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ENERGY IN THE FUTURE

A Series of Three Lectures

by

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ERRATA

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<u>Page No.</u>	<u>Paragraph No.</u>	<u>Line No.</u>	
1			Insert paragraph 9 - "What is the maximum plausible role that nuclear fuels might play?"
2	6	3	Change on to <u>for</u> .
6	6	9	Change 1.1 to <u>11.1</u> .
10			Enter point at <u>11.1</u> for <u>1951</u> .
11	1	1	Change 1.1 to <u>11.1</u> .
17	3	3	Change 1.19 to <u>6</u> .
24			Delete <u>the</u> from line 3 of caption.
35			Last word in first line of caption should be <u>energy</u> .
37			Remove point at 700, year 2000.
39			Remove second <u>the</u> from line 4 of caption.
40			Caption should read - "Figure 20. United States: Trends in the relative proportions of the three components of the energy system--work, process heat, and comfort heat".
53			Replace Figure 28 with attached revision
55	4	6	Change 5-4 to <u>3</u> .
78	5	1	Change we to <u>he</u> .
82			Replace Figure 37 B with attached revision.
84			Change date in second line of caption to <u>data</u> .
89	5	5	Seventh word of this line should be <u>search</u> .
91			Table 8 - Line one in the second section should read <u>Fuel wood</u> .
94	4	6	Change weapon to <u>weapons</u> .
95		2	Insert after "Homogeneous Reactor Experiment" the words "located at the Oak Ridge National Laboratory".
105	1	2	Change 8-3 to <u>11</u> .

ERRATAENERGY IN THE FUTURE by PALMER PUTNAM

<u>Page No.</u>	<u>Paragraph No.</u>	<u>Line No.</u>	
105	2	3	Change Figure 31 B to <u>Figure 29</u> .
105	2	5	Change 4.5 Q to <u>4.3 Q</u> .
107			Change Figure 45 to <u>Figure 46</u> .
108			Change Figure 46 to <u>Figure 47</u> .
112		1	Change Table 10-1 to <u>Table 12</u> .
115			Attach enclosed <u>Figure 48</u> to manuscript as page 115.

Lecture 1

THE MAXIMUM PLAUSIBLE POPULATIONS TO RECKON WITH

A. D. 1950 - A. D. 2050

Introduction

"Men prophesy, and the future makes fools of them".

We recall that famous episode of the 'eighties of the last century, when a paper was read before the Royal Society "proving" that heavier-than-air flight by man was impossible.

In the 'twenties of this century, there was that flood of distinguished books describing the "new economics" and the permanent plateau of prosperity to which we had climed.

In the bottom of the ensuing catastrophe, demographers predicted that within 50 years our population would stabilize at about 150,000,000 - and that a larger population would be economically disadvantageous. Our population is now about 160,000,000, and growing more swiftly, not only absolutely, but also percentage-wise, than at any time within nearly 50 years.

Lowell Reed has said that he isn't sure that predicting is not a form of vice.

In these lectures I am going to try to answer three questions about the future, without committing the folly of making categoric predictions. The questions have been carefully worded to make this possible.

"What is the maximum plausible quantity of energy that people might demand in the next 50 years or so?"

"What are the minimum plausible contributions by non-nuclear fuels?"

"What is the maximum plausible rate that nuclear fuels might flog?"
Note the wording of those questions. We are to deal with plausible

contingencies - not with categoric predictions.

Everyone knows that the future is uncertain. Perhaps the decay of the race is imminent, or even its destruction.

On the other hand, life may go on developing for at least another century or so, with the accelerations to which people have become accustomed.

When you put a fire extinguisher in your home you do not predict a fire. You are merely providing for a contingency.

Purpose

The purpose of these three lectures is to try to put ourselves in the position of a Trustee of Energy. We want to estimate, if we can, the maximum plausible contingency to reckon with.

In this first lecture we shall review what can be said about past population growth, in order to estimate the maximum plausible populations of the future.

In the second lecture we shall review what is known about past patterns of energy consumption, in order to estimate the maximum plausible per capita and total demands *for* energy by the populations that we shall specify tonight.

In the third lecture we shall review the economically recoverable reserves of fossil fuels, to see how urgent is the need for developing alternative sources of low-cost energy. We will consider Solar energy, especially controlled photosynthesis. And so we shall reach our conclusion - a preliminary first estimate of the maximum plausible role of nuclear fuels.

Assumptions

We shall have to make some simplifying assumptions. Let us assume that there will be no cataclysm - physical, military, political or

technological - and no change in climate, or in any other feature of the biosphere, that will significantly reduce the demands for energy throughout the next century.

Let us also assume that there will be no sustained barriers, economic or otherwise, to the export of food surpluses, fuels and know-how, at least among the non-Communist countries.

Finally, let us adopt, as the specific contingency to be reckoned with, the continuation, at the currently accelerating rates, of the worldwide movement to replace illiterate subsistence farming with literate industrial-urban-farm patterns of life.

Problems Ignored

The contingency as stated conceals or ignores some formidable problems.

There is the problem of the pressure of population from the potentially still more crowded areas of the future into the less crowded - pressures that may become more acute as the fruits of technical competence become more evenly distributed.

There are the economic and political problems of distributing food surpluses; and of establishing a better balance in the terms of trade between world-factory and world-farm.

There is the problem of bringing average farm yields closer to best yields, and of seeing to it that yield outstrips population. There is the problem of somehow avoiding a major increase in the real unit costs of raw materials. There is the problem of the water supply. There are other problems.

Much is heard, and rightly so, about these and similar problems, from those who think that the Road to Survival across the hot, dry face of Our

Plundered Planet may be strewn with the jobless victims of Cybernetics.

But tonight we are Trustees of Energy. It would be imprudent if we gambled on human disaster to keep the demands for energy low.

So, let us ignore these problems, without implying that they are certainly going to be solved.

Having established a frame, let us now start to paint the picture in broad, simple strokes.

Let us begin tonight by painting in the record of world population so far as it is known or can be surmised, in a search for some clues as to the size of the maximum plausible population 50 and 100 years from now.

World Population

In the late Neolithic, hunters and gatherers may have averaged about six in each hundred square miles. This appears to have been the density in England then. It is also the density of recently observed hunting and gathering cultures in Tasmania and Alaska. And the value is consistent with the somewhat greater post-Neolithic densities estimated for various parts of the Americas.

The area of original forest is fairly well-known. Some of it was probably too rugged for habitation. But some of the steppe was apparently inhabited by groups practicing irrigated agriculture as early as 8000 B. C. If the total habitable area was inhabited by hunters and gatherers, and if it amounted, as we think, to 16,000,000 square miles, then the population of this late-Neolithic world was on the order of 1,000,000 persons

The uncertainty in this estimate is obviously large. On balance it seems a little more likely that the actual population of 10,000 B. C. exceeded 1,000,000 than not.

Over the next 10,000 years, urbanization gathered headway. By the

Figure 1. Inferred growth of world population
10,000 B.C. to A.D. 1950

time of Augustus the percentage urbanization of the "known world" may have been about $1/3$ - about the same as today - and the population may have amounted to some 275,000,000.

The uncertainty of this estimate is less than in the case of the estimate for the late Neolithic, but it is still large. Actual population may have been 50 millions greater, perhaps located largely in Africa. But it is difficult to know how to allocate as many as 100 millions more. Perhaps 275 ± 80 millions is as reasonable an estimate as any for A. D. 1. I offer it for criticism.

Following Augustus, world population appears to have declined, not only in the Mediterranean Basin, but also in China, which is curious. The low point in both regions was apparently reached in the seventh or eighth century. (Figures 1 - 4).

Then there began, very gradually at first, that growth in world population which has since become explosive, not only in the West, but also in China. The first doubling took some 950 years; the second, about 200 years; and the third, ending in 1950, about 100 years. At present rates, it will double yet again in the next 60 years, reaching 4.8 billions by A. D. 2010.

What can be said about the plausibility of this fourth doubling?

Figure 5 shows the estimated trend in the rate of growth since A. D. 700. The segment of the curve until A. D. 1650 is schematic. It merely reflects the judgment that sometime during the Dark Ages the growth-rate passed through zero. We know progressively more about the curve from A. D. 1650 on, although it is not based on "observations" as you physicists know them. By 1947 the rate had become about 8.5 persons per thousand per year. The State Department believes that the rate is increasing, and that it will reach about 9.4 by 1955. (In 1952 the U. N. estimated that the 1951 rate had been 11.1. Because of under-enumerations, the rate was probably

Figure 2. Estimated trend in growth of world population from
A.D. 1 to 1950, showing the band of uncertainty

Figure 3. Population of China from A.D. 2 to 1933

Figure 4. Estimates of the population of the world,
A.D. 1650 to 1950

Figure 5. Estimated trend in the rate of growth of world population, A.D. 700 to 1950. The point for 1951 was estimated by the U.N., 1952

higher than 1.1).

Are there laws of population growth that would help us evaluate our stated contingency?

The reversal of the apparent down-trend in the Dark Ages, the sustained explosion, its regularity, its simultaneous development in China and the West - all suggest causes that should be identifiable and which, if understood, might provide means of predicting future trends.

But the causes of the explosion remain obscure. Why did the upsurge take place simultaneously in the Mediterranean Basin and in China? Why has it been so sudden?

One can recite a list of factors operating during the sixteenth and seventeenth centuries in Europe that might have contributed indirectly to a decrease in mortality - the discovery of new continents stimulated by the decreasing eccentricity of Polaris and the first appearance of printed correction tables for its general use; improved transportation; fewer local famines; increased commerce; handicraft production; expanded ocean transport; improved agricultural techniques and farm machinery; the enormous stimulation of trade; the rapid movement of persons, ideas, and goods; and the parade of inventions, all gathering momentum as a composite whole, and in part amplifying each other by feedback.

But were these factors effective in China during the sixteenth and seventeenth centuries? China did not then enjoy an age of exploration. She was not stimulated by the opening up of a new continent. So far as we know, the inventive genius of the Renaissance in Europe did not have its counterpart in China, then or later. And, during the hundred years from 1750 to 1850, China was not urbanized and made literate in the wake of an Industrial Revolution.

One must agree with the recent British Royal Commission that the ultimate causes of the explosive outburst in world population since the Middle Ages are not yet well understood. Operating deep within human behavior patterns, they have not yet been measured because they have not yet been brought to light.

Although we do not understand the past course of population growth, many attempts have been made to predict its future trend. The predictions have been of three types - the Malthusian; the component; and the mathematical.

The Malthusian "Law"

The Malthusian "Law" is not very helpful to the Trustee. In 1798 Malthus said that population tends to increase geometrically, while the food supply can increase only arithmetically. Let the ultimate food supply be limitless, still, said Malthus, its increase must progress less than geometrically - a positive check on population growth. An audience of physicists will perhaps be quick to agree that science also progresses geometrically. There is no practical limit, other than available solar energy, to the quantity of food we can grow - and no practical application of the Malthusian "Law" that will help us to set a limit either to total world population within the next 100 years or so, or to its rate of growth.

What about solar energy? Does its supply set any sort of practical limits to the size of world population? About 960×10^{18} BTU, or, for convenience, about 960 Q, reaches the land surface of the earth in an average year. Let us suppose a time when everybody in the world consumes twice as much energy as we do, per capita, in the United States today.

Let us suppose that the sunlight falling on 10% of the land surface is harnessed with a photosynthetic efficiency of 10 per cent. Then we find that

we could meet the energy requirements of a population of about 20 billion.

Such calculations must ever remain indefinite so long as the endless frontiers of science continue to roll back. They are helpful, however, in that they serve to place the central problem in some perspective.

We must conclude that no argument is apparent by which to set an upper limit to the size of world population in the next century or so.

The Component Method

What about the component method? The component method consists of attempts to forecast the birth rate and the death rate separately. Can birth and death rates be forecast with assurance?

An examination of the record shows that, while certain death rates can be predicted with some assurance, birth rates have proved unpredictable.

A good example is the population of the United States. Our rate of growth was some 30 persons per 1,000 per year in A. D. 1790. The rate declined, with increasing swiftness, until it hit a low of 6 per thousand in the '30 's. But today it has climbed back to over 17, a value not seen since 1905, and not predicted at all. Our rate of growth has fluctuated because of fluctuations in our fertility patterns - something that we do not yet understand and cannot predict.

The fluctuation in the U. S. birth rate has paralleled that in 14 other countries. (Figure 6).

Mathematical Manipulations of the Crude Growth Rate

What about purely mathematical manipulations of the crude rate of growth?

The most famous attempt in this direction was made by Reed and Pearl in the '20's. They fitted logistic curves to a number of populations and extrapolated for 100 years or more.

Figure 6. The recovery in the gross birth rates of 14 countries,
A.D. 1913 to 1947

Figure 7. The population growth of the United States

Today, 25 years later, it is possible to list the results. Of 14 populations whose size in 1950 was predicted in 1924, 10 have exceeded the forecast, by margins up to 122 per cent. In four cases the errors were less than 5 per cent. One of these is the United States. However, our population is apparently about to depart from the Pearl-Reed forecast by rather a wide margin. (Figure 7).

Probably it is true that populations often, perhaps always, evolve along a logistic curve - but one never knows when the constants are about to alter.

As a predictive device the logistic has no assured value.

Having begun by saying that we would not predict if we could, we now find that, as regards the growth of even massive populations, we could not if we would.

As Trustees who seek to define the maximum plausible contingency to reckon with, there are two steps we can take.

First Step

First, we can study the curve of Figure 5 and we can select the most plausible of the three possible courses it might take in the next 100 years.

The first course is that the curve may break and decline. We know that it must do so sometime. If it continued for only a few thousand years, there would be a galactic sphere of flesh, expanding into space at many times the velocity of light.

Is there anything in sight that will certainly cause it to decline during the next 100 years? There is nothing. The Malthusian devil is cornered in the West, and the means are at hand for controlling him in the East. The only immediate limits to the food supply are (1) the capital we

are willing to invest in producing it, and (2) the political and economic adjustments necessary to distribute it when produced.

It is true that Nehru has allotted 1.3 million dollars in the first Five Year Plan to a search for means to reduce India's birth rate from 40-odd to 20-odd, and in advance of general literacy and an increased per capita income. If he succeeds, it will be without precedent. The odds against success are pretty long. If he can avoid an explosive growth of 3 per cent and keep it down to 1.5 or 2.0 per cent, it would be remarkable. And the Trustee can hardly with prudence rely on such success, not only in India, but on a world-wide scale.

The second course is that the curve may break and accelerate. Such a new growth cycle may have started in those 14 countries of the West shown in Figure ~~14~~⁶. And it may have started in Ceylon and be about to start in India, Columbia, and elsewhere.

However, these potentially disastrous upsurges have been checked by such measures as the legalization of abortion in Japan, which appears to have brought the growth rate down from the postwar high of 4.76 per cent in 1947 to 1.70 per cent in 1950.

If the Trustee assumes a world growth-rate reaching quickly to such very high values as 2 or 3 per cent, he must also assume an equally quick increase in the growth-rate of agricultural output to 3 or 5 per cent and in advance of literacy and of that accumulation of capital necessary to modernize a country. Such extreme assumptions regarding population growth run counter to national policy in Japan and India, for example, and also involve the great risk of Malthusian disasters in many places.

So, perhaps the second course is within the realm of possibility as regards the demographically advanced West. On a world scale, however, it

creates so many special difficulties that its plausibility can hardly be ranked high.

The third course is admittedly not very satisfactory. If the Trustee sees that a population trend has persisted for some time and if he can find no good reason for it to change in the near future, then he must conclude that its persistence for yet a little while longer is too plausible to ignore.

This argument too is similar to that of Pearl and Reed. But there is a difference. They attempted to predict changes in the rate of growth. We are adopting, as a contingency, the assumption that rates of growth not very different from today's rate of 10 per 1000 per year will persist for 50 or 100 years. Another and perhaps more important, difference is this. Pearl and Reed did not have access to the critical studies of Willcox and Carr-Saunders for the period 1650-1935; or to the many estimates for the period 1935-1950, which have formed the point of departure for our extrapolations.

Willcox and Carr-Saunders had made three sets of estimates of world population - not entirely independent of each other. Their estimates form a remarkably concordant series. Graphic extrapolations, based on the smoothed first and second differences of their estimates, give the results shown in Table I and Figures 8 - 11.

Table I

The Maximum Plausible Population of A. D. 2000 and A. D. 2050,
Found by Extrapolating the Smoothed First and Second Differences
of the Three Estimates of World Population
between A. D. 1650 and about 1935 by Willcox and Carr-Saunders

<u>Based on</u>	<u>A. D. 1950</u>	<u>A. D. 2000</u>	<u>A. D. 2050</u>
		<u>Billions</u>	
Willcox in 1931		4.0	7.4
Carr-Saunders in 1936		3.6	6.0
Willcox in 1940		4.0	8.1
The Means	2.4 ± 0.2	3.9 ± 0.3	7.2 ± 1.0

Second Step

The Trustee's second step is to test whether this mathematically plausible trebling within 100 years can be allocated without causing specific implausibilities.

To carry out this test, it is convenient to construct an S-curve of demographic evolution, to show graphically the transition from the pattern of illiterate subsistence farming to that of the literate industrial-urban-farm life. (Figure 12).

At the right-hand side of the curve are those countries which are completing a cycle of growth. Literacy rates are high - also real income per capita and per capita demand for energy. The rate of growth is tending to decrease. At the left-hand side are those countries near the beginning of a growth-cycle. Birth-rates are high, but so are death-rates. The dependency on agriculture is heavy.

Figure 8. Hypothetical World population to A.D. 2050
(found by graphic analysis of the smooth curve of second
differences of the estimates of World populations for
A.D. 1650 to 1950 made by Willcox in 1931)

Figure 9. Hypothetical World population to A.D. 2050
(found by graphic analysis of the smooth curve of second
differences of the estimates of World populations for
A.D. 1650 to 1950 made by Carr-Saunders in 1936)

Figure 10. Hypothetical World population to A.D. 2050
(found by graphic analysis of the smooth curve of second
differences of the estimates of World populations for
A.D. 1650 to 1950 made by Willcox in 1940)

Figure 11. Estimated trend in the growth of World population from A.D. 1 to 1950, (showing the band of uncertainty), with projections to A.D. 2050, (based on Figures 8, 9 and 10)

Figure 12. The principal population groups of the World
classified according to their positions on the
S-curve of ~~the~~ demographic transition

Figure 13. Schematic diagram showing the past and the potential paths of evolution of the principal populations of the world along S-curves of demographic transition

(1) Rest of Africa	(13) Uruguay
(2) China	(14) U.S.A., Canada, Australia, & New Zealand
(3) India and Pakistan	(15) French North Africa
(4) Egypt	(16) Netherlands
(5) Indonesia	(17) Union of South Africa
(6) Rest of South America	(18) Japan
(7) Southwest and Southeast Asia and Ceylon	(19) Northeastern Europe
(8) Middle East	(20) Eastern and Southeastern Europe
(9) Middle America and Caribbean	(21) Southern Europe
(10) Brazil	(22) Central Europe
(11) Argentina	(23) Northwestern Europe
(12) U.S.S.R.	

The inflection point defines the demographic transition. Populations lying above the inflection point are faced with decreasing rates of growth; those lying below it with increasing rates of growth. The death-rate falls first, under the impact of Western health measures. It has been easy to reduce death-rates. Japan's death-rate was cut in half in two years of our occupation and Ceylon's by two-thirds in three years, with DDT and elementary public health measures.

But the decline in the birth-rate, in the past, at least, has followed the decline in the death-rate only after an interval of several generations. The temporarily widening gap between the swiftly declining death-rate and the more slowly declining birth-rate leads to an increase in the rate of population growth. Nothing we know today makes it likely that the transition can be negotiated without a considerable population increase - on the order of a doubling or a trebling.

Whenever the technical arts are advancing faster than population is growing, the demographic transition can occur. This state of affairs now prevails among nearly half of the world's population. Literacy is an example. World literacy now stands at 40 or 50 per cent. At present rates of gain, it will pass 80 per cent by A. D. 2050. Similarly, the 40 per cent fraction that has now made the demographic transition will eventually become 50 per cent, then 60, then 70 - but perhaps never 100 per cent.

The position of each of the 168 populations of the world on the S-curve has been examined. More or less subjective estimates have been made of the maximum plausible multipliers in each case, to convert the 1950 population to a 2050 population. (Figure 13).

The sums of these rational estimates yield the figures shown in the first line of Table 2, to be compared with the mathematically plausible

estimates of Table 1, shown in the second line.

Table 2

Comparison of Estimates of Maximum Plausible World Population
in A. D. 2000 and A. D. 2050

	<u>A. D. 2000</u>	<u>A. D. 2050</u>
	<u>Billions</u>	
The mathematically plausible estimates	3.9 ± 0.3	7.2 ± 1.0
The sum of the rational estimates of the maximum plausible populations	3.7 ± 0.5	6.3 ± 1.0

The rather rough agreement at least reveals no major specific implausibilities in the mathematical extrapolation. These are not the maximum populations that could come into being by these dates. They are the maximum plausible populations for the Trustee to reckon with.

Summary and Conclusions

A population of 6 or 8 billions may never come into being; but, if it does, it will not be based on illiterate subsistence farming - a system that cannot feed many non-farmers. It could only be based on literate industrial-urban-farm patterns of living. Inevitably, it would be characterized by a higher average per capita demand for energy than that of today.

In a general way, it seems plausible that the larger the ultimate population, the greater would be the per capita requirement for energy.

What this per capita demand might amount to will be examined tomorrow night.

Lecture II

THE MAXIMUM PLAUSIBLE REQUIREMENTS FOR ENERGY,

A. D. 1950 to 2050

Never before has there been such a world-wide interest in the rate at which energy is being consumed. Truly, the rate is unbelievable. The acceleration in the rate is even more unbelievable. In the United States, one-half of all the coal ever consumed has been burned since 1920, and nearly one-half of all the oil and gas ever consumed has been burned since 1940.

Purpose

In the previous lecture we concluded that a Trustee of Energy would be imprudent if he failed to reckon with the contingency of a world population of 6 to 8 billions by A. D. 2050. This is not to say that such populations are predicted. It is merely to recognize that the needs, hopes, determinations and plans of very large numbers of people and their leaders all converge towards such an end. The plans may fail. But the Trustee is not allowed to count on this. He must reckon that at least a trebling of population within 100 years is too plausible a contingency for him to ignore.

In this lecture we shall sketch the past growth patterns of the eight great national energy systems of the world. This sketch, combined with the sketch of population growth made last evening, will be used to complete the answer to our first question: "What is the maximum plausible quantity of energy that people might demand in the next 50 years or so?"

Scope

The energy systems of Europe, North America, South America, and Asia have been sampled by analyzing the inputs, efficiencies, and outputs per capita in Argentina, France, Germany, India, Japan, the United Kingdom, the

United States, the U. S. S. R., and the world, for as far back as acceptable records could be found.

The annual inputs for the individual countries have been computed from the production records of fuels and water power, corrected for exports and imports, and adjusted for changes in the stocks on hand.

Reliability of the Findings

Inputs

In recent years, in countries with a tradition of fact gathering, the uncertainty in the value of the total input of energy for any single year probably does not often exceed 10 per cent.

In regard to the United States, for example, there must have been a balancing of errors among the many tens of thousands of reporting sources - including the 7000 coal mines and the 400,000 oil wells. The proof is that even minor fluctuations in the curves of total annual input do, in fact, reflect well-established economic or military events, as we shall see in a moment.

On the whole, it seems probable that the general input-output pattern of the energy systems of the eight countries and of the world has been correctly sketched, at least as regards the ranking of the countries and the general trends. With no greater claim to accuracy, the findings are presented for criticism.

Description of the Findings

The findings have been arranged in a pattern designed to lead us to the answers we want. First, we shall look at total inputs to the world energy system, by source of energy; then, at the total inputs to each of the eight great national energy systems. The total inputs are converted to per capita inputs, which are multiplied by the estimated efficiencies to obtain

per capita outputs. It is the rate of growth in the per capita output of energy that is the key we seek.

A study of these rates of growth of per capita demand during the past 100 years or so is the basis for estimating whether, in the future, the world rate will tend to be higher or lower than the rates already recorded.

When we have decided this point, we shall convert the contingent per capita outputs of the future to per capita inputs, and multiply by the contingent populations specified in the first lecture, to obtain the maximum plausible total requirements for energy.

Total Annual Inputs

The total annual inputs to the energy system of the world from the major sources, A. D. 1860 to 1947, are shown graphically in Figure 14.

Fuel Wood. Fuel wood was the major source of energy until 1880, when it was overtaken by coal.

Coal. Coal's maximum share - 88 per cent - was obtained in 1910. Since then coal's share has dwindled to less than half of the total input.

Farm Waste. More energy was obtained from farm waste than from all the fluid fuels until as recently as 1940.

Fluid Fuels. In 1947 the fluid fuels were contributing 25 per cent of the total energy, while wood and farm waste combined were contributing 21 per cent. The world-wide preference for fluid fuels continues. In 1950 they contributed 30 per cent to the world energy system; in the United States, over 50 per cent.

Water Power. Although the proportion contributed by water power has been increasing, it does not yet amount to more than 1.0 per cent of the total.

Cumulative Totals. In the first 18-1/2 centuries after Christ, the

Figure 14. Total annual input to the energy system of the World
from the major energy sources, A.D. 1860 to 1947

Figure 15. Total annual inputs to the energy systems of 8 countries and the World from the major sources of energy

Figure 16. United States: Total annual input to the energy system from the major energy sources, A.D. 1800 to 1949

total burn-up probably amounted to 6Q, possibly 9Q, reaching a rate of about 1.0Q per century in the year 1850. In the next hundred years the burn-up was about 4.0 Q. In 1947 the burn-up was 0.093Q - at the rate of 9.3Q per century. By 1950 the rate had reached over 10Q a century.

The increase in the rate since A. D. 1850 has been provided principally by the combustion of coal, oil and gas. By 1948 the cumulative all-time burn-up of coal was about 2.3 Q, of which one-half had been burned since 1923. Oil and gas had provided 0.48Q, of which one-half had been burned since 1938. Wood and Farm Waste has provided about 1.2 Q, and water power about 0.01 Q.

Total Annual Inputs in Each of the Eight Countries. The total annual inputs to the energy systems of eight countries are compared with that of the world in Figure 15 . There are several interesting points.

Since A. D. 1830 the United States has been the heaviest consumer of energy. Prior to 1830 India may have been the leader. After 1860 the United Kingdom was second, India third, and the U. S. S. R. fourth.

In A. D. 1900 the United Kingdom was still second, but Germany, which had come up very fast, was third, and the U. S. S. R. was fourth. By 1929 the United States had pulled away from the others.

In 1950 the United States was still first, but the U. S. S. R., which had come up very swiftly, had moved into second place, and the United Kingdom and Germany were tied for third place.

In 1850 the United States contributed about 27 per cent to the total world energy system. By 1913 this had increased to 33 per cent, and by 1950 to about 37 per cent. In the same century the energy system of the United Kingdom has dropped from about 15 per cent of the world total to about 6 per cent, while the energy system of the U. S. S. R. has been

Figure 17. United States: Per cent of the total annual input of energy that was supplied by crude oil plus natural gas, A.D. 1850 to 1949

increasing from 7 per cent of the total to about 12 per cent.

There are some points of special interest in the energy system of the U.S. (Figure 16). Coal did not pass wood until nearly 1890; oil and gas combined did not pass wood until nearly 1920; wood is still nearly five times as important as water power; and oil and gas passed coal in the late 1940's.

The rate of relative growth of the fluid fuels in the United States has been rapid. If present preferences continue, it is not difficult to imagine that the fluid fuels will be contributing between 65 and 85 per cent of the total within 25 years. (Figure 17).

The contribution by water power has been increasing in the United States and now amounts to 1 per cent.

Annual Per Capita Inputs in Each of the Eight Countries. In Figure 18 are shown the estimates of the annual per capita inputs to the energy systems of the eight countries and of the world, from all sources of energy, for various portions of the century and a half between A. D. 1800 and 1947. One of the most striking feature is the general lack of advance in recent years.

In the United States the per capita inputs during World War II averaged about 220,000,000 Btu, only fractionally above the 205,000,000 average of World War I.

In the United Kingdom the 1917 peak of 150,000,000 Btu during World War I was not much higher than that of 1883, and there has been a drift downward since 1917 to an average of 130,000,000 Btu during World War II.

The German annual per capita input reached a peak in 1913 of about 100,000,000 Btu after a swift, sustained rise from the 13,000,000 Btu level in 1860; however, the general trend since 1913 has shown no gain.

These trends have suggested to some a slowing down and a maturing

Figure 18. Annual per capita inputs to the energy systems of 8 countries and of the World from the major energy sources

within the industrial systems of the United States, the United Kingdom, and Germany. They have been interpreted to mean that it is the primary (or extractive) industries and the secondary (or manufacturing) industries which are energy-hungry and that, as the tertiary (or service and consumer) industries come into prominence, the per capita demands for energy tend to stabilize. It has been implied that the per capita consumption of energy in the industrialized countries is leveling off.

Such conclusions may be very misleading, as will be seen when the annual inputs are multiplied by the respective efficiencies to yield estimated annual per capita outputs.

Efficiencies

A distinction must be made between technical efficiency and economic efficiency. If 100 tons of coal are raised, transported, and fed into the boilers of a steam-generating station, the efficiency of use of that 100 tons may be found by dividing the heat equivalent of the electricity generated by the heat content of the coal. In the most modern station the answer might be 38 per cent. This is technical efficiency.

However, to get that 100 tons of coal into the boiler requires the energy of about twelve more tons of coal - in mining, washing, drying, grading, and transporting. Furthermore, in delivering the electricity to the point of end use, there are losses of perhaps 15 per cent. Therefore, the economic efficiency measured between the 100 tons of coal in the national reserve in the ground and the electricity as it enters the motor of a vacuum cleaner, may be $88 \times 85 \times 38$ per cent, or 29 per cent.

The curves of technical efficiency shown in Figure 19 have been derived as follows. First, the energy system of the United States in 1947 was broken down into 126 end uses and an efficiency was estimated for each

Figure 19. United States: Efficiencies of each of the three components of the energy system -- work, process heat and comfort heat -- and the weighted average efficiency of the whole system. The efficiency with which ~~the~~ electricity has been generated in steam-stations is also shown.

Figure 20. United States: Trends in the relative ^{pro}portions of *the 3* components of the energy system -- work, process heat, and comfort heat

Figure 21. Weighted average efficiency of use of energy in the energy systems of 8 countries and of the world, for various periods ending in about 1950

end use. Next, these 126 end uses were collected into three categories - Comfort Heating, Process Heating, and Work. The trends in the relative proportions of these categories were estimated back to A. D. 1800, and the aggregate efficiency within each category was also estimated. The trend in the efficiency of work was estimated by using as a yardstick the central station efficiencies reported by the Federal Power Commission. (Figure 20).

A weighted average efficiency for the United States was then computed.

The weighted average for the United Kingdom is based largely on a single point, for 1946, estimated by the Ministry of Fuel.

The weighted averages of the other countries and of the world have been put together as well as possible, using rational arguments based on the literature. (Figure 21).

The reliability of these estimates can not be high. The best point is probably the 1947 value for the U. S. of 29 ± 4 per cent.

The other values have less reliability, but the general pattern probably has some real significance. It is a first approximation, offered for criticism.

It will be seen that the average technical efficiency in the United States has nearly tripled in 50 years, rising from about 11 per cent in 1900 to about 30 per cent in 1950. In the same period, world efficiency has perhaps doubled, rising from about 11.5 per cent to about 22 per cent.

When the per capita inputs of Figure 18 are multiplied by the efficiencies of Figure 21, the per capita outputs of Figure 22 are obtained.

Per Capita Outputs

In the United States, while per capita input was advancing by no more than 7 per cent between 1917 and 1947, the growth in the per capita output

in the same period amounted to 260 per cent.

In the United Kingdom, where per capita input has remained stationary or has declined since 1883, per capita output has increased nearly 300 per cent.

In Germany the per capita input that failed to advance steadily after 1931 is to be compared with an output that had increased two-thirds by 1939.

These three examples illustrate the point made previously that per capita inputs of energy have been most misleading guides to the growth of an energy system.

Rates of Growth of Per Capita Output. In the United States, counting from A. D. 1860, the first doubling in the per capita output of energy took about 45 years, the second about 36 years, and the third perhaps will have taken place within 19 years, that is, by A. D. 1960.

As regards the world average per capita output, the first doubling, counting from A. D. 1860, took about 39 years, the second about 37 years, and the third apparently will have taken place within 16 years, that is, by A. D. 1952.

It is interesting to compare the rates of growth in Germany and the United Kingdom. The curve for Germany shows the highest sustained rate of any of the nine examples. There is a strong convergence toward that of the United Kingdom, the gap between them being nearly closed in the mid-1920's. In 1860 the German per capita output had been not more than 20 percent of that of the United Kingdom.

The U. S. S. R. curve, looked at as a whole, seems to suggest that the present regime has just about made up for the Revolutionary losses and will soon have reached the point that the Czarist regime would have reached

had a fair curve for the period 1860 to 1910 been continued to 1950. The rate of growth in the per capita output of Russia since the setbacks of the revolution has been very swift.

The rate of growth of per capita output in Japan between 1900 and 1940 was very swift.

It has been little realized how much more energy was consumed per capita, before 1860, in the United States and in the U. S. S. R, than in countries like the United Kingdom, Germany, France, and in the world as a whole. In those days the United States and Russia were eating their way through their forests and consuming wood lavishly, particularly in the fairly cold winters.

In A. D. 1800 world average output was about 1,000,000 Btu per capita per year. In 1950 it was approximately 10,000,000. In the 150 years during which the world average was multiplied by 10, the United States average, high to begin with, was multiplied by about 7.

Summary of Rates of Growth of Per Capita Output of Energy

In the past in the West, as is well known, there have been sustained rates of growth in such indexes as population, gross national product, agricultural output, accumulation of capital and real income per capita which have fallen often in the range between 1 and 2 per cent a year compounded, but which have seldom greatly exceeded this range for long periods. In this same period the demand for the output of energy per capita has tended to grow at higher rates. Sustained average rates of 3.2, 3.4, 3.9 and 4.4 per cent per annum compounded annually have been recorded in Japan, the United States, the U. S. S. R., and Germany. The world rate, since 1860, has averaged 2.2 per cent. It has been increasing. It now stands at about 3 per cent.

Figure 22. Annual per capita output of energy in 8 countries and the World from the major energy sources, measured at the point of end use, for various periods ending about 1950

The growth in the output of energy for the past 50 years can be largely accounted for by increases in the efficiency with which energy has been used. In the case of the United States the national average efficiency of use has trebled since 1900. It now stands at 30 per cent. It can hardly treble again. Future increases in the demand for the output of energy must be met to a greater extent than before by proportionate increases in the input of energy. It would be hardly plausible to expect that, once again, nearly $2/3$ of the increase in output could be met by means of gains in efficiency, as was done in the United States during the period 1920-1940.

The central question for us as Trustees of Energy becomes something like this: The rate of growth in the world average per capita demand for the output of energy has averaged some 2.2 per cent compounded for nearly 100 years. It has been increasing. It appears to be running at about 3 per cent currently. Is there any reason to suppose that the maximum plausible rate of increase will fall below 3 per cent in the future? If not, how high might it go?

In the past 100 years the growth in the average world per capita demand for the output of energy has been weighted largely by the needs of a few hundred millions in the West. In the future the growth will be based not only on further demands in the West, but also on rapidly increasing and overlapping demands from many hundreds of millions of people in presently under-developed countries like Russia, Brazil, India and China.

A brief sketch of Russian performance data will suggest to the Trustee what other under-developed nations may do; for, what Russia appears to have accomplished, with sound and fury and much internal waste, others now believe they can accomplish. They will wish to copy her results, while perhaps improving on her performance.

Figure 23. United States: Projection to A. D. 2050 of the minimum plausible trends in the efficiencies of the 3 components of the energy system; of the generation of electricity; and of the weighted average of the entire system

Figure 24. United States: Projections to A. D. 2050 of the relative proportions of the 3 components of the energy system --- work, process heat, and comfort heat

In the U. S. S. R. in the 12-year period between 1928 and 1939, the annual rate of growth of all industry appears to have been about 17.9 per cent; of the total input of coal, about 12.4 per cent; and of crude oil, about 8.6 per cent.

A thoughtful, although admittedly speculative, analysis by Gerschenkron of the next three Five-year Plans has been based on the performance in Russia since 1890, including the first four Five-year Plans. From these analyses, it appears that the expectations of the Politburo, if realized, may be translated into the statement that, in the 12 years ending in 1963, the rate of growth in the per capita output of the Russian energy system will have averaged about 5.5 per cent a year compounded, making a 38-year average since 1925 of about 4.5 per cent. These figures are not very reliable. They may exaggerate the truth.

If Russia is living in the heroic age of her industrialization, other countries are about to enter theirs. Everywhere there is ferment. Masses of people and their leaders want the fruits of mechanization. They know by example what is possible. We have learned, sometimes to our pained surprise, that the fruits of modern technology are rather easily digested by backward people. And the great U. S. and U. N. Technical Assistance programs - Point Four, Mutual Security Administration, the Export-Import Bank; the Food and Agriculture Organization, the World Health Organization, the World Bank - are sending thousands of experts and billions of dollars into the under-developed countries, to give direction and acceleration to the ambitious but feasible plans of Brazil, Columbia, India, Iraq, Mexico, Turkey and some 70 other countries.

In the aggregate these programs would tend to bring the under-developed world abreast of our 1950 position at a faster rate than we have maintained

Figure 25. The weighted average efficiency of use of energy in 8 countries and the World, with projections of the minimum plausible trend in the efficiency of the U. S. energy system and of the World energy system

Figure 26. Total annual inputs to the energy systems of 8 countries and of the World from the major sources of energy for various periods ending in about 1950, with hypothetical projections to A. D. 2050 based on various rates of growth in the per capita demand for the output of energy

in the United States in arriving there during the past 100 years - a rate that has resulted in an average annual growth of the per capita demand for the output of energy of some 3.4 per cent a year compounded.

So, our hypothetical Trustee of the world's energy finds no assurance that during the next 50 years the rate of growth in the world average per capita demand for the output of energy will fall below the current rate of 3.0 per cent a year. On the contrary, he finds that he must accept as plausible a rate higher than 3.0 per cent.

To convert rates of growth of per capita output into actual annual requirements for the input of energy is a matter of arithmetic, using the projected world efficiency shown in Figures 23 - 25. The results are shown in Figure 26, for several cases, based on assumed growth-rates of 1, 2, 3 and 5 per cent in the per capita output of energy.

A hasty critic will perhaps suggest that an estimate based on the multiplication of a maximum plausible per capita demand by a maximum plausible population is a mere multiplication of maximums, and is, a priori, implausible.

But such a criticism misses the point of the argument.

It is impossible that the population of the world should double or treble unless most of the illiterate subsistence-farm groups succeed in making the transition to literate industrial-urban-farm patterns of life. But such a pattern implies high productivity per capita, high real income, and high demands for energy.

So, the one plausible maximum implies the other. A great increase in world population without a great increase in per capita demand for energy is not plausible.

Some of the implications of a sustained rate of growth of 3 per cent

Figure 27. United States. Quanta of energy output required per quantum of real national income as a function of the general economic level

Figure 28. United States. Total annual cumulative input to the energy system from all the major energy sources, A. D. 1800 to 1949; with projections to A. D. 2000

in the output of energy per capita may be brought into perspective by comparing the actual increases of the past 100 years with the hypothetical increases of the next 100 years. During the past hundred years there has been a ten-fold increase in annual output per capita - from 0.9 million Btu to 9,000,000 Btu. If the present 3 per cent rate is not exceeded, then the next century will see a twenty-fold increase - to about 175,000,000 Btu per capita, or some 2.5 times the 1950 figure for the United States.

The figures for the U. S. during the past 50 years and the next 50 years are of more specific interest. During the past 50 years, the increase in annual output per capita was five-fold, from 13,000,000 Btu to 68,000,000 Btu. If this 3.4 per cent growth-rate of the past 50 years becomes 2.0 per cent over the next 50 years, then, by A. D. 2000, the further increase would be 2.7-fold, to some 185,000,000 Btu per capita.

The 2 per cent rate of growth (in ~~the~~ per capita output of energy in the United States in the period A. D. 1950-2000), has been selected because the quanta of energy output required per quantum of real national income have ceased to increase. In 1897 we required some 32,000 Btu of energy output per International Unit of national income; in 1929 about 60,000; and since the mid-thirties the ratio has steadied down at about 62,000 Btu per I. U. (Figure 27).

Real national income per capita has been growing, since A. D. 1897, at about 2 per cent a year compounded.

If it is plausible to assume that real national income per capita will continue to grow, at about 1.5 per cent or so, and if the growth-rate of population should decline along a straight line from the 1953 value of 1.73 per cent to an assumed rate in A. D. 2000 of 0.89 per cent, averaging about 1.3 per cent for the period; and if the growth-rate of the average

system efficiency, derived from Figure 23, is taken to be about 0.65 per cent; then it follows that the growth-rate in the demand for the per capita output of energy will be about 2 per cent or a little more.

Admittedly this chain of reasoning is open to challenge at every step. A case could be made for a growth-rate in the output of energy per capita both lower and higher than 2 per cent.

But, based on what evidence is available in this report, no rate appears more plausible than 2 per cent, so it is selected, for the United States.

If abundant low-cost energy is forthcoming, then perhaps an I. U. of national income will consume more than 62,000 Btu of energy; in which case the growth-rate in the per capita demand for the output of energy may not drop to a 2 per cent average. If it does not drop, then requirements for energy in the United States would become very great indeed. The possibilities are set out in Table ~~27~~³ and Figure 28.

Table 3

Cumulative Requirements for Total Annual Inputs
to the Energy System of the United States, from A. D. 1950 to 2000,
Based on Three Assumed Rates of Growth in the Demand for the Output of Energy Per Capita
and on Assumptions Regarding the Increase
in the Weighted Average Efficiency of the System
and the Decline in the Rate of Population Growth that are Explained in the Text.
Cumulative Total Annual Inputs are Given in Q.
Rates of Growth in the Demand Per Capita
for the Output of Energy Are in Per Cent Per Year Compounded.

<u>Year</u>	<u>1%</u>	<u>2%</u>	<u>3%</u>	<u>5%</u>
1950	- - -	- - -	- - -	- - -
1960	0.56	0.60	0.64	0.73
1970	1.04	1.18	1.34	1.74
1980	1.62	1.95	2.36	3.52
1990	2.32	2.97	3.84	6.66
2000	3.14	4.29	5.97	12.10

These figures give the answers to our first question: What is the maximum plausible quantity of energy that people might demand over the next 50 years or so in the United States?

In the United States our population may reach 225 millions by A. D. 1975 and nearly 300 millions by A. D. 2000. If the accelerating rate of growth in the output of energy per capita reverses its trend and drops from the fifty-year average just recorded of 3.4 per cent to a fifty-year average of 2.0 per cent a year compounded, then the total

additional requirements for energy in the United States would be about 1.6 Q by 1975 and about 4.3 Q by A. D. 2000.

We have said that in the first 18 - 1/2 centuries after Christ the burn-up in the world energy system was 6 to 9 Q, reaching a rate of about 1.0 Q a century in the year 1850. In the next 87 years we burned up half as much again - about 4 Q. In 1947 the burn-up was 0.093 Q - at the rate of 9.3 Q a century. By 1950 the rate had probably reached over 10 Q a century.

If the presently increasing rate of growth of the world average per capita demand for the output of energy -- which has averaged about 3 per cent for the past 15 years, as indicated in Figure 22 -- should cease to grow, but should stabilize at 3 per cent, then, by A. D. 2000, we shall have burned up a further 10 Q, and by A. D. 2050 a further 70 Q, (including the 10 Q).

If the presently increasing rate of growth should continue to increase until it will have averaged 5 per cent, then the world burn-up in the next 50 years will be an additional 22 Q; and in the next 100 years an additional 487 Q, including the 22 Q. (Figure 29).

Tomorrow night we shall match these maximum plausible requirements against the minimum plausible reserves of economically recoverable fuels, in order to answer our third question: What is the maximum plausible role of nuclear fuels?

Figure 29. Estimates of the maximum plausible cumulative World demand for the input of energy A. D. 1947 to 2050, assuming 4 different maximum populations, 3 different maximum rates of growth in the per capita demand for the output of energy measured at the point of end use, and 1 minimum trend in the weighted average efficiency of the World energy system

Lecture III

RESERVES OF ENERGY IN THE CONVENTIONAL SOURCES

A. D. 1950 to 2050

Introduction

It may be convenient to preface tonight's lecture by a brief summary of the two previous lectures.

In the first lecture we examined the past record of the growth of population. We found that population had apparently passed through a minimum in the seventh or eighth century, both in China and in the West. There is no satisfactory explanation of this curious phenomenon. Thereafter, the first "known" doubling took some 950 years. Beginning in about A. D. 1600 there was an explosion in world population. The second doubling took 200 years; and the third, ending in 1950, 100 years. At present growth-rates world population will double yet again in 60 years, becoming about 4.8 billions by A. D. 2010. But, the present growth rate is increasing. It is now about ten or eleven per thousand per year. If the average does not exceed ten per thousand, then the population in A. D. 2000 will be just under 4 billions; in A. D. 2050, just over 7 billions.

Perhaps these large populations will never come into existence. But if they should come to pass, they could not be based on illiterate subsistence farming - a system that cannot feed many non-farmers.

A population of 7 billions 100 years from now could only be based on the continued transition to the literate industrial-urban-farm patterns of life. These patterns imply large per capita demands for energy.

In the second lecture we reviewed the past patterns of energy consumption. We found that in the first 18-1/2 centuries after Christ the total input to the world energy system was 6 to 90. In the next century,

ending in 1850, we burned up half as much again - about 4 Q. The rate of growth of the present world average per capita demand for the output of energy has averaged 2.2 per cent a year compounded during the past 90 years. This rate of growth has been increasing. During the past decade or so it appears to have averaged about 3 per cent compounded, and it appears to be about to increase still further. If, however, we assume that it fails to increase further, then the maximum plausible contingency is that we shall burn up some 10 Q by A. D. 2000 and some 70 Q by A. D. 2050.

Similarly in the United States, if the presently accelerating rate of 3.4 per cent ceases to grow further, but declines to an average of 2.0 per cent, then our input since A. D. 1950 will have amounted to 1.6Q by A. D. 1975 and to about 4.3 Q by A. D. 2000.

If the presently accelerating per capita growth-rates should continue to increase, then the additional accumulated burn-ups would be very large indeed.

What are the prospects of finding energy in such abundance and at low cost?

POSSIBLE SOURCES OF ENERGY

A. D. 1950 to 2050

- A. Capital Sources. The Economically Recoverable Reserves of Energy in the Fossil Fuels - Coal, Oil, Gas, Oil Shale, and Tar Sands.
- B. Income Sources. Fuel Wood, Farm Wastes, Peat, Water Power, Wind Power, Heat Pumps, Temperature Differences in Tropical Waters, Tides, Solar Heat Collectors for Cooking, Hot Water and Comfort Heating, Solar Power Collectors, Biological Photosynthesis (Chlorella) and other income sources.
- C. Nuclear Fuels.

A. The Capital Sources of Energy

There is no such thing as an absolute reserve of coal, oil and gas.

Reserves are relative. There is more coal, oil and gas in the earth's crust than will ever be used. It is not a question of emptying the bin. It is only a question of deciding how deep it is economical to dig.

If all the fossil hydrocarbons owe their origin to chlorophyll, and if all the oxygen in the atmosphere is a by-product of that process, then the total geologic endowment of coal, oil and gas can be calculated from the known weight of atmospheric oxygen, as suggested by Kelvin. On this basis, the "reserve" has a heat content of something like 10,000 Q. If part of the oxygen trapped in the weathering of surface rocks has the same origin, the estimate can be increased. Urey suggests that not all of our oxygen has come from photosynthesis. He thinks that much of it has been liberated in the outer atmosphere, by the dissociation of water. If he is right, the total geologic endowment may contain only a few thousand Q.

How much of the total endowment has survived metamorphism and erosion, no one knows. Nor is it important to know this. What is important to know is: How much more coal, oil and gas can be produced at approximately present unit costs?

The trend in the unit costs of winning coal has started upward in the United States; in Europe, where unit costs have long been from two to four times as high as in the United States, the trend is continuing upward and perhaps at a steeper rate than in this country; the costs of finding and producing oil have now risen so far as to bring us within sight of the economic synthesis of oil from natural gas, shale, coal and perhaps later, from other things.

We appear to be entering an elbow in the cost-curve of energy from fossil fuels. Any sharp increase in such energy costs will hasten the day when new sources of energy appear on the market. Therefore, it is of little

interest to compute the "ultimate reserves" in the deepest, thinnest, and least accessible coal beds, and in the deepest and least accessible of the geologically inferred submarine oil fields.

In this lecture the purpose is to estimate the assured reserves of mineral fuels whose heat content can be brought to market substantially at present costs.

A recapitulation will permit a comparison between the reserves of capital energy and the maximum plausible future demands that we estimated yesterday evening.

The Reserves of Coal

It has long been accepted that the reserves of coal in the United States amount to "about 3.1 trillion tons, sufficient for nearly 3400 years at a yearly rate of production approximating the maximum rate in the past - 600 million tons - and with current mining losses".

I have quoted from testimony in Senate hearings of May, 1947, offered jointly by representatives of the U. S. Geological Survey and the U. S. Bureau of Mines. (Figure 30).

The total geologic endowment of that part of the earth's crust that underlies the continental United States may in fact contain 3 trillion tons of coal - or more. But the implication that this is an economically recoverable reserve, containing some 68 Q, that can be entered on the books of a Trustee of Energy as a current asset, is just not so.

The figure dates from about 1909, when Campbell, of the Geological Survey, put it forward. But Campbell also said that much of this large quantity was not mineable, and much that was mineable was inaccessible. Allowing for these two factors, he arrived at a figure of 1.4 trillion tons of economically recoverable coal, about which he added that much of it was

low-rank coal, and, said he, "... the bulk of coal being mined today is the best in the country, and before long, perhaps within 50 years, (i.e., by 1959), much of the high-rank coals will be exhausted".

That is, Campbell thought of our practical reserves as having a heat content of some 30 Q, not all of which could be won without an increase in real unit costs.

Since Campbell's day, approximately 1.3 million oil wells have been drilled; state geologists have done a great deal of field work; coal-mining companies know a great deal more about the individual coal fields; and it has become possible to supplement Campbell's correction factors by a correction schedule based largely on Fieldner, but supported by private correspondence with the 48 state geologists. The correction schedule can be summarized as follows.

First, we now know that some of the geologic inferences of 1909 were on the high side.

Second, the inclusion of coal in seams as thin as 14 inches and at depths as great as 3000 feet is no longer considered realistic.

Third, recoverability is less than Campbell had assumed, and has not been helped by mechanical mining.

Fourth, Campbell included coals with an ash content up to 30 per cent - a specification that is not now acceptable.

Fifth, the inaccessibility, atmospheric instability and low rank of much of our Western reserve of coal requires its conversion to fluid fuels, for shipment to centers of demand, with a loss of half the heat content.

A sixth factor should probably be added. The average heat content of coal being delivered to public utilities is declining, and Fieldner thinks it will continue to decline.

When these correction factors are multiplied together, the over-all factor becomes about 0.10, reducing the heat content of our economically recoverable reserve from the 68 Q, reported to Congress in 1947, to about 7.0 Q. Crichton of Pittsburgh has estimated that it amounts to about 6.0 Q. And, during the past winter, the Geological Survey has confirmed these figures, with an estimate of about 7.6 Q. However it is by no means certain that all of Crichton's 6 Q or the Survey's 7.6 Q can be won at substantially present costs.

Cumulative Production to Date

To date the United States has consumed coal containing about 0.8 Q, three-fourths of it in the last 40 years. (Figure 31). Of the assured reserves, not quite one-third, or about 1.9 Q, lies east of the Mississippi. Thus, in the past 40 years, a quantity has been burned equal to about one-half of what now remains in the assured reserve that is readily accessible to industry at substantially present costs.

The World Situation

Somewhat the same situation exists regarding estimates of the world reserves of coal. They stem from the meeting of the Geological Congress in Toronto in 1913, which found a heat content in the global reserve of some 180 Q, of which 90 Q was credited to the U. S. (Figures 31 A, 31 B).

Of the balance of 90 Q credited to others, more recent and more critical studies suggest that only about 26 Q are economically recoverable at substantially present prices. The world schedule is as follows:

Figure 31. United States: The total annual cumulative input of energy from all coals, A.D. 1800 to 1949.

Figure 31 A. Potential oil-bearing basins of the Western Hemisphere.

Figure 31 B. Potential oil-bearing basins of the Eastern Hemisphere.

Table 4

Heat Content in Reserves of Coal
that are Economically Recoverable

<u>Country</u>	<u>Q</u>
United States	6
Canada	2
United Kingdom	1
Others	<u>7</u>
<u>Sub-total</u>	<u>16</u>
China	6
U. S. S. R.	<u>10</u>
<u>Sub-total</u>	<u>16</u>
Total	32 Q

By the end of 1950 the world burn-up of coal had consumed some 2.4 Q. Three-quarters of the burn-up had occurred since 1900.

Oil - Gas

For convenience, oil and gas will be lumped together, in the ratio of 3000 cubic feet of natural gas for each barrel of oil. The composite heat content of a barrel of crude then becomes 8.8 million Btu.

The proved reserves of the United States contain some 0.25 Q. The undiscovered but economically recoverable reserves are estimated, by geological inference, at twice that, or about 0.5 Q. Some, but not all, of the inferred tideland reserve is included. (Figure 32). It is not certain that all of the 0.5 Q could be won at substantially present costs.

The similar world figures are: proved, 0.99 Q; undiscovered, 4.1 Q; total, 5.0 Q.

Figure 32. Trends in drilling depths in the United States

That is: the ultimate reserves of oil-gas, recoverable substantially at today's costs, have a heat content equal to about one-sixth that in the coal reserve. (Figures 32 - 34).

Oil-Shale

The Geological Survey estimates the assured and economically recoverable U. S. oil from oil-shale at 0.4 Q. The assured world reserves contain a very uncertain 1 Q.

Tar-Sands

The Athabasca tar sands are sticky, hard to handle, and under heavy overburden. (Figure 34). The economically recoverable reserve may contain 0.02 Q.

Summary

The world reserves of energy in the capital sources, economically recoverable at substantially present costs, come to about 38 Q, as follows:

Table 5

Economically Recoverable Energy in the World Reserves

of Fossil Fuels A. D. 1950

Coal	32
Oil-Gas	5
Oil-Shale	1
Tar Sands	<u>0.02</u>
Total	38 Q

Of this reserve, about 7 Q is found in the United States, as follows:

Figure 33. The continental shelves of the United States

Figure 34. The projected petroleum situation in the United States,
1938 - 1951, with projections to 1965

Table 6

Economically Recoverable Energy in the U. S. Reserves
of Fossil Fuels A. D. 1950

Coal	6
Oil-Gas	0.5
Oil-Shale	0.4
Tar Sands	<u>nil</u>
Total	6.9 Q

Heat Loss in Converting Solid Fuels to Fluids

Before the world reserves of 38 Q or the U. S. reserves of 7 Q are compared with the maximum plausible cumulative demands of Figure 29, an adjustment must be made for the heat-losses incurred when converting coal into fluid fuels.

Obviously, the adjustment can be made only in broad strokes, to establish an order of magnitude.

The Position of the United States

Today, fluid fuels are carrying nearly 57 per cent of the total load. The preference for them is increasing. Among domestic users in the United States, 87 per cent would have used oil or gas in 1945, if it had been obtainable. It has been estimated in the industry that in 1960 fluid fuels will be carrying 67 per cent of the load. By 1975, the proportion may reach 70 per cent.

Figure 28 suggests that by 1975 an additional 1.4 Q may have been put into the energy system of the United States. On the average over the 25 years, some 65 per cent of this, or 0.91 Q, must be fluid.

In the United States the economically recoverable reserves of oil-gas are estimated to contain 0.50 Q.

Figure 35. The Athabaska Tar Sands dip westward and
lie under deep overburden

If these plausible figures prove correct, it would be economically attractive to make all fluid fuels synthetically by about A. D. 1975. (For both simplicity and prudence, imports are ignored).

The impact on the coal reserves would be heavy because it takes about 200 Btu of coal to make 100 Btu of fluid fuel. Thus, after A. D. 1975, the idealized date on which the last drop of economically recoverable gas-oil will be extracted, coal must furnish directly the energy for 30 per cent of the demand and, via synthesis at 2 for 1, the energy for 70 per cent of the demand. For every 100 Btu of composite demand after 1970, there must be mined 170 Btu of coal. The small contributions by wood and waterfalls are here ignored.

By 1975, about 0.5 Q of coal would have been burned in the ordinary way (Figure 29), leaving an economically recoverable reserve of about 5.5 Q which, divided by the loss-in-synthesis factor of 1.70, leaves a net available reserve of some 3.2 Q. The position is recapitulated in Table 7.

Table 7
Net Reserves of Energy in the Fossil Fuels of the
United States, Recoverable at Cost No Greater Than Twice
1950 Costs, and Adjusted For Loss-in-Synthesis

Coal	3.2 Q
Oil-Gas	0.5
Shale-Oil	<u>0.4</u>
Total	4.1 Q

When this net effective reserve of economically recoverable coal of 3.2 Q is matched against the maximum plausible cumulative demand, it is found to be enough to last until about A. D. 1995 (Table 3). The 0.4 Q

in shale-oil would postpone the date less than five years. (Figure 28).

What annual use of coal is implied in A. D. 1995? In that year, coal at the tipple would have to contain at least 250,000 trillion Btu in order to feed the plausible maximum input of about 150,000 trillion Btu into the national energy system (Figure 26). A sixteen-fold expansion of the 1950 coal-mining industry is implied - an annual output of some 8 billion tons.

Would such an expansion be technically feasible, economically attractive or socially acceptable? The prudent Trustee of Energy must conclude that a sixteen-fold increase in our coal-mining industry within 45 years is not something he can count on. He is pretty well forced to conclude that the social and economic incentives to develop new sources of energy may become compelling in the United States before A. D. 1975.

Imports of oil would, of course, postpone for a few years the need for synthetics, while creating a temporary vulnerability

The Position of the World

Today, fluid fuels are carrying about 30 per cent of the load. The world preference is increasing swiftly and could well reach beyond 55 per cent by A. D. 2000.

By A. D. 2000, an additional 10 Q (Figure 29) may have been burned, of which on the average over 50 years, about 50 per cent, or 5 Q, would be fluid. The economically recoverable world reserves of oil-gas are estimated at 5 Q.

If these plausible figures should prove correct, then it would be economically attractive to meet all the world fluid-fuel requirements in A. D. 2000 by synthesis.

If the source were coal, the position would be this: by A. D. 2000, about 5 Q of coal would have been burned in the ordinary way (including some 2.3 Q lost by conversion to fluid fuels in the United States). There would be left, in the economically recoverable reserve, about 27 Q.

If the figure 27 Q is adjusted by a loss-in-synthesis factor of 1.5, there is obtained a net effective economically recoverable world reserve in coal of some 18 Q in A. D. 2000, assuming that none had previously been used in synthesis outside of the United States.

So, the gross world reserves of some 38 Q must be adjusted by a loss-in-synthesis factor of about 9 Q, to become a net reserve of some 29 Q.

A further adjustment should be made for the increasing quantities of oil, gas and coal that are consumed by non-fuel uses. This adjustment has been ignored, however, in this first approximation.

Conclusions

When the maximum plausible requirements in the United States of some 4.3 Q by A. D. 2000 are matched against net economically recoverable reserves of some 4.1 Q, the Trustee is pretty well forced to conclude that peak production of each of the fossil fuels may occur some time in the next 50 years - perhaps in the order: oil-gas, good coking coal, good coal in the East, all coal, and oil-shale. Perhaps some of the associated increases in real unit costs will occur before 1975.

The effects on the economy of such increases in the real unit costs of energy are not yet known with assurance. True, the cost of energy in the United States is less than 2 per cent of the gross national product. But its influence is pervasive and repetitive throughout the economy. There appear to be leverage factors. It may be more than a coincidence that the less lively economies of northwestern Europe have long been saddled with real unit costs of energy from 2 to 4 times as high as in the United States. In the absence of proof to the contrary, the prudent Trustee will search for alternative sources of energy costing no more than twice present real unit costs.

If we are to avoid the risk of serious increases in the real unit costs

of energy, alternative low-cost sources should be ready in the United States by 1975, and should be capable of carrying much of the load, here and throughout the non-Communist world, by A. D. 2000.

Where can the Trustee turn?

B. The Income Sources of Energy

We can quickly dismiss quite a number of income sources of energy.

Winds, waves and tides will not solve the Trustee's problem. They can not be expected ever to make more than minor contributions to the world's energy system. Nor can he look to temperature differences in tropical waters, or to the direct collection of solar energy for power, or to atmospheric electricity or to the heat of the earth, as sources of truly abundant, transportable and low-cost energy.

There are some dreams that ~~he~~ cannot count on, although a new discovery may make a reality of any one of them: thermocouples, photo-voltaic cells, oxidation-reduction systems; photochemical decomposition of water; storage of heat in crystal lattices; storage of light in phosphors; non-biological photosynthesis. Doubtless you in the audience can add to this list.

Let us now look at income sources already in use or that might be used.

Wood

In 1950 fuel-wood contributed some 0.004Q to the world energy system - about 4 per cent of the total.

There are 3 billion acres of forest in use and 5 billion of virgin forest. Once there were 12 billion acres. Four billion have been destroyed. If, over the next 100 years, 1 billion acres were restored, there would be a forest reserve of 9 billion acres. If all of this were brought under management and made to yield 2 tons an acre within 100 years

Figure 36 A. Forests of the Western Hemisphere

Figure 36 B. Forests of the Eastern Hemisphere

and if half of this yield were consumed as fuel, the contribution by A. D. 2000 would be some 1 Q and by A. D. 2050 about 5 Q. (Figures 36 A, B)

Clearly these are unrealistic expectations. The minimum plausible contribution by wood is perhaps on the order of 0.4 Q in 50 years and perhaps 1 Q in the next 50 years, for a one hundred-year total of about 1.5 Q.

Farm Wastes

Farm wastes have been contributing about 20 per cent to the world energy system. Coffee in Brazil, wheat and corn in Argentina, bagasse in Cuba and Hawaii, and dung cakes throughout the Middle East and India, are important fuels.

Some farm wastes will doubtless always be burned. But if dung is returned to the soil, the aggregate contribution by A. D. 2050 becomes an uncertain 1.0 Q.

Water Falls

In 1950 waterfalls contributed about 0.7 per cent to the total world system requirement.

The rate of growth of new capacity has been declining, from 22 per cent a year compounded in 1900 to 6 per cent in 1930 and 4.75 per cent in the decade ending in 1950.

Perhaps there will be a five-fold increase in installed capacity within 50 years. The cumulative contribution would then be about 0.2 Q. In 100 years there might be a 15-fold expansion, leading to a total contribution by A. D. 2050 of some 0.6 Q. (Figures 37 A, B, C).

The Heat Pump

The heat pump is a device for lifting the low-energy heat-content of the ground, or a body of water, or the air, to a higher energy level and

Figure 37 C

World water-power resources, potential and/or developed. Estimates based on ordinary minimum flow. Data usually given by countries or major political subdivisions; most important exception is Asiatic U.S.S.R. for which data are shown by river basins. Data included on map are only for places with more than 50,000 kw (amounts over 50,000 shown as full 100,000), with graph base approximately centered in area of greatest water-power concentration.

delivering it to a room for comfort heating. Its method of operation can perhaps be made clear by a rough analogy. A mechanical miner of coal sends up to the surface 20 tons of coal, while it consumes the energy in one ton of coal in doing so. A heat pump is a sort of mechanical miner of energy. The recovery ratio is not yet 20 : 1, but of the 1000-odd heat pumps now in operation in the country, many are working at recovery ratios of 4 : 1 and some at 6 : 1. (Figure 38).

By turning a valve, the thermodynamic cycle may be reversed in summer to provide air conditioning, which may become the principal duty of heat pump installations.

The capital investment in a heat pump is about three times the investment in a home heating installation. So a heat pump is economically justified only in certain regions, that is, where the costs of electric energy are low while the costs of domestic fuel are high.

Comfort heating accounts for about 30 per cent of the total national energy system, and of this fraction perhaps one-third lies in parts of the country where the heat pump has a potential market. If, ultimately, the heat pump should be successful in meeting half the requirements in this potential market area, then the saving might amount to 5 per cent of the total national requirement for energy.

But the saving would not be net because we must subtract from it the electricity which would be consumed during the air-conditioning cycle - a cycle that may prove to be the major load. Until more experience has been accumulated with the heat pump, the hypothetical Trustee is not justified in looking to it for any net contribution to the national energy system.

Comfort Heating with Solar Energy

The direct collection of solar energy for comfort heating has been much

Figure 38. Heat pump installations. The map shows only those installations for which authoritative data have been received by the Joint Association of Edison Illuminating Companies--Edison Electric Institute Heat Pump Committee

in the news in recent years. Houses deigned to be heated entirely by sunlight have been built at M. I. T., University of Illinois and at Purdue. This system holds promise. (Figure 39).

A thoroughly insulated house is equipped with fairly large south windows in order to admit sunlight directly into the rooms in winter. A solar collector is built into the roof. It consists of pipes lying against a black surface and enclosed in a system of glass panes separated by gas-filled spaces. The heat collected in the fluid in the pipes is transfered to some system of heat storage in the house. One ingenious system consists of a great many small cans of Glauber's salt - $\text{Na}_2\text{SO}_4 \cdot 10 \text{H}_2\text{O}$ - built into the south wall of the house. The heat is stored in the fusion of the salt.

Hottel has concluded that in Boston a home-owner would be justified in spending up to \$3.00 per square foot of collector area on a solar heating system. Hottel and Lof at the University of Colorado believe that designs are in sight which can meet the \$3.00 limit.

It seems plausible that over the next one hundred years much of the new home construction in the southern tier of states and some of it in the middle tier of states will rely entirely on solar collectors for heating. If this should prove to be the case, then perhaps 20 per cent of the comfort heating load, or about 6 per cent of the total energy system, might be borne by solar collectors for home heating. (Figure 40).

The heat pump can be combined with solar collection. There are some engineering advantages to this, with the further advantage that the solar-heat system would then be capable of providing air-conditioning in summer.

Solar Lighting - An Economically Desperate Expedient

The validity of this analysis of energy in the future turns on an

Figure 39. Solar house types

Figure 40. Feasibility of solar heating systems

economic assumption; namely, that it is important to prevent serious increases in the unit cost of energy.

In northwestern Europe, coal is already costing as much as three times what it costs in the United States. This increased cost has brought in its wake a device for lighting buildings directly by sunlight. It is known as the Arthel Heliostat. On the roof there is a tracking mirror which automatically follows the sun, concentrating its rays to a certain extent, and sending them down a shaft inside the building. At the various floor-levels individual mirrors intercept fractions of this somewhat concentrated beam of sunlight and direct them into suitable diffusion systems located along the ceiling mouldings. A department store and several newspaper offices are among those that have installed this rather cumbersome and costly device, whose only economic justification is that when the sun is shining, the owner can turn off his still more costly electric lights.

Biological Photosynthesis

Each year the earth's atmosphere intercepts sunlight with an energy content of about 5000 Q. Of this, about 3200 Q gets through to the surface of the earth in an average year, and of this, about 960Q strikes land surfaces, exclusive of the Polar Regions. About 50Q reaches the continental United States.

Chlorophyll uses some of the energy falling on it to reduce carbon dioxide and to fix the carbon in a series of sugars, fats, proteins, and other carbohydrates contained in the tissues of the plant. In the United States, the total carbon fixed in one year has been estimated to contain about 0.05 Q. That is, the efficiency of conversion was about one-tenth of 1 per cent. If all the carbon that was fixed in one year was burnt and the energy recovered, it would only amount to about one and one-half times the

present requirements of the national energy system.

If we are ever going to turn to biological photosynthesis for much of our energy requirements, then it is clear that we must learn how to make vast improvements on nature's system for converting solar energy.

Recently there has been much talk about Chlorella farms. Chlorella is a single-celled organism that forms a green scum on fresh water ponds. It is one of the algae. Chlorella absorbs energy throughout the visible spectrum. A pilot plant for the production of several pounds a day of Chlorella is now in operation by Arthur D. Little in Cambridge under the direction of Vannevar Bush. The Chlorella culture is circulated through plastic bags about 4 feet wide and 4 inches high. The solution contains the necessary nutrients and the half-inch air-space is enriched with carbon dioxide, up to 5 per cent. It is a continuous process, the Chlorella being harvested by centrifuge.

At the moment the system appears to be operating with an efficiency of something less than 3 per cent. The costs are high. The nutrients alone cost about one-half cent for each pound, dry-weight, of Chlorella. The carbon dioxide costs another one-half cent, and the depreciation on the plastic bags, which is not now known, may amount to a cent or more. If the cost of the land and its preparation, together with pumping equipment, cooling water, labor and supervision are added, it looks as though Chlorella might cost as much as 27 cents a pound.

Now a pound of Chlorella contains about 10,000 Btu, that is, about the same as a pound of coal. So Chlorella, at 27 cents a pound, would cost about \$540.00 a ton to compete with coal which, in some places in the United States at least, can be had in quantity for \$4.50 per ton. What are some of the things that might be done to reduce the unit cost of energy from

biological photosynthesis?

Nitrogen is a costly nutrient. Perhaps we could find an alga that would fix its own nitrogen, while maintaining a high growth-rate.

If the alga were burned at the site, the CO_2 could be recovered from the flue-gases and re-cycled.

If we could find an alga that would tolerate high temperature, we might be able to avoid the costs of pumped cooling water.

Chlorella is only one of some 17,500 algae about which very little is known. Krauss believes that perhaps 10,000 species justify investigation; each species is probably capable of producing up to 50 strains with widely divergent characteristics so that we should, perhaps, look at a total of several hundred thousand forms in a search for an alga which would have a high growth rate, tolerate high temperature and fix its own nitrogen.

But even if such a search were reasonably successful, it would not be plausible to think that we could ever harvest algae-fuels for unit energy costs as low as that of coal. It is just conceivable that the cost might be reduced as low as \$250.00 per ton.

So, if we are to look to biological photosynthesis for low cost energy, we cannot rest here. We must do still other things.

We have said that chlorophyll absorbs energy in the visible spectrum, but of the 960Q reaching the land surfaces, only about 45 per cent or less than 450 Q, lies in the visible spectrum. Another 400Q lies in the near infra-red. Perhaps ways could be found to harness some of the non-sulphur purple bacteria, within a composite culture or in superimposed cultures, to permit us to extract the energy in the near infra-red, thus in theory, at least, doubling the over-all efficiency of our farm. In the ideal case, the unit cost would be nearly cut in half, bringing us into the range of

\$125 a ton. Such a cost is probably quite unrealistic. Even so, it is still far too high, being about 30 times as high as coal costs. Presumably, if the energy system of the country were dependent on a source whose costs were much over 2 times the present costs, ~~there~~ would be a serious braking effect on the national economy.

There is one more thing that might be done. We might find an alga, or we might get the geneticists to design us one, which contains some high-value constituent - perhaps a pharmaceutical that would yield us cortisone; perhaps some animal protein factors that would stimulate growth in livestock and human beings. Perhaps we could find a marine form which selectively extracts ~~rare~~ elements that we need badly, from sea water. There are doubtless other useful high-value constituents not now foreseen. If these valuable constituents paid for most or even part of the harvest, we would be left with a residue that could be used as fuel and whose cost might just conceivably compete with coal. But the by-products, if any, would be available in prodigious quantities, leaving the economics of this suggestion in serious doubt.

If some day we could operate algae farms with a 10 per cent efficiency and if we could harness not only the visible spectrum but also the near-infra-red, then it would require an algae farm less than 200 miles on a side to supply the energy that was required in the United States in 1950.

In Table 8 there are recapitulated rational estimates of the quantities of energy that our Trustee may plausibly expect to win, at "low-cost", from sources of "income" energy either already in use or known to hold some economic promise during the next 100 years.

Table 8

SUMMARY OF INCOME SOURCES

<u>INCOME SOURCE</u>	<u>PLAUSIBLE CUMULATIVE INPUT TO THE WORLD ENERGY SYSTEM IN 100 YEARS</u>
Solar Heat Collectors, for:	Q
Space heating	4
Water heating	0.05
Mid-day cooking	0.02
Air Conditioning	-
Refrigeration	-
Distillation	-
Total	4.07
Fuel wood	TAKE: 1.5 5 Q
Farm wastes	1.0
Water power	0.5
Wind power	0.1
Solar power collectors	0.05
Tem. diffs. in tropical waters	0.05
Peat, sustained yield	0.035
Tides	0.001
Natural steam	0.0005
Solar lighting	negligible

Earth's heat	negligible
Waves	negligible
Atmospheric electricity	negligible
Controlled biological photosynthesis	none
Heat pumps	<u>none net</u>

TOTAL INCOME ENERGY 8.236 Q

TAKE 5 to 10 Q

Thus there are 9 sources of "income" energy which might supply 7 to 15 per cent of the cumulative hypothetical demand during the next hundred years at costs no higher than 2 times 1950 costs.

C. The Maximum Plausible Role of Nuclear Fuels

At the beginning of the Atomic Era, the emphasis was on peace. Testimony before Congress was optimistic about the economic future of nuclear fuels. We drew up a plan for international world-wide control and inspection of all fissionable processes. We assumed that Russia would go along with such controls. It was basic to the plan of control that the beneficent uses of atomic energy be vigorously developed.

In the face of continued Russian intransigence, her refusal to agree with any plan which offered minimum safeguards, and her preparation for world conquest, the United States had no alternative. Bombs came first. Atomic power had to wait.

Then, in 1948, the Commission felt strong enough in its weapons programs to begin to think about that portion of a reactor program which had military objectives but whose prosecution would add greatly to reactor technology for any application. Most important for power reactors - military or civilian - was to obtain high flux densities and high temperatures.

Figure 41. Flow diagram of the homogeneous reactor experiment

To give momentum to the development of such reactors, the Reactor Development Division was created and put under the direction of Dr. L. R. Hafstad.

Reactor design has come a long way from the designs of the 1945 era, which formed the basis for the cost estimates of such authorities as Condliffe (1946), Wagner and Hutcheson (1946), Davidson and C. A. Thomas (1946), M. C. Leverett, and Isard and Lansing (1949), and Schurr and Marschak (1951).

Although the body of reactor technology has been growing rapidly, capital costs, useful life, maintenance costs and the like still involve many unknowns. And these are the factors which will determine when and where nuclear power will become economically competitive. The outlook is promising.

There is no longer doubt about technical feasibility. Doubt centers on costs. But here the range of uncertainty is small compared with the fifty-fold difference between coal costs and Chlorella costs about which we learned in Chapter 7. The uncertainty applies to a much narrower range of costs - from a low that is a little lower than that of coal to a high twice that of coal. And even without an atomic weapons program, the plutonium produced as a by-product in a power reactor would have value as a nuclear fuel.

How Much Nuclear Fuel is There?

Ideas about the abundance of nuclear fuels have been changing.

First, the ultimate success of breeding is now accepted as plausible. So, we shall assume that we can "burn up" 100 per cent of the uranium and

Figure 42. Artist's conception of building and facilities for 1000-
kilowatt Homogeneous Reactor Experiments *located at Oak Ridge Nat'l. Lab.* The reactor and its associated
fuel-handling system are located inside the 7-foot thick concrete shield
shown in the center of the building. In the center foreground is the
control room from which the reactor is operated by remote control. The
steam turbine and generator for producing electric power are shown on the
right of the reactor shield in the cutaway section. The small analytical
laboratory, where chemical analyses of the highly radioactive fuel are
performed, is shown in the cutaway section to the left of the reactor
shield. Underground valve and pump pits are shown beside the shield in
the left foreground. The building is of steel framing covered with sheet
metal. Completely equipped, the reactor and all facilities cost approxi-
mately \$1,100,000 to build.

Figure 43. This cutaway pictorial drawing shows the 1000-kilowatt Experimental Breeder Reactor and its power plant which are located at the National Reactor Testing Station in Idaho. Two liquid metal heat transfer systems convey heat from the reactor to the steam boiler. The first, which enters the reactor, is radioactive. Power from this reactor, an early experimental installation primarily for other purposes, is uneconomic. The reactor core arrangement is shown in schematic detail in Figure 44.

Figure 44. Schematic detail of the foot-ball-sized core arrangement of the 1000-kilowatt breeding reactor shown in Figure 43.

thorium reserves, and that it will pay out, economically, to achieve a net burn-up of about a third of this.

Second, although concentrated deposits of it are rare, uranium is actually a common constituent of the earth's crust. The heat "content" of the uranium in a ton of granite is greater than the heat content in a ton of coal. It is true that common granite does not yet look like an economic source of uranium. However, there are useful sources, less concentrated than the deposit at Shinkolowbe in the Congo or at Bear Lake in Canada, but more concentrated than in granite.

In the gold deposits of South Africa, uranium occurs in the quartz. It can be extracted easily after the ore has been treated for the gold content. Another source is phosphate rock, from which uranium can be extracted in the course of producing triple super-phosphate. Yet another source is uranium-bearing shale, occurring principally in the United States, Sweden, and near Leningrad. And there are the deposits of carnotite in Colorado and elsewhere in the western United States. Thorium occurs in the monazite sands of Travancore and Natal. The principal deposits are shown on the map of Figure 45.

A detailed statement of world-wide reserves, tonnages, and costs would be classified information. But the best unclassified statement that can be made makes possible a general statement of the greatest interest.

Figure 45. Deposits of uranium and thorium. Where significant quantities have been produced the localities are indicated by stars. A small percentage of the many other occurrences are also shown in order to suggest the world-wide distribution of these elements in the earth's crust.

Surveys to date indicate a world reserve of about 25 million tons of uranium and about 1 million tons of thorium, recoverable for less than \$100 per pound of metal content. The heat generated by the fission of a pound of uranium metal is calculated to be 3.3×10^{10} Btu. So, assuming breeding, the total heat content of the economically recoverable world reserve so far mapped is

$$26 \times 10^6 \times 2 \times 10^3 \times 3.3 \times 10^{10} = 1716 \times 10^{18} \text{ Btu} = 1716 \text{ Q.}$$

If, as is believed, it would be economical to recover about a third of the total heat content, by breeding and chemical reruns, then there would appear to be a net world reserve of nuclear fuels containing about 575 Q- over 25 times the net economically recoverable reserve of coal, and over 100 times that of oil-gas.

A good part of this reserve occurs in the United States.

Whatever the total costs of nuclear power, the direct fuel cost, plus carrying charges on the fuel investment and the cost of re-processing the fuel, would amount to about one mil per kilowatt. hour in 1953.

How Much of the Total Load in the Energy System of the World Is Technically Suitable for the Application of Nuclear Fuels ?

First, let us consider the maximum plausible energy system of the United States in A. D. 2000, recapitulated in Table 9.

Table 9

The Maximum Plausible Input to the Energy System of the United States in A. D. 2000 and Its Distribution

	<u>Per Cent</u>	<u>Btu x 10¹²</u>
Work	58	87,000
Comfort Heat	30	45,000
Process Heat	<u>12</u>	<u>18,000</u>
Total	100	150 x 10 ¹⁵ Btu

Work

The generation of electricity is the principal item of work energy that appears to be suitable for nuclear fuels. In 1947 the generation of electricity, at an average efficiency of about 22 per cent, claimed some 4300×10^{12} Btu in a total input of $33,700 \times 10^{12}$ Btu - about 13 per cent. Of this total input about 30 per cent represented generation either by hydro or by quite small units, leaving about 3000×10^{12} Btu - 16 per cent of the work load and 9 per cent of the total input - as suitable for the application of nuclear fuels.

During the past 40 years, the output of electricity has doubled every decade - a sixteen-fold increase since 1910. Let us assume an eight-fold increase over the next 50 years. Because of the assumed growth in efficiency, there is implied a six-fold increase in the input, which would become some $25,000 \times 10^{12}$ Btu in A. D. 2000.

If 70 per cent of the total input to the generation of electricity should be provided by nuclear fuels, then the annual requirement for them would be some $17,500 \times 10^{12}$ Btu in A. D. 2000 - 20 per cent of the work load and 12 per cent of the total.

Stated another way, we find that if, in 1947, nuclear-fueled steam generating plants had borne about 70 per cent of the electric generating load, then the reactor capacity would have furnished some 100,000,000 kilowatts of heat for the boilers. To produce the hypothetical input of $17,500 \times 10^{12}$ Btu in A. D. 2000 would require a reactor capacity of half a billion kilowatts, more or less, measured in terms of the equivalent heat output. By 1975, the figures would be about 250,000,000 kilowatts.

The corresponding world figures for 1975 and A. D. 2000 would be 750 and 1800 million kilowatts of reactor capacity, measured by the heat generated.

Comfort Heat

A few American cities combine severe heating seasons with dense populations, forming a technically plausible market for nuclear district heating. Boston, Buffalo, Chicago, Jersey City, Milwaukee, Newark, New York, all have densities higher than 13,000 per square mile and quite rigorous heating seasons.

Solar collectors could hardly meet this demand. Nor does it appear to be the ideal application for the heat pump. So perhaps it is plausible to estimate that this one-sixth of the total urban comfort-heat load, or about one-tenth of the total national comfort heating load, could be carried by nuclear fuels.

The maximum plausible requirement in A. D. 2000 would thus amount to about $4,500 \times 10^{12}$ Btu, supplied by an installed capacity of 100,000,000 kilowatts, more or less, depending on efficiencies.

Process Heat

Perhaps also one-tenth of the process heat requirements could be met by nuclear fuels - about $1,800 \times 10^{12}$ Btu - supplied by an installed capacity of 50,000,000 kilowatts more or less, again depending on efficiencies.

The Maximum Technically Plausible Market for Nuclear Fuels in the United States by A. D. 2000

The preceding speculations have been made merely to establish an order of magnitude. The reader needs no warning that the numbers put forward can have no great claim to accuracy. When added together the following results are obtained:

Table 10

Maximum Plausible Role of Nuclear Fuels in the United States in A. D. 2000

	<u>Input</u> <u>Btu x 10¹²</u>	<u>Installed</u> <u>Capacity Btu x 10¹²</u>
Work	17,500	600
Comfort Heat	4,500	100
Process Heat	<u>1,800</u>	<u>50</u>
Total	23,800 x 10 ¹² Btu	750 x 10 ⁶ kw

That is to say: nuclear fuels might be suitable for carrying about 15 per cent of the total maximum plausible energy system in the United States in A. D. 2000. (The "Total" of Table 10 divided by the "Total" of Table 9). Perhaps this feasibility ratio could be expected to increase with time, as urbanization advances.

To reach an installed reactor capacity of some 750,000,000 kilowatts in A. D. 2000, with the beginning in 1970, would require an average construction rate of about 25,000,000 kilowatts a year.

The cumulative energy input would amount to 0.25 Q by A. D. 2000.

The world requirements would demand some 0.75 Q by A. D. 2000, and a construction rate of some 75,000,000 kilowatts a year.

By A. D. 2050, the maximum plausible input to the world energy system from nuclear fuels would be 18 per cent of 72 Q, or 13 Q; and the plant capacity then would amount to some 130 billion kilowatts.

These are very large figures indeed. Yet they ignore the big problem. We have learned by the example of Chlorella the difference between the ease of living off our capital of coal-oil-gas and the struggle it would be to live off our income of solar energy. If we attempt to harness sunlight by

chlorophyll, energy costs may soar 50 times or more as high as they are today. Other means of harnessing solar "income" energy on a vast scale appear very costly so far.

If, as we suppose, an abundance of low-cost energy is one of the essentials for a lively economy, then an energy system, 85 per cent of which is unsuited for nuclear fuels, may be the wrong kind of energy system to have, beginning in A. D. 2000 or earlier.

So long as a large fraction of the total energy system consists of small fuel-burning units like automobiles, buses, trucks, airplanes, trains ships, and houses, we shall be unable to escape the prohibitive costs of "income" fuels from solar energy. If these costs should prove to be 50 times as great as present energy costs, the effort to harness solar energy would lower the standards of living and might create intolerable stresses through the Free World.

Perhaps, therefore, we shall see strong economic and social pressures converging on the problem of modifying the energy system so that it could rely more heavily on nuclear fuels. One solution would be a great expansion in electrification.

It would be costly to electrify most of the house heating. It would be more costly to electrify most of the through highways used by buses, trucks, and cars and to convert the automotive fleet to operate from overhead power lines on main routes and to use batteries on feeder roads and side streets. And it would be costly to equip most ships and aircraft with nuclear reactors.

But the increased costs of these developments would hardly be of the same order of magnitude as the fifty-fold increase that would result if we should turn to sunlight for power on a vast scale.

To point up the problem and provoke discussion, therefore, let us

consider an energy system in A. D. 2050 that draws from sources distributed somewhat as in Table ~~8~~¹¹. Nine sources of "income" energy bear 15 per cent, of the load, residual fossil fuels 25 per cent, and nuclear fuels the remainder, or 60 per cent.

On such a basis the total cumulative requirements for nuclear fuels by A. D. 2050, from a beginning in 1970, might plausibly amount to some 35 Q, out of the plausible grand total cumulative requirements of 72 Q (Figure ~~31~~³²). Similarly, the cumulative requirement for nuclear fuels in the United States by A. D. 2000 might amount to 2 or 3 Q in a total of 4.3 Q.

Table 11.

The Hypothetical Energy System of A. D. 2050

<u>Source of Energy</u>	<u>Per Cent Contribution</u>
"Income" energy	
Fuel wood and farm wastes	
Solar collectors for comfort heating, in middle latitudes	
Water power	
Solar cookers in arid zones	
Solar collectors for power in arid zones	
Wind power, in certain regions	
Temperature differences in certain tropical waters	
Heat pump (no net contribution)	
Total "income" energy	15
"Capital" energy	
Residual fossil fuels	25
Nuclear Fuels	<u>60</u>
Total "capital" energy	<u>85</u>
Total System	100

Summary and Conclusion

Population and Per Capita Demands for Energy. Many of the illiterate subsistence-farming populations of the World are in demographic transition toward literate industrial-urban-farm patterns of life. Conceivably they could make the transition without a great increase in numbers.- but not plausibly. Everything we know suggests that World population will double and may treble if the balance of forces, now favoring transition and gathering momentum, should persist for a century or so. And the reverse is the Malthusian truth. Everything we know suggests that World population cannot treble unless the transition becomes general. Illiterate subsistence-farmers cannot feed many non-farmers.

The "maximum plausible" World population of 6 to 8 billions in A. D. 2050 is not the largest possible one on that date. A hypothetical Trustee of World energy who plans for at least the smaller number - 6 billions, or 2.5 times the 1950 population of 2.4 billions - will hardly be criticized for imprudence. (Figure 46).

Such a large, industrial and urban World population implies a large per capita demand for low-cost energy - a World demand whose growth, measured at the point of end use, is already averaging about 3 per cent a year, while reaching some 5 per cent in the U. S. S. R. and other underdeveloped countries. (Figure 47).

The population of the United States is growing nearly twice as fast as World population. Even if its growth-rate should decline to zero in a hundred years, our population will be nearly 375 million by A. D. 2050. And per capita demands for energy, already large, are growing at 3 or 4 per cent a year, measured at the point of end use.

Figure 46. The weighted average efficiency of use of energy in 8 countries and the World, with projections of the minimum plausible trend in the efficiency of the U. S. energy system and of the World energy system

Figure 4d. Total annual inputs to the energy systems of 8 countries and of the World from the major sources of energy for various periods ending in about 1950, with hypothetical projections to A. D. 2050 based on various rates of growth in the per capita demand for the output of energy

Living High off the Cream of Coal-Oil-Gas. The United States and much of the Free World have been living high off accumulated capital energy in the cream of the coal, oil and gas reserves. Rates of extraction of these non-renewable fossil fuels have been unbelievable and efficiencies of use have trebled. Until quite recently the average efficiency of use has increased faster than the average cost of extracting the raw fuel. We cannot again treble the efficiency of use. Yet the costs of extraction continue to rise, while the average heat content in a ton of coal has begun to decline, at least in the United States. And the heavy conversion losses, when solid fuels are converted to the preferred fluid fuels and when both fuels are increasingly consumed in the generation of the more convenient but thermally less efficient electricity, are rising.

Low-Cost Reserves are Growing Scarce. By "low-cost" is meant a cost, measured in 1950 dollars, that is no higher than 2 times 1950 costs. Reserves of such "low-cost" capital energy in the fossil fuels are small by comparison with the maximum plausible demands.

If, as is supposed, "low-cost" energy is essential to the liveliness of an economy, then new sources of "low-cost" energy must begin to carry some of the load by A. D. 1975 or sooner, and 75 per cent of it by A.D. 2000, if we are not to run the risk of seeing economic systems throughout the non-Communist world falter in the face of steeply rising costs of energy.

"Low-Cost" Income Energy is Limited. Sources of income energy that are economical could make only minor contributions to the great hypothetical energy systems of the future. Fuel wood, farm wastes, water power, solar heat collectors for comfort heating in middle latitudes, solar cookers and power collectors in arid zones, wind power in certain regions, temperature differences in certain tropical waters, tidal power at a dozen special sites, and the heat pump, are sources of continuously available current

income energy. But, in aggregate, they could hardly carry over 15 per cent of the total load at "low-cost".

How can the balance of some 60 per cent be carried at "low cost"?

Solar Income Energy as a General Solution Would Be Prohibitively Expensive. The direct collection of solar energy on a vast scale by myriads of tracking mirrors, thermo-couples or other devices, its overnight storage, its conversion to transportable electricity, and its delivery at "low cost", from Arizona to Pittsburgh or from the Sahara to the Midlands or from the Gobi to Manchuria, appears remote. And moving industry to the deserts would be equivalent to a heavy capital charge against this source of income energy. Nor can these systems as yet economically yield those fluid fuels upon which about half of today's energy system directly rests.

Chlorophyll today is without promise as a means of harnessing solar income energy at "low cost". So far as can be seen, the energy from Chlorella-fuel, although not restricted to arid zones, would be 50 or 100 times as costly as from coal.

Other means of harnessing solar income energy are more attractive, in theory, than mirrors, thermo-couples, or Chlorophyll. But today, at least, not enough is known about the direct conversion of sunlight to electricity in photo-chemical reactions or its storage in crystal lattices, as examples, to suggest that these systems hold promise as sources of solar income energy able to supply the bulk of the World's needs at "low cost".

Nuclear Fuels are Abundant but Unsuitable Today for General Application. Nuclear fuels are a source of abundant capital energy. They hold promise of competing with present coal costs, or nearly so - principally in the generation of electricity. But they are not suitable for carrying

much more than 10 or 20 per cent of a total energy system, whatever its size, so long as its pattern is like ours of today.

In 1950, 15 per cent of the United States energy system would have consumed the heat from a block of nuclear furnaces (reactors) producing some 170 million kilowatts of heat, more or less, depending on efficiencies and use factors. Fifty years later the same fraction of domestic requirement might plausibly amount to 750 million kilowatts of heat. And the equivalent world requirement might be 3 times as much, or some 2,250 million kilowatts of nuclear furnace capacity (not generating capacity).

More Effort is Required to Live off Income than off Capital. Everything we know today tells us that far more effort would be required to live off solar income energy than has been required to live off the capital energy in the cream of the coal, oil and gas reserves. If the extra effort required was very great, it would doubtless have a very great and depressing effect on living standards. The demographic transition would be denied to many. Lively economies would be checked in their growth.

Before we reconciled ourselves to so bleak an outcome, we would doubtless study any alternative that appeared less undesirable.

Could We Rely More Heavily on Nuclear Capital Energy? Perhaps it would be less costly, for example, to modify the pattern of the energy system so that nuclear fuels might bear half to three-fourths of the load.

Blanket electrification would be one way. Could we electrify most of the railroads and much of industry? Could we run overhead power lines along main toll-roads and redesign trucks, buses and cars for electric operation, relying on batteries for off-highway travel? Could we look forward to an energy system, 50 or 100 years hence, which would draw its

energy from sources somewhat as suggested in Table ¹²~~11~~?

Table 12

A Hypothetical Energy System of A. D. 2050

<u>Sources of Energy</u>	<u>Per cent of Total Energy Input to the System o/o</u>	
Income Energy		
Fuel wood		
Farm wastes		
Water power		
Solar heat collectors for comfort heating in middle latitudes		
Solar cookers and solar power collectors, in arid zones		
Wind power in certain regions		
Temperature differences in certain tropical waters		
Tidal power at a dozen sites		
The heat pump (no net contribution)		
Total income energy		15
Capital Energy		
Residual fossil fuels	25	
Nuclear fuels	<u>60</u>	
Total capital energy	85	<u>85</u>
Total System		100

Such a major transition to nuclear fuels might not be so costly as major reliance on solar income energy, yet clearly it would be very costly. Perhaps the transition will never be made except in certain most favored

countries. Perhaps it would come more easily in those countries not yet heavily committed to present patterns of energy consumption - countries like the U. S. S. R., India, Manchuria, Brazil and China.

And in countries like the United States the costs of such a program would doubtless justify us in first digging deeper for coal, thus postponing for a time the fullest transition to nuclear fuels.

"Low-cost" reserves of nuclear fuels are abundant. If the cost of energy can be kept from rising far, the demand for energy in the World at large and the United States in particular may become enormous. Energy in the reserves of "low-cost" nuclear fuels is some 20 times as abundant as in the reserves of "low-cost" coal-oil-gas - 575 Q compared with 27 Q. Even if great expansion of electrification should take place, nuclear fuels could support the bulk of the maximum plausible energy systems of the United States and the Free World for several centuries. (Figure 48).

Conclusion

The Time for Action Has Come. Our hypothetical Trustee recognizes that the economic and social pressures directed at finding new sources of abundant "low-cost" energy are about to become compelling. As a prudent Trustee, he would say the time for action has come.

He would urge that the nation's talents, public and private, be released for the development of nuclear furnaces (reactors) capable of furnishing heat for the generation of electricity, for district central heating and for industrial process heating.

He would urge that we continue to explore nuclear reactions other than the fission of uranium and thorium. There is hope of domesticating the fusion reaction that makes the hydrogen bomb go.

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Economical fusion of the hydrogen contained in a cubic mile of sea water would be a source of capital energy equal to all conceivable needs for many hundreds of years.

He would be concerned about the vast quantities of metals, some of them already in short supply, that would be required by very large nuclear power programs. He would suggest that we search for these metals by methods yet to be developed, and in novel places, including the sea.

Finally, as our ultimate anchor to windward, he would urge the exploration of all ways to obtain income energy from sunlight in more useful forms and at lower costs than now appear possible.

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The figures in this report are almost entirely taken from cuts prepared by the D. Van Nostrand Company.

Figure 48