and therefore giving greater time for the needed research, development, and capital investment to build the new inexhaustible resources.

There are two methods by which we could make improvements, but only one of them looks hopeful. The first (well-known because of its relation to space age technology) is the electrochemical fuel cell. The overall action of a fuel cell (see Fig. 7) is well-known, but there is a subtlety within this action which is not widely realized. When we attempt to convert fossil fuels to mechanical energy, the chemical happening is the exchange of one set of molecular orbitals for another, and the sum of the potential energies of the one side of the equation differs from that of the other, so that heat is evolved, causing expansion which then can be transduced to mechanical energy. The critical event is a molecular collision between the molecules in the hot reacted gas, and the piston head of the transducer. In such a process, as hundreds of high school calculations show, there is a *loss* of energy, namely the translational (heat) energy is not all imparted

to the piston. Much of the energy which is given out in the reaction (the "Heat of Reaction") is lost. This is the origin of the Carnot efficiency difficulty of heat engines. In electrochemical engines, however, there is not the same difficulty, for there, the essential act, corresponding to the change of the orbitals in the chemical reaction, is the electron transfer from molecule to metal at the interface, and not a collision, an exchange of energy from translation.

Hypothetically we could get at least the ΔG , if not the ΔH out of a reaction in this electrochemical manner, and for many years from about 1836 until the 1950's there were very serious ideas abroad that fuel cells could give up to some 95% of the energy of the chemical reaction occurring in them back into electrical energy. Here again, however, nature shows another difficulty—quite a different one—but in effect analogous to that of the Carnot cycle. I refer to the overpotential of electrochemical reactions.¹⁷ The high chemical efficiency limit expected from the fuel cell and the carrot which has spurred on research workers in this area for many years, turns out to be feasible only at "infinitely low rates" of function in the same way that one could say that, ideally, a heat engine could work at 100% efficiency if the sinks temperature could be reduced to zero degrees Kelvin. The overpotential reduces the net potential one can obtain from a cell, and the net is smaller and the energy converted from the original chemical reaction therefore smaller than one had hoped for.

Nevertheless, in spite of these limitations, the fuel cell is much more efficient than the heat engine and on the whole one can rely on a conversion efficiency of more than 50% from it with quite realistic hopes of 60%, and a "not unfeasible" hope of perhaps 75% with certain fuels. All this means, therefore, that the conversion of our industry, whilst it still runs upon the fossil fuels, to an electrochemical one, would be the best way to span out the fossil fuel supply.

It would not be honest, however, to leave this recommendation without some reservations. On the one hand, fuel cells do not burn the classic fossil fuels, in particular coal, in any direct way. It would be necessary firstly to extract from the basic fuel, a derived chemical fuel—probably hydrogen—and of course, there would be certain losses in this conversion.

However, probably a greater difficulty is the fact that we must admit to a less than perfect understanding of the lifetime of fuel cells. If we quote a cost of a converter, it is understood as a comparative one, and the comparison is the internal combustion engine. This may have a life of 10–20 yr and when one conceives of a cell with a life of 2–3 yr, the costing comparison should not be done by a simple comparison of dollar kW.

Why is it that fuel cells do not, at the present time, have a lifetime which compares with those of heat engines?

The scientific aspect of the lifetime of fuel cells arises from recrystallization problems. Thus, catalytic activity depends upon the crystal size and, at the beginning of its life, the electrode catalyst shows an activity such that the overpotential is fairly low. Thus, the potential of a fuel cell is given by equations of the form

$$E = E_{\text{thermo}} - \sum \eta,$$

where η is the overpotential and is given by equations of the type:

$$\eta = \frac{RT}{dF} \ln \frac{i}{i_0},$$

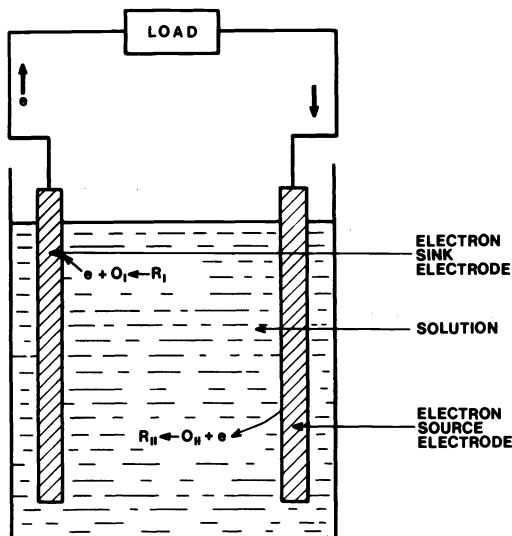


Fig. 7. The electrochemical energy converter (fuel cell). Conversion of energy in it does not suffer the Carnot Loss.

where i is the current density, or reaction rate per unit area. The i_0 factor represents the electrocatalytic activity of the surface upon which, e.g. oxygen molecules, are reduced to water. The larger this is, the smaller is the overpotential, and the larger the net potential of the working fuel cell. The desired efficiency of conversion of fossil fuels directly to electrical energy will occur when the overpotential is minimal or the exchange current density is maximal.

The lowering of the exchange current density (which occurs as a result of crystal growth) will lead to a loss of efficiency in energy conversion, and this is what is happening when the recrystallization occurs upon the surface of the electrode. The details of this process of recrystallization are not yet known, but there is a gain in size of the particles concerned, so that the major factor is the so-called Ostwald ripening.

Thus, the difficulty with lengthening the time at which a fuel cell electrode remains active is that one has to counteract a *thermodynamic* tendency. This does not imply exactly a pessimism in the task which concerns researchers in the practical abnegation of a thermodynamic trend. Doing that is a standard part of chemistry. However, at present, there is a limitation on fuel cell life due to the absence of a satisfactory method of, e.g. reactivating the electrode catalyst during its lifetime, and a satisfactory lifetime of fuel cell electrodes of more than about one year is difficult to confirm.

There is another approach to the question of a higher efficiency in the conversion of fossil fuels: that in which one produces hydrogen directly from coal, and then uses hydrogen and air-derived oxygen to work a so-called Aphodid engine. This is, in fact, a steam engine, but not of the usual type. Both oxygen and hydrogen are led in together and combined. The resultant steam thrust is applied to a turbine and in this manner a very small engine, about one-hundredth the volume of a classical steam engine of corresponding power, can be made.¹⁸

Progress with the Aphodid engine is not sufficiently far for us to be able to state confidently its efficiency and economics. Sixty per cent efficiency of conversion has been maintained, as good as fuel cells, but, of course, the power is not electric and the further stage with a generator is necessary. Further, another negative aspect of the Aphodid engine is that it requires hydrogen *and* oxygen, and the necessity of obtaining oxygen from air will reduce the economic viability of the method compared with the fuel cell. The trade-off between the two depends much on the solution of the lifetime problem with the fuel cells; together with the question, in the individual application, as to whether mechanical power (Aphodid engine has the advantage) or electrical power (fuel cell has the advantage) is needed.

It is interesting to note that acceptance of either or both these methods of converting fossil fuels to usable power would double the life of the oil and natural gas supply, so that were it feasible to think of a widespread use of these methods to be on stream within a decade, we might be able to stretch the use of the remaining oil and natural gas to about 2010, thus gaining a valuable decade breathing for the development of atomic and solar sources.

†It would, of course, be feasible to make breeder reactors clean as far as air pollution is concerned. The question is the cost. For example, completely burying a breeder reactor, running it in an atmosphere of argon, or locating it upon a remote area of the sea, should give rise at least to a more satisfactory situation, except for the disposal of plutonium which still presents the same difficulty.

6. THE DEGREE OF ADVANCEMENT OF ATOMIC ENERGY

Perhaps the most powerful feature of the present energy situation, and the one which has given rise to the greatest downward revision of our hopes of avoiding difficulty, is the poor rate of development of the breeder reactor. Earlier it has been assumed that the use of breeder reactors would be fully in swing during the 1980's. At present, the estimate is that they *may* be available early in the next century.

This lamentable change of expectation ("the revolution of falling expectation") arises from several causes.

(a) The actual function of the breeder reactor is as yet unsatisfactory.

(b) The problem of wastes is still unsolved in practice. Dealing with the *plutonium* wastes from the breeder reactors is something which could become too dangerous, because of the large number of breeder reactors which exist. At present far-out possibilities are considered, for example, putting wastes into orbit around the sun, or allowing the hot wastes to bury themselves in Antarctic ice.

These suggestions, however, are paper tigers on the side of the breeders and make little impression on the voting populace.

The other change in the picture of the breeder reactor is due largely to the work of Sternglass.¹⁹ Much criticized, it has at least been admitted by Sternglass' opponents that they cannot disprove its validity.²⁰ Briefly, the work suggests that there is indeed physiological damage to be obtained from *air* pollution in the vicinity of an atomic reactor.

How is it possible that an addition to the pollutional situation which is below background can cause an enhanced number of deaths, as indeed it seems to according to the work of Sternglass (Fig. 8)? There are two clues to the apparent anomaly. The human organism has developed over millions of years in an exact steady state with a certain amount of radiation damage, and a change in this upsets the established equilibrium, even though the change is small.

At the same time, the work of Petkau²¹ is of great significance. Petkau showed that the damage due to radioactive material was not linear with concentration, but passed through a maximum so that the calculations made, which assume that no radiation damage occurs until a certain threshold is reached (upon which the safety calculations of reactors are based), is incorrect. If the damage follows Petkau, a *smaller amount of radiation can be more damaging than a larger amount*.

The difficulties of breeder reactors on the pollutional side are often asserted as being subjective. There does appear, at this time, however, scientific evidence which suggests that the breeder reactor should not be built,²² and that the atomic energy programme should be confined to the far-off development of fusion reactors.

7. BASIC SOURCES OF ENERGY BY WHICH NEW CHEMICAL FUELS COULD BE GENERATED FOR A POST-2000 TIME

The amount of the conventional fossil fuels will not last past the end of the century unless transduced by electrochemical, or other special means; and that the use of coal to replace oil and natural gas has a dusty future. Furthermore, the expected use of atomic reactors (except for fusion) is not likely to be feasible at least in the time before the exhaustion of the fossil fuels.†

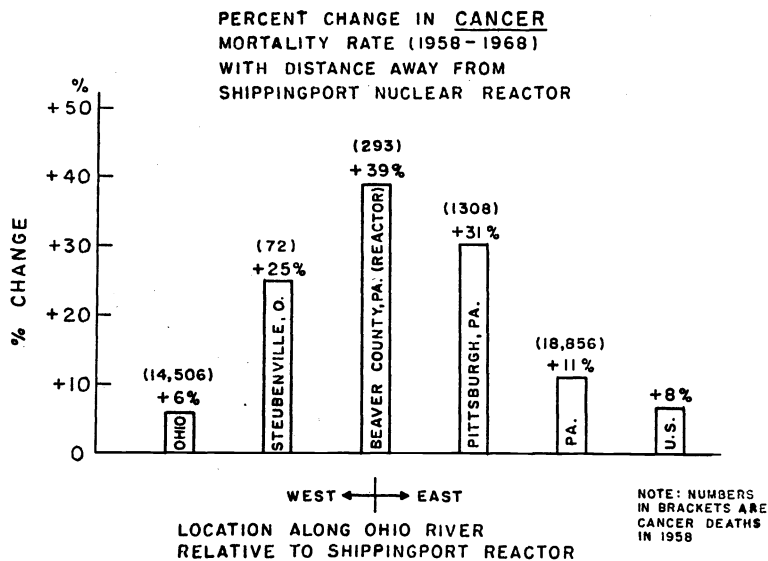


Fig. 8. Evidence of pollution from radioactive plants.

Under these circumstances (until, and if, fusion reactors ever become both possible and economic) there are only two other sources of energy which could be developed: the solar and the solar-gravitational sources.

There has been misunderstanding concerning the gathering of electrical energy from the sun. The conventional treatment pictures the cost of converting photons to electrons as impossibly high (100-1000 times greater than that of fossil fuels), but this view is archaic.

The method usually indicated in discussions of solar energy is the photovoltaic method, largely because this is the one hitherto proven. An analysis of the costs of photovoltaic and collective solar energy based upon the type of technology used by NASA in the space vehicles, does show a horrendous cost. A more positive analysis of this cost was first made in 1970 by Ralph²³ who pointed out that many of the costs involved in space technology could be reduced in a possible application to a massive supply of power. On the one hand, many of the reliability precautions used in space vehicles were not necessary in ground-borne reactors. On the other hand, the massive demand for the single crystal silicon sheet necessary for the making of such reactors would give a reduction in price. Analyses on these lines led to the figure of \$1000 per kilowatt, a considerable improvement, but not one which would be acceptable. One of the seminal advances came from the Tyco Laboratory and the work of La Belle and Mlavsky.²⁴ A modification of the Czochralski method of growing single crystals could be applied to pure silicon and that this could be in sandwich type strips. Although the situation at the time of writing²⁴ is that such strips are only one foot long and a few inches wide, it is projected that they may be feet long and one foot wide. With this method, therefore, the major cost component of making the single crystals has been overcome—previously they were made by hand—and the cost of solar-produced electricity could be pushed down towards a practical value.

The projection used by the Tyco workers is \$250/kW of collector, but this must be at least doubled because it omits the conditioning apparatus, storage devices, etc. Another modification of the costing quoted by Tyco is characteristic of solar energy methods which depend

upon the immediate incoming radiation—rather than that stored from earlier insolation—because there is the diurnal variation of the solar radiation; and the obscuring of the disk by cloud. These two factors, even in southerly climes, increase the cost by a factor of 4 so that the cost of the effective kilowatt in photovoltaic conversion—even with the projections of Tyco—is more than \$1000/kW, i.e. more expensive than atomic energy. In spite, therefore, of the lowering achieved by recent work in photovoltaics—which brings it in a range of prices which could be considered—there would still be a price disadvantage of going to this form of power production, rather than that of atomic energy.

There is, however, another method of producing solar energy and this is the sea-solar power method. It is illustrated in Fig. 9. One utilizes the temperature gradient in the tropical seas which may be 25°. Ammonia is evaporated upon the surface. The fluid works heat engines and generators in a conventional way and is then condensed by cold water brought up from the sea depths (see Fig. 10).

The method is efficient only about 2%. However, this hardly matters because of the great availability of the heat source concerned. Costing of this method runs to about 0.6¢/kW in 1975 terms and even at some thousands of miles from the tropical sea, the method would seem to yield energy at a suitable price.

There is a fundamental reason why this method gives rise to a more satisfactory yield than does the photovoltaic method: sea-solar power collects *stored* solar energy. It does not depend on the rate of energy coming in, and is not subject to diurnal variations or weather changes.

Lastly—and of great importance—is the availability of belts of high velocity wind. These exist in various parts of the world (Fig. 11) and if the wind within them exceeds about 25 km/hr, a 100 m rotor will yield about 4 MW. The wind is sporadic, but in a given location, it is constant over the year so that there is great significance in the value of the mean annual wind.

To be sure, a rotor of 100 m in radius has not yet been made, but engineering designs which would avoid the impossibility of having to suspend such a rotor upon its axis are available (Fig. 12). Even if the individual rotor of

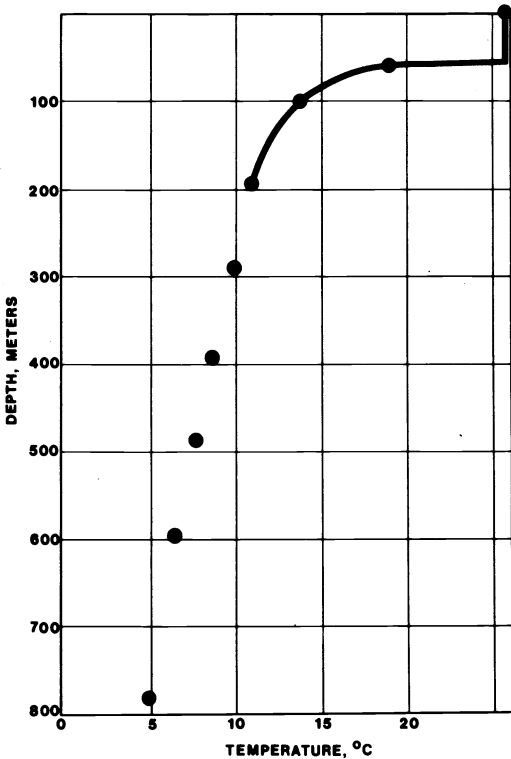


Fig. 9. The temperature gradient which is the origin of sea-solar power.

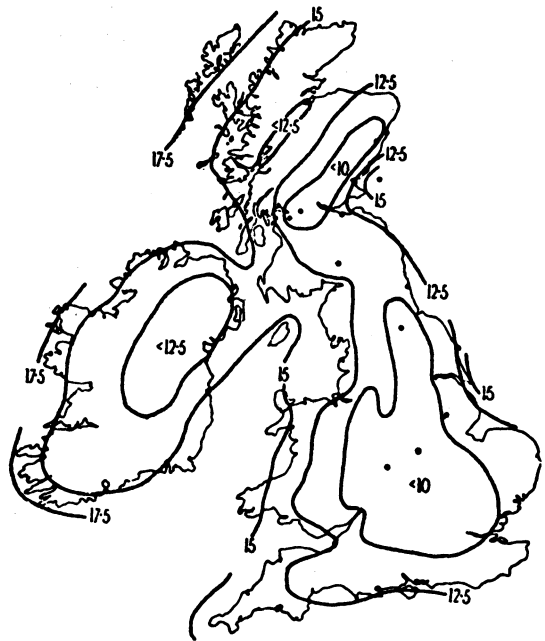


Fig. 11. Evidence of windbelts of more than 20 mph.

100 m turned out to be impractical, achievement of something near to their power could be made with smaller rotors covering the same area.

8. CHEMICAL FUELS POST 1990

Having discussed the major source of energy for the future—it will be advantageous to discuss the fuels with which they will be associated. The new sources of energy

produce electricity directly and it is a feasible proposition that there will be only one fuel in the future: electricity. Thus, a popular concept in the United States is a nuclear-electric economy in which nuclear reactors are small and frequent, so that they supply centres not more than 100 miles or so from themselves. Then, the electricity from them would not be raised significantly by classical transmission through a grid.

There is much to suggest, however, that such a course could be unwise. Thus:

(1) A transfer to an all-electric economy, to be carried out so quickly (25 yr), is unfeasible. It would imply an enormous increase in the rate of development of electrochemical technology, and the amount of research

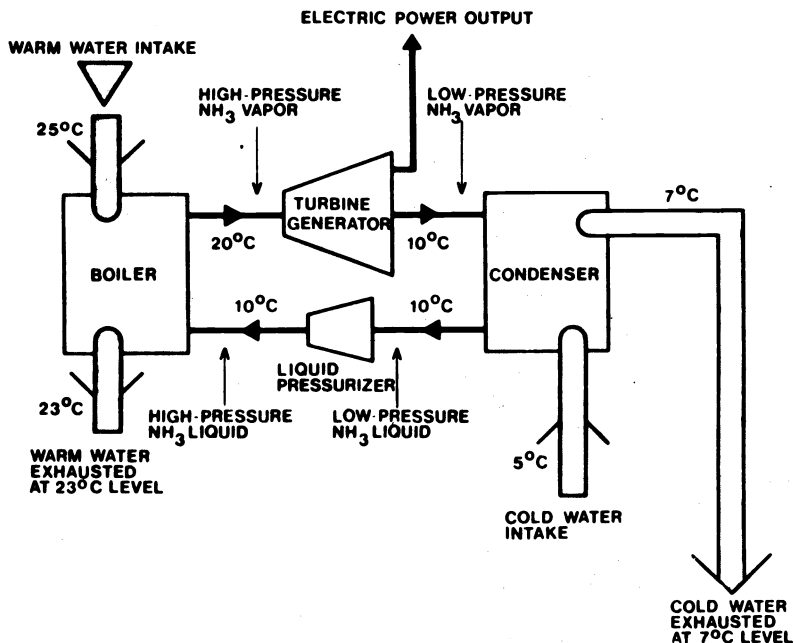


Fig. 10. A schematic diagram of a sea-solar power plant.

and development in this field which would have to be done could not be carried out in such a short time.

(2) Independently of the time element, it is advantageous to have a greater distance between the source of the energy and the site of use. This conclusion arises for two reasons:

(a) If the sources are fission and fission-breeder atomic reactors, there is a pollutional problem and a large distance between the source and sink is necessary. If the reactor is very large (and hence its product very cheap), it may not be practical to take the electricity over the distance concerned in wires: it would have to be taken in hydrogen, or another chemical fuel, perhaps methanol.

The advantage from taking electricity over long distances in the form of hydrogen is shown in Fig. 12, a key figure of this paper.²⁶ The advantage begins at 300 miles, and, at any practical voltage, would be present at over 700 miles.

(b) If the energy originates from a solar source, it will be desirable to locate the collectors between the latitudes 30 N and 30 S, probably largely in the latter zone. Thus, one could imagine collectors for South East Asia being in Australia, those for Europe being in North Africa, and those for the United States being in the Caribbean Sea, and the South Eastern Pacific. Under these conditions, transfer of energy in the form of hydrogen would be essential.†

The case for methanol is less clear in respect to the coupling with atomic and solar sources. Thus, methanol would have to be made from atmospheric CO₂ and hydrogen produced from water so that it is difficult to see that it could be cheaper than hydrogen. However, a case for methanol can be made. Thus:

(1) It overcomes the psychological difficulties of hydrogen, presenting the public with a fuel which is similar to the one to which they are accustomed.

†For distances of more than 4000 miles, Ehrlicke²⁷ has suggested that transfer by means of power relay satellite would prove to be a cheaper mode of energy transfer.

(2) It is more convenient to handle than hydrogen.

There may be a way in which methanol is produced, via photosynthesis. An attractive path for Australia would be by the use of solar insolation at sugar canes where an efficiency of 1% can be expected. The drawback is the low efficiency and the larger area of ground which would be needed.

A fuel which must be mentioned in passing—if perhaps to bury it—is hydrazine. At first it would seem to have enormous advantages. It does not produce CO₂ upon burning, it is a liquid with acceptable properties of boiling point and the only disadvantage put forward is that it is too expensive. However, the expense might yield to mass production, and it resides in the crystallization stage, whereas it is not necessary to pass through this stage before dissolving it in solution to use in a fuel cell.²⁸

Two disadvantages are associated with hydrazine in respect to massive chemical use. In contact with metals, there is a rate of dissociation to ammonia, so that a hydrazine-driven car allows itself to be detected nasally. There is also evidence that hydrazine may have carcinogenic properties and it is discussed much less than formerly.

9. CHEMICAL FUELS AS TRANSMISSION AGENTS

Thus, chemical fuels will exist in the post fossil fuel age:

(a) Because the sources of energy will be far from the corresponding sinks and the transmission costs are lower.

(b) Because it is convenient to utilize chemical fuels for many tasks in chemical and metallurgical technology for which the electrochemical methods needed to couple directly with electricity are not yet ready. Eventually, electrochemical methods can probably be worked out for many of the situations concerned, but the question of transmission does not seem likely to be overcome, and the long term existence of the chemical fuels depends upon its necessity.

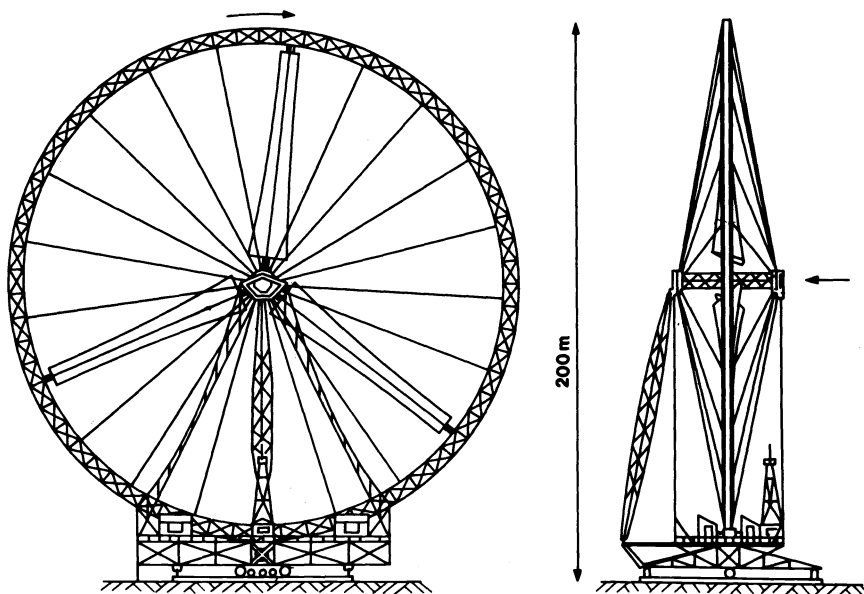


Fig. 12. A possible design for a large rotor. The weight rests on twelve axes at ground level.

10. THE ADVANTAGES OF A HYDROGEN ECONOMY

There have been hints for many years that the eventual fuel would be hydrogen and a briefer view of the history of the suggestions has been made by Bockris.²⁹ The term "A Hydrogen Economy" was used first by Bockris and Triner²⁹ in 1970. Dean and Schoepfel³⁰ used the same term independently at about the same time. The phrase is meant to cover a concept in which the forthcoming energy sources (solar-gravitational, solar, fusion) are coupled to water to produce abundant hydrogen and oxygen. The cheap hydrogen would then be piped to the cities and utilized as the universal fuel. In houses, it would run heating and cooling systems, and produce electricity from fuel cells. In transportation, it would run cars either by substitution for gasoline; or by fuel cell-electric motor combinations; and industry, it would replace natural gas. It would have many other uses, some of them in metallurgy, and been perhaps, as a significant supplement to the fresh water supply³¹ (Fig. 13).

All these applications of hydrogen as a fuel, taken together, would make a Hydrogen Economy, and there is, to look at the matter generally, an advantage in attempting such an economy on ecological grounds. It is the only suggestion in which the ease of transmission of energy over long distances is coupled with the great breadth of the possible applications, and a *completely* ecologically sound situation. Thus, the use of hydrogen fuel is circular, for it arises from water, and the end product is water. Application of hydrogen fuel would provide a quite general solution to all air and water pollution problems.

There are two difficulties to be overcome in the concept of a Hydrogen Economy.

Dangers and difficulties in the use of hydrogen: there is no doubt that hydrogen is a more dangerous fuel than the nearest comparison, synthetic natural gas, because its flash point covers a wider temperature range than does that of methane.

On the other hand, there are ways in which hydrogen may be safer than natural gas. For example, in an automobile accident, where gasoline, or liquid natural gas,

is spilt, the hydrocarbon vapour remains low near the ground and can cause explosion easily on contacting a hot body; whereas hydrogen rapidly evaporates upwards, reducing the danger of fire.

One difficulty is illusory. the concept of easy explosions with hydrogen is not a likelihood, for these only can occur in enclosed spaces, where, of course, great precaution would have to be taken.

The other alleged difficulty of hydrogen is in the pricing. However, this difficulty arises largely from a misunderstanding for it only exists if comparison be made with the present price of the disappearing fossil fuels. Thus, the ex-refinery price of United States gasoline in mid-1974 was about \$2.40 per MB.t.u. The price of hydrogen, available at that time, was about twice this. However, there is no doubt that the price of hydrogen can be lowered, by using one of the several new methods proposed below; and there is no doubt that the price of gasoline will rise, because it is exhausting.

Thus, it is better to compare hydrogen with methanol which is really the only useful competitor to hydrogen for it (methanol) could be made continuously from solar energy and vegetation or from fusion-derived energy it could be made from atmospheric CO₂ and electrolytically produced hydrogen.³² However, the photosynthetic method would require prodigious quantities of insolated land and is really only worth considering in Australia. The second matter is that the fusion and CO₂ derived methanol would come only from hydrogen. Economically, it would be more expensive. Methanol's main advantage is psychological.

11. ON NEW METHODS FOR THE PRODUCTION OF HYDROGEN

The classical methods of producing hydrogen have been from natural gas, but its production from this substance, and from naphtha can be neglected in the future time because of the lessening availability of such fuels. Water is the only fuel which can be used. The following summaries include methods of producing hydrogen from water.³³

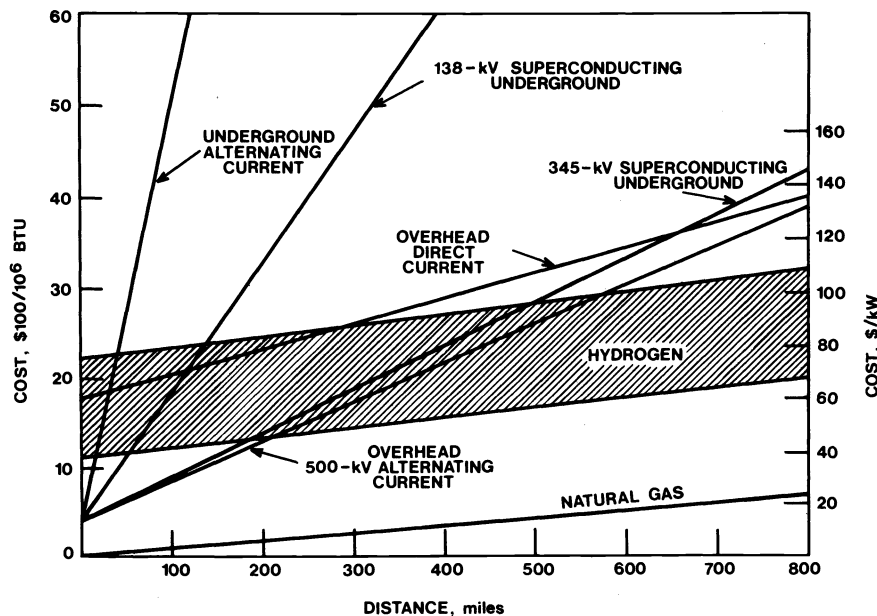
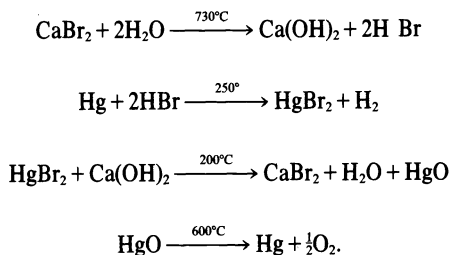


Fig. 13. The cost of the transportation of energy by hydrogen and by electricity.

The chemical synthesis method

There is no practical possibility of producing hydrogen from water merely by heating it because there is an insufficiency of hydrogen in the equilibrium gas even at the impractical temperature of 2000°C. However, if a series of cyclical reactions are carried out, some of which have positive and some of which have negative entropy changes, then, by making the temperature high for those with positive entropies and low for those with negative entropies, the overall hydrogen production can perhaps be attained at much lower temperatures than 2000°, e.g. at 1000°.³⁴

This method is that on which the majority of the new work on hydrogen production is now centred. A typical example of the sequence of reactions used would be as follows:



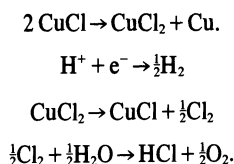
However, this type of method has its troubles. Firstly, it had apparently been forgotten by the originators that if the gases are to be heated and cooled during the cycle, and there is a change in pressure, there must be an equivalent of the Carnot efficiency factor involved. This has been examined by Appleby,³⁵ and also by Funk.³⁶ The results obtained indicate that the efficiency of hydrogen production will often be low, less than the overall efficiency of conversion of heat to hydrogen via electricity. In those cases where this is so, there is no point in pursuing the chemical cycles method, with its complications of several reactors, high temperatures, and necessity for a high degree of cyclicity.

Where the efficiency of the cyclical method exceeds 40%, there may be point in pursuing the method. However, the important thing is the final cost of the product and this does not only involve the question of efficiency, but also that of maintenance costs. Those for complex high temperature processes are notorious. Would the degree of cyclicity be sufficiently high?³⁷

New methods in electrolysis

A host of new developments in the electrochemical method have become available during the last 5 yr. Those which may be mentioned here are as follows:

(a) Methods which involved electrolysis of an easily decomposed material, with a thermal assist to complete the cycle. For example:³⁸



(b) Methods which involve direct electrolysis of steam at a low electrical potential, but maintain the temperature of the cell by using outside (relatively cheap) heat which is directly converted to hydrogen.³⁹

Photo-production of hydrogen

This method, which is in its infancy, looks the most hopeful. Thus, one may be able to photoproduce hydrogen as a result of impingement of the solar radiation upon an electrode, stimulating the emission of holes from a semiconductor type material, such as TiO₂ and the effective injected electrons (e.g. from OH⁻) are then fed round a circuit to cause hydrogen evolution on the other side, a photodriven fuel cell.⁴⁰

Photosynthesis of hydrogen by the enzymes which decompose water is another aspect of interest, and the work of Bennermann,⁴¹ and of Neil and Bockris,⁴² have shown that reasonable efficiencies and yields can be obtained, although the lifetime of the algae which contains the enzyme is problematical (Fig. 14).

In Table 4 are given numerous estimates of the price of hydrogen with new methods. There is a chance that this fuel will be cheaper in the next decade than is petroleum in the present one (Fig. 15).

Storage of hydrogen

There are three methods:

(i) *Storing in hydrides.* Many new hydrides have been suggested but those which seem to have excellent properties, e.g. those containing the rare earths, are too expensive. Magnesium hydride is a possibility, but it decomposes at a high temperature and the hydride method, excellent because of its safety and convenience, is too expensive.⁴³

(ii) *The storage of hydrogen underground.* For large quantities of hydrogen, underground storage, similar to that now used for natural gas, seems indicated.⁴⁴

(iii) *As a liquid.*⁴⁵ The creation of liquid hydrogen would cost about 85¢/MB.t.u. and thus increase the price by about 33%.⁴⁶ It is problematical whether such a price

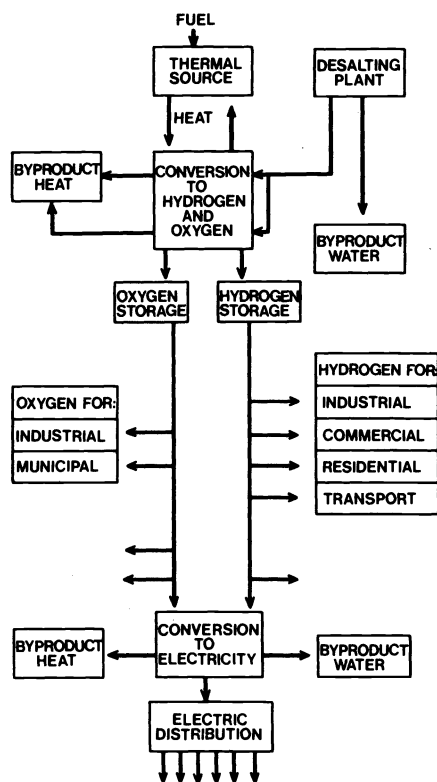


Fig. 14. The Hydrogen Economy.

Table 4. Cost estimates compared

Method	Estimate for MB.t.u.	Remarks
Coal	2.65-3.10	Coal assumed \$14 per ton. 50% added purify 96%-99.9%. Process not yet realised. \$1.50 quoted June 1973 for 96% H ₂ from coal at \$8 per ton.
Cyclical thermal decomposition	1.40-2.10	50% efficiency <i>assumed</i> . \$1.40 accepts author's estimate fixed costs = steam reforming. \$2.10 takes fixed costs as doubled. Process not realised.
Electrolytic, classical	1.76-2.72-5.66	Range is for 2.4-10 mils electricity. Technology obsolete.
Emerging technology	1.00-1.77-3.83	Range is for 2.4-10 mils electricity. Good experimental basis.
Solid electrolyte, 1000°C + atomic heat	2.14	Assumes no IR heat, negligible overpotential.
Anode depolarised aqueous	1.51	Assumes available zero cost CO, SO ₂ , NO, sewage in large quantities used in reaction at anode. Experimental basis.
Electrolysis of HI	2.35	At 7 mils. Some experimental basis.
Electrolysis of CuCl	2.19	At 7 mils. Outlook for feasibility excellent.
Electrolysis of FeCl ₂	3.93	At 7 mils.
Electrolysis of SnCl ₂	2.05	At 7 mils. Side products?
Photodecomposition of HI	1.50	Some experimental basis.
Photoelectrochemical direct to H ₂	1.00	Assumes negligible use noble metals. Experimental basis at 3% efficiency.
Photosynthesis, nitrogenase enzyme	0.30	Speculative estimate. Assumed unknown reaction rate is middle range other photosynthetic reactions; assumes nitrogenase cheaply mass-producible.
Aero generators	2.10	Cost of aero generators main contribution. As yet speculative.
Plasma torch photolysis	See remarks	Depends on price of fusion produced electricity. 70% cost of electrolysis using that electricity. Hypothetical.

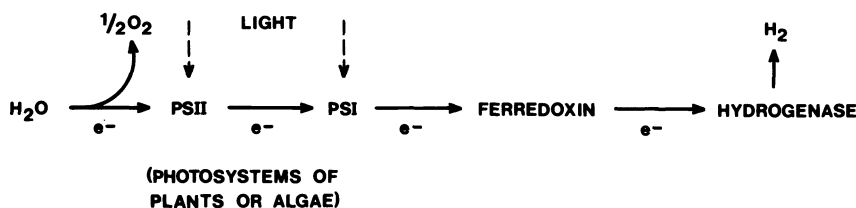


Fig. 15. The photosynthesis of hydrogen.

increase is worth the advantage to be gained, for, e.g. in transportation sufficient hydrogen can be retained in cylinders for a reasonable range (e.g. 250 miles) for a car.†

12. HYDROGEN IN TRANSPORTATION

There is every chance that hydrogen would be an acceptable fuel for transportation: in fact, its only rival is methanol. In both cases, the modification to the present internal combustion engine would have to be rather slight⁴⁷ so that the economics of change-over to one of these fuels would be favourable. Both would reduce the pollutional difficulties of transportation although NO would be a difficulty and with methanol carbon dioxide could cause the greenhouse effect.

One aspect of the transportation picture heavily favours hydrogen.⁴⁸ It is an excellent fuel—perhaps an indispensable one, for advanced aircraft (Fig. 16). The concepts of this paper could not be realized in a time of less than 10 yr, and largely from 1990 to 2000 onwards, so

one must think of air transportation not in respect to the SST but to the hypersonic transport.⁴⁹ This vehicle, which would be capable of about 6 Mach, could only be run on hydrogen, for weight reasons. However, the reason for this is not only the obvious one of the amount of energy to be carried for a reasonable range, but the more subtle one of the materials of which the plane can be made. Ideally, these are light-weight alloys. However, many of them would not stand the temperature which will be experienced by the skin of an aircraft travelling at approximately 4000 mph. Under such circumstances a cooling system would allow light-weight alloys to be used, and thus the carrying capacity of the aircraft enormously increased. Such a cooling system, with glycol water mixtures, would be possible with hydrogen as a fuel.⁵⁰

13. THE CURIOUSLY 1960 NATURE OF 1976 GOVERNMENT'S FUNDING OF ENERGY RESEARCH

In view of the present prospects for the fuels of the future, the funding of research by the United States Government has a curiously old-fashioned appearance about it. It consists of the support, with sums in the orders of hundreds of millions of dollars per year, of the development of the older fuels, those which are exhaust-

†Appleby⁴⁶ has suggested the storage of hydrogen within a tubular structure of the car itself. The hydrogen would drive fuel cells which would charge batteries, used for producing boosting power during acceleration.

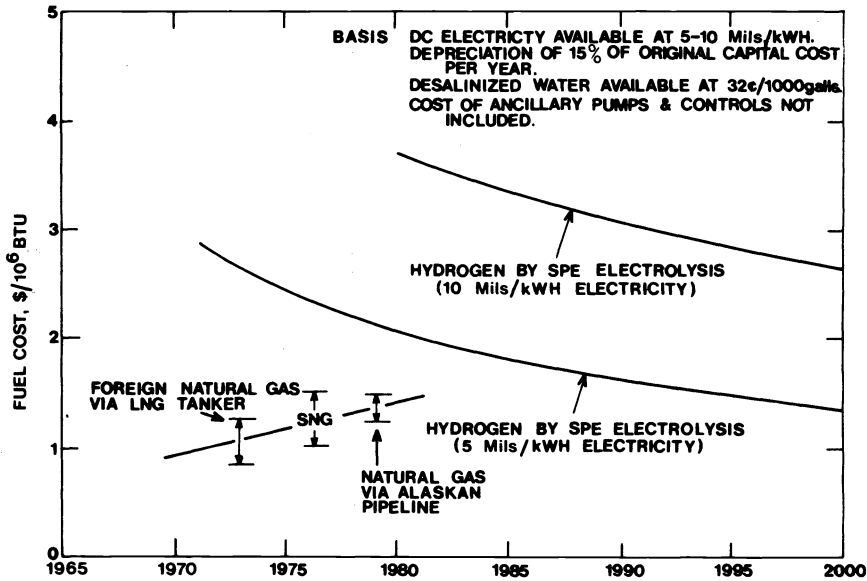


Fig. 16. The predicted hydrogen price in constant dollars as a function of time.

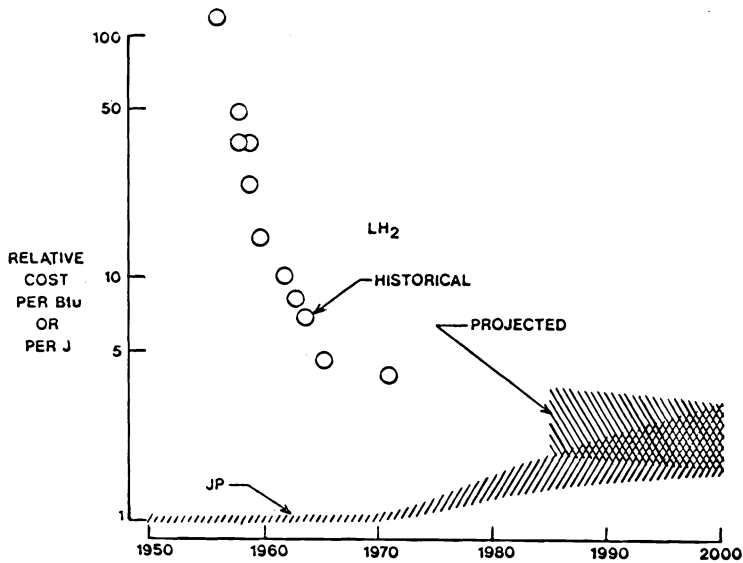


Fig. 17. The projected cost of hydrogen as a fuel.

ing, and which cause air pollution. Support of Atomic Energy is still running in the hundreds of millions per year. Support of research into the newer fuels, those which will couple with the near future energy sources, and which will remove the pollutive difficulties of our economy, is in the tens of millions of dollars per year. There seems little coupling between ecological thinking, concepts of abundant clean energy, and the creation of appropriate fuels.

14. ON NEWTON'S FIRST LAW AND THE FUTURE OF MANKIND

According to Newton's First Law, a body continues to move with the same momentum, unless acted on by another force. The present situation in the world energy policy appears to be an illustration of Newton's First Law, because the general posture of the Nations is one which continues, long after the bell has rung, with the same type of energy policy—now obviously hobbling

badly—as that appropriate to the 1960's. Synthetic natural gas and Breeders are supported. It is the new chemical fuels which must be supported—and those which will couple with the new energy sources, hydrogen above all, and perhaps methanol, maybe even hydrazine. The question, now, is, can such conversions be made *in time*.

Acknowledgements—I am indebted to Mrs. Dorothy Hampton and Mrs. Christine Battersby in respect of editorial work on this paper. Mr. McCann has helped me with diagrams.

REFERENCES

- ¹D. H. Meadows, D. Meadows, J. Randers and W. W. Behrens, *The Limits to Growth*. Potomac Associates, Washington (1972).
- ²M. K. Hubbert, Energy sources, in *Resources and Man*. National Academy, San Francisco (1969).
- ³M. A. Elliott and N. C. Turner, presented American Chemical Society, Boston (1972).
- ⁴M. K. Hubbert, Energy resources for power production, in *Environmental Aspects of Nuclear Power Stations*. Vienna (1971).

- ⁵H. Linden, Analysing world energy supplies, World Energy Conference, Chicago (1974).
- ⁶M. A. Brennan, in *Physics and the Energy Industry*. Flinders University, Adelaide, pp. 1-14 (1974).
- ⁷C. Starr, *Scientific American* (Sept. 1971).
- ⁸H. R. Linden, Energy self-sufficiency, Institute of Gas Technology, Chicago (1971).
- ⁹C. N. Watson-Munroe, World energy resources, Sydney University (1974).
- ¹⁰D. B. Thompson, *Industrial Week*, p. 17 (26 Nov. 1973).
- ¹¹J. Arthur, Duquesne Light Co., Pittsburg, Po., private communication (1974).
- ¹²P. N. Thompson, *Appraisal of Underground Gassification*. U.K. National Coal Board (May 1974).
- ¹³J. O'M. Bockris and A. K. Reddy, *Modern Electrochemistry*. Plenum, New York (1970).
- ¹⁴S.P.E.C. Report, *Man's Effect on the Environment*. M.I.T. Press, (1973).
- ¹⁵S. Manabe and R. T. Wetherald, *J. Atm. Sci.* **24**, 241 (1967).
- ¹⁶G. Plass, *Tellus*, **8**, 140 (1956); *Electrochemistry of Cleaner Environments*. Plenum, New York (1972).
- ¹⁷J. O'M. Bockris, Overpotential, *J. Chem. Educ.* **48**, 352 (1971).
- ¹⁸J. O'M. Bockris, *Energy: The Solar-Hydrogen Alternative*. Australia-New Zealand Book (1975).
- ¹⁹E. J. Sternglass, *Low Intensity Radiation*. Earth Island Press (1973).
- ²⁰*Ibid.* Preface to *Low Intensity Radiation*. Earth Island Press (1973).
- ²¹A. Petkau, *Health Phys.* **22**, 293 (1971).
- ²²A. R. Tamplin and T. B. Cochran, *Radiation Standards*. Washington (1974).
- ²³E. L. Ralph, *Proc. 8th Photovoltaic Specialists Conference*, Seattle (1970).
- ²⁴H. E. La Belle and A. T. Mlavsky, *Mat. Res. Bull.* **6**, 571 (1971). F. Collins, National Science Foundation, Memo. (May, 1974).
- ²⁵D. Jewett, private communication (1975).
- ²⁶D. Gregory, H. Long and N. Ng, *Electrochemistry of Cleaner Environments*. Plenum, New York (1972).
- ²⁷K. A. Ehrlicke, Report before the Committee on Space Science (Oct. 31, 1973).
- ²⁸J. O'M. Bockris and D. Drazic, *Electrochemical Science*. Taylor & Francis, London (1972).
- ²⁹J. O'M. Bockris, *Chem. & Eng. News*, p. 14 (June 1972).
- ³⁰J. L. Dean and R. J. Schoepel, paper presented to the 1971 *Frontiers of Technology Conf.*, Oklohoma (30 Sept. 1971).
- ³¹J. O'M. Bockris, *Energy: The Solar-Hydrogen Alternative*. Chap. 14, Australia-New Zealand Book (1975).
- ³²M. Steinberg, private communication (1974).
- ³³J. O'M. Bockris, *THEME Conference*, Miami (1974).
- ³⁴C. Marchetti, *Chemical & Engng Rev.* **5**, 7 (1973).
- ³⁵J. Appleby, *Nature*. To be published (1975).
- ³⁶J. L. Funk, W. L. Conger and R. H. Carty, *THEME Conf.* Miami (1974).
- ³⁷J. Marchon, *THEME Conf.* Miami (1974).
- ³⁸J. O'M. Bockris, *THEME Conf.* Miami (1974).
- ³⁹J. O'M. Bockris, *Advanced Energy Conversion*. London (1975). In press.
- ⁴⁰A. Fujishima and G. Honda, **238**, 38 1972.
- ⁴¹J. R. Bennermann *et al.*, *Proc. natn. Acad. Sci. U.S.A.* **70**, 2317 (1973).
- ⁴²G. Neil and J. O'M. Bockris, To be published (1975).
- ⁴³J. H. N. Vucht, F. A. Kuijpers and H. C. A. M. Bruning, *Philips Res. Report*, **25**, 113-140 (1970).
- ⁴⁴M. R. Tek *et al.*, New concepts in underground storage, Monograph on Project PO.50, University of Michigan (1966).
- ⁴⁵J. O'M. Bockris, *Energy: The Solar-Hydrogen Alternative*. Chap. 10 Australia-New Zealand (1975).
- ⁴⁶J. N. Appleby, Private communication, London (1975).
- ⁴⁷N. C. Hollett, N.A.S.A. Report, C.R.-73226 (1968).
- ⁴⁸L. O. Williams, *Cryogenics*, **669**, (Dec. 1973).
- ⁴⁹J. O'M. Bockris, *Energy: The Solar-Hydrogen Alternative*. Australia-New Zealand Book (1975).
- ⁵⁰R. D. Wittcofski, *7th Intersociety Energy Conf.* San Diego (Sept. 1972).
- ⁵¹J. V. Beeker, *Astronautics and Aeronautics*, **9** (8), 32 (1971).