PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

World Coal Resources and their Future Potential [and Discussion]

G. Armstrong and J. M. Cassels

Phil. Trans. R. Soc. Lond. A 1974 **276**, 439-452
doi: 10.1098/rsta.1974.0030

Phil. Trans. R. Soc. Lond. A. **276**, 439–452 (1974)
Printed in Great Britain

World coal resources and their future potential

By G. Armstrong
Mining Department, National Coal Board, London, SW1X 7AE

Despite the uncertainties which arise from drawing inferences from the published figures of world coal resources which are based on a variety of assessment procedures, there can be no doubt that coal is the world's most abundant fossil fuel, with total reserves of the order of 9×10^{12} tonnes.

Industry, however, can only be interested in those reserves which are exploitable now or seem likely to be in the future. As time passes, the proportion of recoverable reserves varies and is controlled by advances in technology, changes in the economic circumstances and the level of exploration.

There is a continuing need to balance reserve availability and productive capacity against present and future demand. The locating of economically recoverable coal reserves takes time, and so does the build-up of the necessary market requirements (e.g. construction of new power stations). When there is a need to increase or replace productive capacity, it is important to plan well in advance in the exploration, production and marketing phases.

Timely investment in world coal exploration and productive capacity appears essential in view of possible shortages of other fuels.

1. Introduction

Demand for energy in one form or another will always be with us and the balance of utilization of the world's basic sources will depend on their availability at currently competitive prices. In regard to coal, there are a number of fundamental controls which affect its economic availability. These are partly geological, with which must be linked the engineering resources appropriate to a particular geological environment, and partly economic and logistic. The economic circumstances are mainly determined by the price levels of competitive fuels, and logistics by the location of reserves in relation to markets and feasibility of cheap transport.

It is important to note that, apart from the basic geology of the deposits, all the remaining factors, including the degree of knowledge of geology, are variable with time. Engineering efficiency can improve, albeit generally slowly, with fresh technical innovations, as can transport; while the economic climate is probably the greatest variable and is likely to change rapidly and unexpectedly.

Because of all these variables, estimates of reserves, particularly those thought to be economically recoverable, can vary from time to time even though the basic geological environment is fixed and the gross total of coal reserves changes hardly at all.

2. Geological factors affecting assessments of reserves

The principal coal reserves of the world are geographically widely distributed and spread over a very broad band of geological time ranging from the Carboniferous to the Tertiary. The bulk of the economically important reserves, however, are in the Carboniferous of Europe and eastern North America and the Permian of the Southern Hemisphere and Asia, while the bulk of the western reserves of the U.S. and Canada are of Cretaceous age. In addition to its widespread geographical distribution, and its extensive spread of age of origin, coal occurs in a variety of geological environments depending on the original conditions of deposition and the effect of subsequent metamorphosis, mainly arising from temperature changes generated by compressive earth forces.

The substance we call coal, therefore, is sometimes lignite, sometimes bituminous coal, or anthracite or an intermediate type. Each type can contain, depending on its origin, variable amounts of dirt, sulphur and other constituents, all of which can affect the value of the coal and hence the proportion of the gross reserves considered at any one time to be economically workable. The geological conditions which largely control the ease with which the coal is mined are, however, the basic controlling factors in determining reserve assessments.

The sedimentary environment of the coal seam demonstrates the original mode of origin and is of critical importance. Different regional rates of variation may be exhibited by different sedimentary phenomena which include the coal seam structure itself, i.e. incidence of splitting and the thickness and disposition of bands of dirt and inferior coal, together with its overall thickness and physical and chemical properties. The sedimentary environment has also given rise to such vital factors as the composition and physical properties of the roof and floor strata, the occurrence of washouts and associated compactional disturbances.

Earth forces subsequent to the original deposition of the coal create the tectonic environment in which the coal seams are found today, and this is a particularly important element in assessing the workable reserves in many parts of the world. The rates of regional change exhibited by the different tectonic phenomena, which include gradient, faulting, jointing and cleat, need to be considered in conjunction with the sedimentary factors, but probably the most important single item is the actual intensity of faulting which can seriously retard the continuous cycle of mining operations that is so necessary for economical working. The regional (lateral) and vertical rates of change of the various geological factors affect the economic workability of an area of reserves and determine how closely spaced the points of geological information must be for the allocation of those reserves into the recoverable category. In Britain, an area where the information points are over 3.2 km apart would normally be excluded from reserves in this category.

3. Engineering factors affecting assessments of reserves

The economically recoverable reserves in a coalfield depend to a very large extent on the capability of the mining systems in use to cope with the difficulties presented by the particular geological environment. In many parts of the world, in recent years, mining systems have been evolved which help minimize the effect of some types of adverse geology and ensure high levels of productivity. In Western Europe, where mines are now virtually 100 % mechanized, this means that coal is cut on the face mechanically, is conveyed automatically to the shafts, hauled to the surface, cleaned and beneficiated in modern plants and loaded into wagons for transport direct to the markets.

The very sophistication of these systems – designed to produce coal at minimum cost – inevitably rules out the working of large areas of coal where the geological conditions are unsuitable. In the past, reserves of marginal value were often included when estimating the potential of a colliery or a coalfield, in the belief that improved technology would enable this coal to be worked economically in the future. In fact, to date, the reverse has been true, in that the modern rather inflexible mining systems require coal seams to be in a particularly favourable geological environment in order to support intense and continuous output which is needed for economic production. In old coalfields reserves lying in these favourable conditions are becoming increasingly difficult to locate, so that there is a real need to evolve more flexible mining systems capable of dealing with a greater range of geological conditions, and for mining layouts specifically planned to minimize the effects of stress and instability caused by depth and previous workings. Here indeed is a rich field for research which could well lead to some increases in economically recoverable reserves in many of the world's developed coalfields.

4. Economic factors affecting estimates of coal reserves

(a) *The nature of coal deposits and the relative ease with which they are found*

There are physical differences between deposits of coal and those of competing energy minerals which render the processes of recovery the most cost-significant to coal industries throughout the world. Coalfields usually consist of a multiplicity of flattish sheets of coal, all set in a very distinctive suite of enclosing rocks and generally of huge areal extent (although the individual seams form only a small percentage of the total ground within the coalfield). Thus when their edges crop out at the surface they are an unmissable target to the geologist and mining engineer. When concealed, one exploratory hole is often enough to 'prove', in the sense of test or sample, the presence of a concealed coalfield. In contrast, major new oil or gas fields must, for their existence, always be sealed beneath other strata and can occur as pockets of small areal extent in almost any strata that are sufficiently porous.

Because a concealed coalfield competes with its exposed neighbours for exploitation, it is depth that counts initially, almost more than anything else. Unlike gas or oil, coal does not flow out of its enclosing rocks towards the discovery hole under the huge natural pressures in overlying strata, so we have to go down and get it. Because this is so, and because in all of the world's coalfields except one or two temperatures increase with depth, depth of extraction is limited to the temperatures that we can work in without expensive cooling processes. In world terms the deepest discovery hole for any new mineable concealed coalfield is never more than a thousand or so metres. By contrast, such relatively shallow depths rarely provide sufficient pressure from the overlying rock to squeeze petroleum out of the strata in economic quantities. Thus search depths for target bodies of petroleum are measured in kilometres. These bodies are also relatively small compared with coal deposits, and not in any unique suite of associated strata. Hence greater weight is given to risk capital expenditure on finding new fields of petroleum than of coal. Only in regard to petroleum is exploration the most economically sensitive link in the chain between the energy mineral as it occurs in the ground and as it is finally utilized.

For the many reasons given above I suggest that, unlike petroleum deposits, the location of the vast majority of the world's coalfields, in terms of gross tonnage of coal, have already been discovered. Since, as will be shown, we are nowhere near having exhausted the coalfields already discovered in the world, there is relatively little potential for greater world-wide expenditure on the search for completely new coalfields.

(b) *The nature of coal deposits and the relative difficulty with which they are recovered*

In the petroleum field the mineral flows through the reservoir rocks towards the access points in variable proportions through routes which do not have to be known in advance and are not discovered in any detail during extraction. In deep mining for coal each route into the deposit and precise location where continuity of extraction can be obtained is, at every stage in life of the field, a matter for management decision. The position of each minor geological change in the relatively thin coal seams has either to be known in advance or is expensively encountered after the decision has been made.

The significance of having to move into the deposit – instead of only having to drill a hole for earth pressure to push it out to the surface – is that in coal mining decisions can be made concerning precisely which portions and how much in each portion shall be extracted.

(*c*) *The economic influence of depth on recovery of the world's coal reserves*

Only a limited proportion of coal in the world's coalfields lies at opencast depths, of less than a hundred or so metres. These reserves can only be a small percentage of the world's total, since most of the mineable coalfields lie between the surface and a thousand or so metres. The capital expenditure on facilities for making access to opencast coal, however, is both highly productive in manpower terms and, unlike that for making access to deep-mine coal is, to a large degree, transferable to other sites. Thus the history of most of the recently discovered coalfields is mainly one of recovery by the opencast method. Just under half of the coal from the fields of the United States and more than half of the U.S.S.R. output is still produced by this inherently cheap method, and soon 50 % of Australian output will be opencast as well. In Britain we are unable to mine a similar proportion because such coal in our fields was extracted by less-efficient shallow mining, before opencast methods permitted mining more than a few metres below the surface.

If mining is to recover more than the small fraction of the world's coal resources which are available to opencast, it must obviously be by deep-mining methods. However, the expenditure on making initial access for deep mining is enormous, and most of the capital equipment which has to be provided is not transferable but thereafter is only serviceable out of revenue. Historically, once provided, these access points generally last four or five times as long as those provided for access to oil and gas fields. The long delays before an earning position is reached offset the potential they still offer in their hundredth year, which is concealed by the compound interest rates used in cash-flow accounting.

(*d*) *The effect of geological conditions on the economy of existing deep mines*

Let us, for the moment, defer consideration of the prospect of new deep mines and restrict ourselves to such of the world's deep mines as are currently in operation. One fact of coal mining not always clearly appreciated is the extent to which the variable nature of coal deposits affects the economics of running a mine. Nearly all coalfields show a varying thickness of seam and a degree of local geological change or disturbance.

In any deep mine in the U.K., the greatest financial benefit can generally be attributed to the most productive of its longwall faces. In America and Australia where longwall faces are few, it may be attributed to the most productive of the mechanized pillar or shortwall districts in the mine.

In deep mining, day-to-day costs are largely costs per unit of geologically undisturbed area worked, while for a given quality, the revenue at 'the pithead' is obviously per unit volume worked and raised. (This is why in the majority of the world's existing mines the areas in which the seams are thicker, and of good quality and reasonable accessibility, have already been worked in the less disturbed districts of the mine.)

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

Any local change of geological circumstance which worsens the thickness, or the continuity of the coal, or the face conditions being enjoyed by the best unit in the mine when the time comes to replace it, strikes directly at the profitability, as there is no significant change in overheads. This is because wages and interest charges on the capital equipment on all the faces, and the logistic system behind them are the major items of cost. The deployment of effort and investment among units within a mine, and among mines within a company or national mining industry, is such that those temporarily enjoying the best conditions commonly support a large number of 'average' or 'worse than average' units. In a major company or national context loss of one of these 'best conditions units' therefore has a highly geared numeric effect on the total number of access points which can be maintained in production. It is this aspect of an extractive industry, quite naturally first taking the easiest coal to win, which may be unfamiliar.

In world terms, when there is a period of cheaper energy, quite properly no one wants to finance large coal stocks for long periods. Thus it is nearly always a number of the less economic mines which have to close. Similarly, within the remaining mines, it is the least economic seams in individual mines which have to be written off, when the decision on which seam or district to work next has to be made. Thus, over the last decade, we have a massive reduction in the number of access points in the coalfields of the European coal industry. Let us now examine the manner in which the process of recovery of the world's coal resources is affected by alternative sources of energy, by reference to the case history of Britain.

(*e*) *The influence of energy economics on recoverable reserves – an example from Britain*

In a previous energy crisis, precipitated by a long history of massive growth, the Royal Commission of 1871 lamented that there was a considerable loss of reserves where 'the whole or part of a bed adjoining or lying near to that which is being worked is left behind, where it becomes crushed and unworkable hereafter, because it is of a kind which is not wanted at the time, or if it were worked the cost per ton of coal got would be increased'. This is still true today.

Since about 1900 each successive choice of what coal to work next has had to be taken in competition with petroleum as a significant alternative to coal as a source of energy. It was a case of margin against margin, to hold coal's dominant position against oil in the British energy economy throughout the first half of the century.

What happened took place in spite of Dr Boverton Redwood's evidence before the next Royal Commission required to advise on the future of coal, when in 1901 he reassured them that for 'anything like general employment (of oil) I cannot see where we are to get the supplies'. (World coal production was 790×10^6 t and oil production only 22×10^6 t in 1901.) The Commission rested on expert assurance that if the future of the country required energy it could only come from coal. Thus, whatever portion of the resources was physically workable even if currently too thin to be economic, would at some time or other in the future necessarily sustain the life of the industry as long as the country required energy. The coal resources, down to seams of about 30 cm in thickness, and under 1220 m deep, were therefore nearly all to be included as 'reserves' – in the view of those required to foresee the climate of energy economics at that time.

(*f*) *The source of confusion in estimating the life of coal reserves*

Most of the confusion concerning what should constitute the reserves on which an estimate of the life of a deep-mining industry should be based arises from the fact that it is possible to probe into the future in terms of the presence and condition of the mineral to be extracted in future years. In this sense, extraction by movements through the deposit in future space are equivalent to increments of time, as far as supply is concerned. Because we drill and sample the condition of the mineral ahead, it is possible to estimate the total volumes present in a field which has been thus sampled, or in this sense 'proved'.

Once the physical limitations on what constitutes reserves have been authoritatively agreed, assessments are a matter for sophisticated measurement and calculation. The most relevant figure, with regard to total rate of demand, is the latest average annual production. It is all too simple to divide the one figure of annual demand into the other figure of total reserves in the fields concerned – to obtain an estimate of the life of the world's mineral-energy supplies. Since, however, division of one figure by another is multiple subtraction, each successive year's demand subtracted from the preceding number of tonnes of reserves has a different effect on the remainder, depending on what coal it has been necessary to select and what has been rendered unworkable or too expensive in the process of selection – in other words (as the Commission of 1871 pointed out) on what has happened in the changing climate of energy economics in the previous years. To examine this effect further we must return to the case-history of Britain, remembering that, unlike oilfields, coalfields when discovered in the past usually lasted for hundreds of years.

(*g*) *The trend in Britain in successive estimates of economically recoverable reserves*

The Royal Commission of 1901–5, referred to above, took evidence of what coal seams could be sensibly considered as likely to be capable of sustaining the life of the industry, and of what losses occurred during extraction. Armed with this evidence, their geologists and surveyors then added up the quantity of coal amongst the total resources which lay within the limits imposed, distinguishing such tonnages as were uncertain due to an inadequate degree of physical proving. They did not feel that they should be constrained by any considerations of a time limit on extraction. As we have seen, they thought that there was no real alternative fuel to coal. They obtained a British coal reserves figure of some 144×10^9 t (equivalent to a reserve of between 600 and 700×10^9 barrels of oil, or *ca.* 4.15×10^{21} J, depending on the conversion factor used).

There was renewed apprehension about the sufficiency of coal supplies during the Second World War, and the Department of Scientific and Industrial Research again took similar evidence. However, in the light of the circumstances of the time, they decided that it was prudent to restrict their inquiry to reserves obtainable only over the next 100 years. After due measurement they arrived at the figure of 20.8×10^9 t. A further authoritative assessment of the reserves relevant to the coal industry in Britain was made, this time by the National Coal Board for National Plan purposes, in the late 1950s and early 1960s. In the circumstances of the time (rapidly falling world oil prices) it was considered prudent to consider only coal which was accessible to existing or developing mines, as no capital seemed likely to be forthcoming for any new mines in the foreseeable future. This new assessment revealed some 16×10^9 t of reserves thought likely to be capable of sustaining the industry.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

(*h*) *The depletion rate concept of currently accessible and economically workable reserves*

The trend over these widely spaced intervals of assessment represents a write-off rate, of reserves successively proving likely to be uneconomic to extract, averaging more than 2×10^9 t per year; while actual annual extraction was only a tenth to a twentieth of this amount. The reserves figures were still comfortingly large in absolute terms, but the National Coal Board decided to update the reserves assessment annually instead of leaving it to intervals of a decade or two. The subsequent assessments confirmed that reserves which were considered workable under the national minimum productivity requirements of previous years were still falling annually as national productivity requirements increased. An assessment this year (1973) gave a national total of current workable reserves of some 3.9×10^9 t – enough for nearly 30 years at the current rate of extraction. And it must be remembered that the thousands of millions of tonnes in the virgin portions of the coalfields not yet assessed are still there.

Fortunately, over the 1960s, the last wholly human link in the chain of actions involved in getting the coal from the solid seam into a surface transport system was removed. It was achieved by simultaneously cutting and loading the coal mechanically and then mechanizing all the support and logistic equipment necessary to keep up with the enormously increased rates at which faces could advance into the coal. This final step, in a long succession of technological revolutions in the coal industry, took the usual decade to become disseminated throughout the industry. As is well known, national productivity – in both the thickest and thinnest seams – rose rapidly.

Mines, during this decade, were closed at the rate of some forty per year. The number of faces in the mines remaining open were reduced some fourfold. Output over the decade was reduced by one-quarter (being replaced by cheaper oil) but productivity increased by over 50 %. Without this technological revolution there is little doubt that British coal-mining capacity would have been far more than halved under the onslaught of cheap world oil prices during this decade. Had this happened we would have greatly increased the write-off rate of currently accessible economically workable reserves, instead of being able to hold it more or less constant.

Our concern still lies with the rate of annual write-off and loss of access to reserves which can, under the economic conditions and the technology prevailing at the time of each annual assessment, be considered as likely to be capable of sustaining our efforts in existing mines. In deep coal-mining this has proved to be a far more important factor than the rate of output. The write-off rate is of course directly related to national productivity and costs, and hence, given continued good management, also subject to the advent of fundamentally new technology.

(*i*) *The influence of the depletion rate of coal reserves on planning national energy economics*

The steady rate of loss in workable reserves, despite our increased productivity, was due to the advent of alternative sources of energy over the last seventy years. Fortunately, during the last few years there has been some evidence that the long-run average annual rate may be flattening out. If capital is provided to make access to the best seams in the vast extensions of our existing coalfields, and if our next technological revolution can enable wages costs to rise and industry to retain the men we need, then we should, for the first time since the latter part of the nineteenth century, see an increase in the reserves of coal in Britain which can be considered as economically workable. Provided we can foresee a sufficient number of years of economic supply in the ground to meet foreseeable requirements, then we can respond by taking whatever action is necessary for extracting it at the required rate. The time-horizon with which it is necessary to view coal reserves, provided their assessment is updated annually, is about a decade ahead, as this is the time it takes to make completely new access – to replace reserves which are being depleted at the prevailing rate.

The British case-history is one of loss of access to the coal in our fields at an average rate which, if projected forward, could lead to a hypothetical zero of economically workable reserves within a few years. The danger point occurs when this zero is in sight before new access can be created to replace the loss of economically productive capacity in an extractive energy industry, under competition from temporarily cheaper sources of energy. I am sure this British experience can be duplicated in the other older coalfields of the world.

The point so little realized is that it takes nearly a decade to explore for and select the best site, sink each wholly new access point in deep mining, and bring it into full production. This is a longer response time than either finding and bringing into production a new oil or gas field, or siting and bringing on stream a new nuclear power station.

(j) *The influence of response time to change on multi-fuel energy economics*

Thus it is not a matter of today's relative cost of the three major sources of energy – nuclear, petroleum and coal – but the trends showing their likely costs within their response time to change. And, as we have seen, deep-mined coal has already been responding in the sector peculiar to it over the last seven decades.

It has been shown that it is valueless to add up the world's total reserves of coal and divide by the world's current production. This gives, if the British case-history has any relevance, a world life figure so large that decisions in this sector of the world's energy economy can be safely deferred to the next generation – while we turn our attention to the problems of ownership of the remaining oil. However, we were the first country to start studying this massive process of interaction in energy economics between coal and its new competitors, and we can now perceive what is involved in the process.

We are, in consequence, the first to have to engineer a more efficient response, both to the problems of increasing depth and to a world concept of investment criteria fundamentally unsuited to the huge new scale of, and the long response times inherent in, the energy economy.

Whatever the return on investment in response to more ephemeral human needs, few need reminding that the economic edifice, mainly concerned with the efficient production and distribution of an ever-growing abundance of services, goods and manufactured materials, rests on the security of the world's water, food and energy supplies. We have now a better understanding of the nature of coal reserves with regard to the action such knowledge necessitates.

The way in which these reserves are now viewed is responsive to economic change and cost, and is cast in terms of the level at which a coal industry dependent on those reserves can live (without unforseeable change in current operations). As in all things it is necessary to review and update these assessments continuously, giving emphasis to accuracy within the minimum planning horizon required for our operations. To us, as an industry, knowledge of the future beyond this horizon is unnecessary. It is up to us as a nation to make use of our knowledge of depletion trends in solving the problems which now face us – and will, later, face other owners of coalfields still enjoying a cheap labour supply or largely opencast reserves.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

5. Estimates of world coal reserves

(a) *Basis of estimates*

There is no absolute measure of total world reserves of coal, nor in the nature of things is there ever likely to be one. Cost alone prohibits the comprehensive probing of the Earth's crust and such a programme would be of limited value as industry can only be interested in the resources that are exploitable now or seem likely to be in the foreseeable future. As time passes, the standards of exploitability keep changing as the controls change with advances in technology and changes in the economic climate. It follows that the procedures for assessing reserves will also change.

The various estimates of world coal resources that have been published are summations derived from assessments for different countries based upon differing procedures. Some of these assessments are of the total quantity of coal in place in known and inferred deposits; others are of the quantity of coal physically workable by current mining technology from these deposits; others, again, are of the quantity of coal economically recoverable from these deposits. It is therefore desirable to consider, in the light of the discussion in §§2, 3 and 4 of this paper, the degrees of accuracy or uncertainty associated with these different procedures, and the relative magnitude of these three categories of reserves.

(b) *Categories of reserves and their assessment*

Gross reserves

In the assessment of 'gross' reserves, that is the total amount of coal in deposits, the only coal usually omitted is that in very thin seams (say, less than 30 cm in thickness) and that in seams at great depth (say, more than 1220 m below the surface). The assessment is thus an arithmetical exercise based upon knowledge of the areal extent, contours, thickness variations and density variations of each seam, and the accuracy of the assessment is solely dependent upon the amount and reliability of the information available or obtainable on these factors. This information is obtained from actual measurements in the cases of 'known' deposits, and has to be estimated in the cases of 'inferred' deposits.

It follows that changes in estimates of gross reserves can only result from:

(i) more precise information gained from subsequent proving of the deposits;

(ii) subsequent extraction of reserves;

(iii) subsequent discovery of extensions of deposits; or of additional deposits.

Physically workable reserves

In assessing 'physically workable' or 'total available' reserves, deductions are first made from gross reserves in all areas in which, under present mining technology, a seam is considered unworkable because:

(i) it is too disturbed geologically;

(ii) it is too close to an adjacent seam, which is included in the assessment, for both to be worked;

(iii) it is too badly affected by underworking or overworking;

(iv) it is too wet, through proximity either to a natural aquifer or to adjacent flooded workings;

(v) it is required to remain unworked to support property and surface installations, or to maintain land drainage.

It is usual also, in such an assessment, to discount areas in which a seam is thought to be too poor in quality (e.g. with too high ash and/or sulphur, or with too low a ratio of coal to associated dirt) to ever become economically workable.

It is unlikely that foreseeable advances in conventional mining technology will reduce significantly the proportion of gross reserves that has to be discounted in the assessment of total available reserves. A substantial reduction seems possible only from the successful development of a completely different method of extraction (e.g. in-seam gasification or solvent extraction).

Estimates of physically workable reserves, therefore, differ essentially from estimates of gross reserves in that they are based upon additional factors which are incapable of precise measurement, except perhaps in an area where they have been well established by extensive mining experience. Also, estimates of future changes in the proportion of physically workable reserves to gross reserves are subject to a high degree of uncertainty in the longer term, as these changes would appear to depend principally upon developments of new methods of extraction.

Economically recoverable reserves

The assessment of 'economically recoverable' reserves involves attempting to estimate the proportion of the physically workable reserves that will be exploited under current trends in economic constraints. To the physically workable reserves a percentage deduction must always be applied as an allowance for the effects of geological hazards such as faults and washouts, coal that has to be left in pillars and barriers, etc. In addition, however, the assessment of economically recoverable reserves involves making judgements on proceeds and profitability, based upon estimates of the availability, deployment and cost of mining resources (manpower, machinery and materials) and the marketability and prices of the products. These estimates are subject to constant change in the light of political, social and financial developments in the country concerned and the world at large, irrespective of and in addition to any changes in knowledge of the physical disposition of the deposits, or any changes in the proportion of them considered to be physically workable. This is why, to obtain a trend in economically recoverable reserves, it is necessary to make use of a succession of recent estimates.

Estimates of economically recoverable reserves are thus subject to a very high degree of uncertainty, and also to continuous change from factors independent of the nature of the deposits.

(*c*) *Relative magnitude of different categories of reserves*

The relative magnitude of these different categories of reserves probably varies fairly widely for different deposits throughout the world, but the following two examples on a national summary basis may give some indication of the possible average worldwide relativity.

The latest assessment of gross reserves in the United States (quoted by E. H. Reichl in 3rd Robens Coal Science Lecture in October 1973) is 2.60×10^{12} t in seams to a maximum depth of 915 m, or 2.91×10^{12} t in seams to a maximum depth of 1830 m. Of these amounts less than one-eighth, some 317×10^{9} t, are in 'measured and indicated' (in contrast to 'inferred') deposits, within 305 m of the surface, and can thus be considered physically workable by current United States mining practice. Economically recoverable reserves are reckoned to be contained

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

within these deposits and are assessed at about 136×10^9 t, representing only about 5 % of the possible gross reserves of the country. About 30 % of these 136×10^9 t are recoverable by surface mining.

The latest assessment of gross reserves in Great Britain, made by the National Coal Board for the 1974 World Energy Conference, shows a total of about 163×10^9 t, of which some 99×10^9 t are in 'known' (in contrast to 'indicated and inferred') deposits. These figures relate, in general, to seams with a minimum thickness of 60 cm and within 1220 m of the surface. The physically workable coal accessible from existing or new collieries probably amounts to less than 15×10^9 t, or less than one-tenth of the possible gross reserves; while the economically recoverable coal is currently assessed at approximately 3.9×10^9 t, representing only about $2\frac{1}{2}$ % of the possible gross reserves. About 8 % of these 3.9×10^9 t are recoverable by surface mining. Additionally, however, there are some 2.5×10^6 t available to existing and planned collieries, of which a considerable proportion might become economically workable with beneficial changes in economics and/or technology.

The relative magnitude of gross, physically workable and economically recoverable reserves therefore appears to be of the same general order in the United States and Great Britain; the differences probably reflect the generally easier conditions of mining in the United States.

6. World reserves of economically recoverable coal

The many uncertainties inherent in estimates of world coal reserves, arising from the different bases of assessment referred to in §5 (*a*) of this paper, have now been considered in detail. The most recent estimate of world coal reserves published in 1968 by the World Energy Conference was over 8.8×10^{12} t, comprising 6.7×10^{12} t of bituminous coal and anthracite, and 2.1×10^{12} t of brown coal and lignite. The figures for the United States and United Kingdom were, respectively, 1.5×10^{12} t and 15.5×10^9 t. For these two countries, then, the figures published by the World Energy Conference represent respectively 10 and 4 times the current estimate of economically recoverable reserves, and agree more closely with what would be the current estimate of physically workable reserves.

If this situation is broadly true of other countries, and if it is not unreasonable to assume that 50 % of the physically workable reserves will *ultimately* be economically recovered, we arrive at a world total of 4.4×10^{12} t of economically recoverable coal. This figure is enormous, representing as it does about 1500 times the 1970 world output of about 2.9×10^9 t of coal. Assuming that world coal requirements will increase by 5 % per annum until the end of this century, world coal output in the year 2000 will have risen to over 12×10^9 t, and the total coal extracted between now and then will have amounted to almost 0.2×10^{12} t. However, sufficient reserves would still be remaining to sustain output at the level of year 2000 for over 300 years. Even if we assume that only 10 % of the estimated 8.8×10^{12} t will be economically recoverable – a most pessimistic assumption – there would still be sufficient coal to meet this assumed rate of demand to the end of the century and then to sustain output at that level for over 50 years.

It must, however, be emphasized that world reserves of coal are very unequally distributed among the continents and political blocs, as indicated by the figures at the top of the next page.

It is therefore very probable that, despite the overall abundance of world reserves of coal, severe shortages could occur at a fairly early date in particular regions or countries.

area	approximate percentage of world coal reserves
U.S.S.R.	$61\frac{1}{2}$
North America	$17\frac{1}{2}$
Asia (mainly China)	17
Europe	$2\frac{1}{2}$
Africa	$1\frac{1}{2}$
South America	$< \frac{1}{2}$
Australasia	$< \frac{1}{2}$

7. The balance between reserves, productive capacity and demand

I have already referred to the depletion of British coal reserves. During the 1960s the declining competitive position of coal resulted in a rapid reduction in the coal reserves regarded as economic. These fell from about 16×10^9 t in 1962 to about 6×10^9 t in 1972. This process was accompanied by an accelerated rate of colliery closures on economic or exhaustion grounds, the annual number of operating collieries falling from 616 in 1962 (producing 191×10^6 t of coal) to 281 collieries (producing only 129×10^6 t of coal) in 1972/3.

Coal mining is an extractive industry with the end-point of each individual venture the exhaustion of its natural resources. In Britain, despite a massive rebuilding programme after 1947, the average age of existing collieries approaches 80 years. If there is not continuous investment to prove additional reserves and to provide replacement capacity, the industry as a whole will lose a very substantial part of its present potential by the mid-1980s, even to a point where the total output could well be of the order of only $70-80 \times 10^6$ t per annum, and this at a time when it is estimated that the demand for primary energy in the U.K. will increase by about 40 % to about 460×10^6 t of coal equivalent (13×10^{18} J) to 1985.

There is, therefore, a continuous need for all countries to balance not only the availability of economically recoverable reserves, but also the productive capacity of their coal-mining industries against present and future demand in the world as a whole. In fact, in many countries, decisions have already been reached about their forward coal policy. Probably the most important, and certainly the most impressive because of its scale, is the decision of the United States government to increase the annual output of coal from the present level of about 550×10^6 t per annum to about 1000×10^6 t by the year 1985. This expansion is to be followed by a further massive increase to an annual rate of 1400×10^9 t by the year 2000. To support this massive increase in output, the United States has, at the same time, launched a £4000M research programme covering the whole range of activities from exploration to utilization. That the United States has a coal reserve potential capable of supporting such massive increases is not really in doubt, but an increasing proportion of the output will have to be obtained from deep mines as opposed to opencast production and the locating of economically workable reserves is likely to prove slow and laborious. Important policy decisions have also been made by other major coal-producing countries, certainly in the U.S.S.R. where production, at present slightly less than that of the United States, is being greatly expanded. Plans for expansion have also been made known for China, Poland, South Africa and Australia.

At present Western Europe is a notable exception, probably because the remaining reserves, although plentiful, are generally deep and the seams are relatively thin. But most important of all, the coalfields are often situated in difficult geological environments with heavy faulting, making mining expensive and conditions difficult. From the technical point of view, therefore, there are major problems in increasing the amount of coal mined in Western Europe or even in stabilizing output at the present level. The question which is now being debated by governments within the E.E.C. is precisely what part coal should play in the total energy economy of the Community.

In Britain, we are planning the future of the coal industry in the light of the problems I have outlined, and the world energy situation. We regard our plans as falling into three distinct chronological periods, although each impinges on and overlaps the other. For the rest of this decade up to 1980, the amount of coal we can produce must almost exclusively come from existing collieries, because of the long lead time to prove new reserves and establish new capacity. Major investment will be needed in existing pits to maximize viable production when pits have a long potential life and access to adequate reserves. The second phase, looking into the decade of the 1980s, is the period when any new pits which we sink will be producing, and we are now exploring intensively for new and productive coal reserves and already conducting a great deal of necessary immediate planning. In North Yorkshire, for example, we have already located quite shallow reserves in thick seams, amounting to about 10^9 t – sufficient to support a feasible annual output of 10×10^6 t for many years. Other parts of Britain are also being explored and it is anticipated that we shall prove sufficient reserves both in new coalfield areas and near existing collieries to support an annual output of the order of 30×10^6 t for many years, reaching full production in the mid-1980s.

From the end of the 1980s, throughout the 1990s and beyond, it is possible that we shall be doing what the United States will probably be doing a stage earlier, which is to use coal mainly as a feedstock for conversion into other suitable forms of energy. For this period, doubtless, new forms of mining or coal extraction will be required – perhaps to exploit the massive quantities of coal which lie deep beneath the North Sea out of reach of the mining methods of today.

In Britain, therefore, we can foresee a major departure from the policies pursued in the last decade or so. Whereas in that period we have been closing pits owing to exhaustion, or because of high cost, without replacing the loss with new capacity, the time has now come to bring new capacity into operation without delay. This is a big departure and will involve a very major increase in investment in the coal industry. We have demonstrated that the reserves are there waiting to be exploited. Now we have to convince the government that this is the right policy.

A policy of expanding coal output in Britain must, of course, not be taken in isolation. It should be part of an overall policy, and in Britain we have a unique opportunity of being able to develop a number of indigenous resources, on land and under the sea, in the form of gas, oil and coal. What we are aiming at here – and I am sure that this will emerge with time – is an integrated policy of forward energy planning, making full use of all the resources available, ensuring that each will be used to the maximum advantage.

8. Conclusions

Let me end by emphasizing a number of conclusions which arise out of the points made above. Taking into account only the very conservative figures of recoverable world coal reserves, there should be sufficient to meet the entire growth of coal demand well into the next century or beyond.

Unfortunately, however, this global superabundance of coal is no guarantee against the onset of major and long-lasting local shortages. This is partly because coal reserves are very unequally distributed around the world with the bulk remote from current markets, and partly because in an extractive industry there is a constant need, not always accepted in time, to locate economic reserves and to replace the mining capacity which is constantly being lost.

Movement of coal to the markets where imbalance occurs also presents problems. At present, out of a total world output of about 3×10^9 t of coal, only approximately 190×10^6 t are exported from one country to another to correct these local shortages. The bulk of these exports is from a small number of countries with those from the United States making up about 25 % of the whole. In view of its internal energy situation, it seems very unlikely that the United States will be able to increase, or even sustain, this level of exports in the future; while, despite adequate reserves, it is difficult to foresee the other exporting countries being able to increase their overall productive capacity to the degree needed to provide sufficient exports to significantly alter the basic imbalance that exists in many parts of the world.

In my opinion, it is therefore essential for each country blessed with economic indigenous coal reserves to develop these to the full, remembering the long lead time needed for detailed exploration and to generate new productive capacity. There will undoubtedly be marked changes in the supply pattern in the future, and locally there could be severe disruption due to incorrect anticipation or restrictions imposed by national monopoly interests.

Timely investment in world coal exploration and productive capacity becomes essential in view of the much more likely shortages which will undoubtedly affect the supply position of other energy fuels.

Selected references (Armstrong)

Armstrong, G. 1972 Coal – the world's major fossil fuel. *Colliery Guard.* **220**, no. 11.
Averitt, P. 1967 Coal resources of the United States. *Bull. U.S. geol. Surv.* no. 1275.
Collins, H. E. 1969 Review of world coal production potential. *Colliery Guard.* **217**.
Schurr, H. S. 1963 Energy. *Scient. Amer.* p. 114.
Statistical Summary of the Mineral Industry 1967–1971 London: Institute of Geological Sciences.
Williamson, I. A. 1967 *Coal mining geology*. Oxford University Press.
World Coal Trade 1970 National Coal Association U.S.A.
World Power Conference 1968 Survey of energy resources.

Discussion

Professor J. M. Cassels, F.R.S. (*Physics Department, Liverpool University*). If the market value of coal were to double overnight, by what factor would the National Coal Board's reserves be increased?

Mr Armstrong. Reserves would be increased by about 40 %.