Primary Energy Substitution Models: On the Interaction between Energy and Society

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ABSTRACT

This paper describes an attempt to develop a "synthetic" model of primary energy substitution, using certain rules which proved fruitful in describing the substitution of other commodities. This model will be used for forecasting, and for checking the validity of certain objectives set for R&D in the field of energy.

Trends in Energy Demand

The first point in forecasting energy demand is obviously to look at historical trends, over a century at least, and try to extract the signal out of the white noise and various medium-scale perturbations that occur along the way. Although the long-term extrapolation of these trends may require a more subtle analysis of social and economic trends, it is good to keep them in mind.

The historical trends reported in Fig. 1 and Fig. 2 have something special—they include wood and farm waste which is necessary to get a proper basis for extrapolation because part of the growth of commercial energy sources is due to substitution of wood and farm waste.

As shown in figure 1 apart from the big dip, coinciding with the great recession, "healed" then by World War II and some "overheating" coinciding with World War I and preceding the 1930's recession, the 2% secular trend is followed quite tightly for the world, even taking into account the compression due to the log display.

In the case of the U.S. we also have a well defined trend with the bumps in somehow different positions. The higher value of 3% does not appear particularly significant as the U.S. population has grown roughly 1% faster than the rest of the world in the period considered (1860–1960).

The second point is to look inside the envelope of total energy demand for trends in primary fuels demand. I did this exercise at IIASA, using a methodology completely different from the "modelling" which is so popular in many places of the world, and

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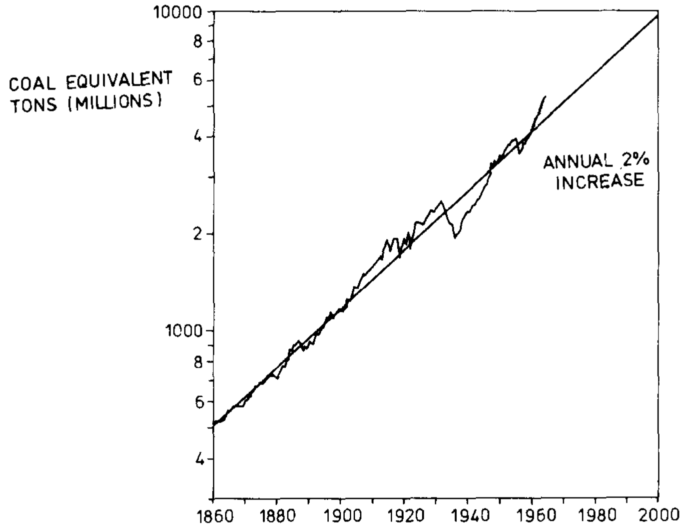

Fig. 1. World energy consumption, including wood and farm waste. The trend line has a 2% slope.

whose contradictory results, when used to forecast over long ranges, cast many doubts on its reliability.

I started from the somehow iconoclastic hypothesis that the different primary energy sources are commodities competing for a market, like different brands of soap or different processes to make steel, so that the rules of the game may after all be the same. These rules are best described by Fischer and Pry [1, 2], and can be resumed in saying

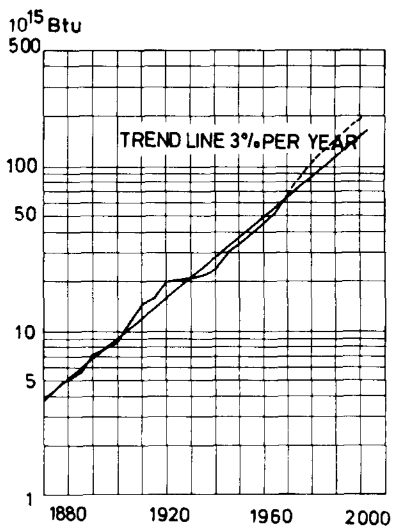

Fig. 2. U.S. energy consumption including wood and farm waste. The trend line has a 3% slope. (Adapted from R.E. Lapp, *The Logarithmic Century*.)

that the fractional rate at which a new commodity penetrates a market is proportional to the fraction of the market not yet covered:

$$\frac{1}{F}\frac{dF}{dt} = \alpha(1 - F), \tag{1}$$

or:

$$\ln(F/1 - F) = \alpha t + c, \tag{2}$$

where: F = fraction of market penetrated, α and c are constants, characteristic of the particular commodity and market.

In Figs. 3 and 4 some cases of market penetration are reported, showing the extraordinary precision by which those curves fit the statistical data (which often are not very precise). All of them refer to competition between two products. In the case of energy we have three or four energy sources competing most of the time and it is

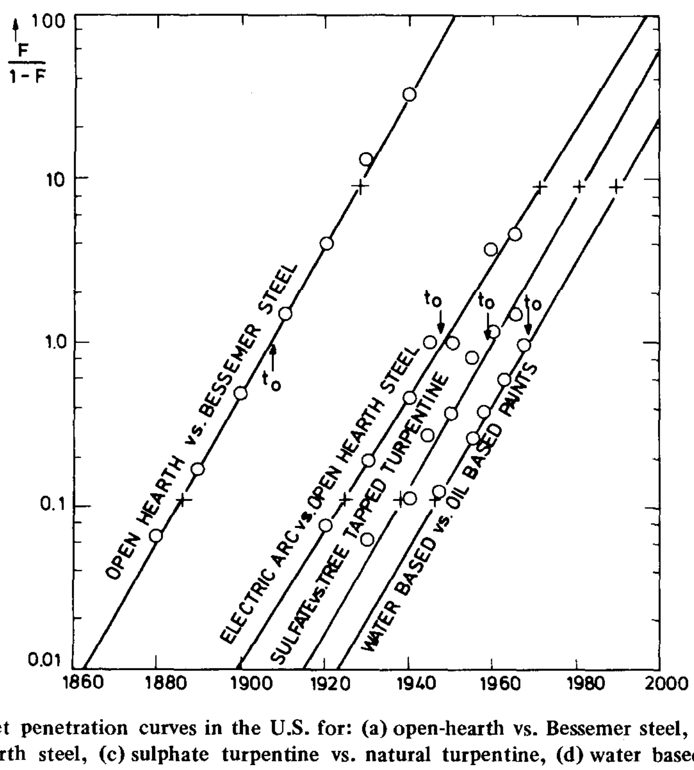

Fig. 3. Market penetration curves in the U.S. for: (a) open-hearth vs. Bessemer steel, (b) electric arc vs. open hearth steel, (c) sulphate turpentine vs. natural turpentine, (d) water based vs. oil based paints. From [1].

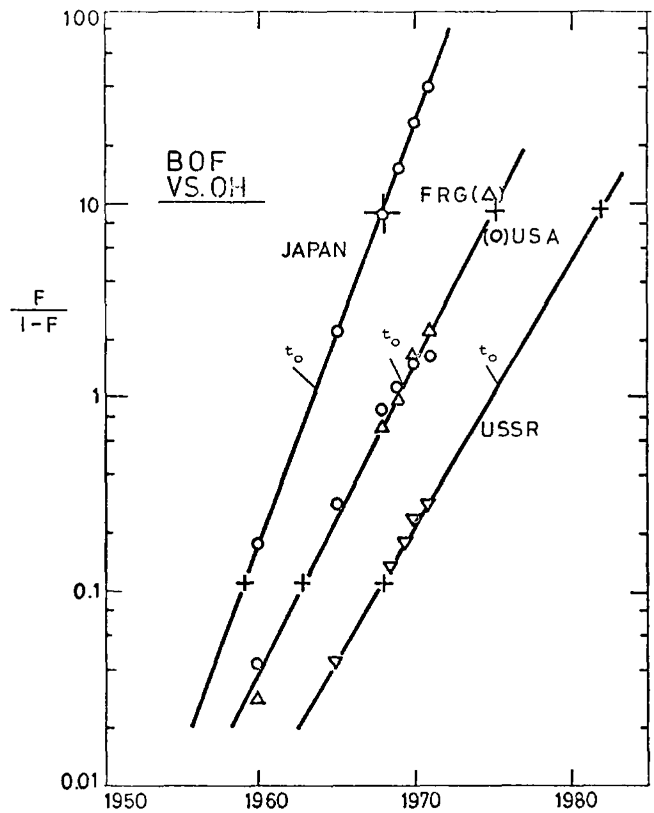

Fig. 4. Market penetration curves for oxygen steel (BOF) vs. open hearth and Bessemer steel in four countries (Japan, U.S., West Germany, Russia). The same law appears to hold also for a socialist economy. Japan appears to be the first to use intensively this technique, originally developed in Austria during World War II. From [2].

mathematically impossible that $\Sigma F_n = 1$, so I had to extend the treatment slightly with the extra stipulation that one of the fractions is defined as the difference to one of the sum of the others. This fraction follows approximately an equation of type (2) most of the time, but not always. It finally shows saturation and change in coefficients. The fraction dealt with in this way corresponds to the oldest of the growing ones. The rule can be expressed in the form: First in—first out. Figure 5 shows the plotting of statistical data for the U.S. in the form $\ln(F/1-F)$ vs. time.

More than a century of data can be fitted in an almost perfect way using only two constants, which come out to be two dates, for each of the primary energy sources (wood, coal, oil, gas). The whole destiny of an energy source seems to be completely predetermined in the first childhood.

As we can see by analyzing the curves and the statistical data in greater detail, these trends—if we can call them that way—go unscathed through wars, wild oscillations in energy prices and depressions. Final total availability of the primary reserves also seems to have no effect on the rate of substitution. The only real departures from the curves are due to strikes in the coal industry, but the previous trend is rapidly resumed and the effects of the strike somehow "healed". On the point of availability it seems that the

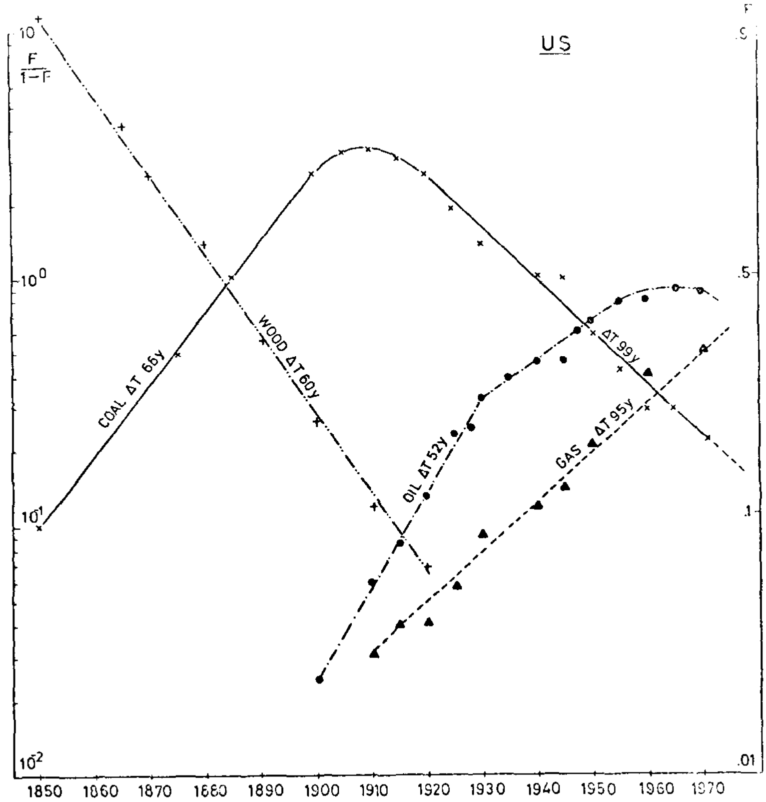

Fig. 5. Fitting of the statistical data on primary energy consumption in the U.S. Straight lines are represented by equations of type (2). Rates of penetration are indicated by the time to go from 1% to 50% of the market (ΔT years). The knee in the oil curve and the saturation regions can be calculated by the rule "first in–first out".

market regularly moved away from a certain primary energy source, long before it was exhausted, at least at world level. The extrapolation of these trends indicates that the same thing is likely to happen in the future, e.g., that oil reserves will never be exhausted because of the timely introduction of other energy sources.

When I started showing around those curves, people said they were fascinated, then that the fit was too good to be true, then that one should find the explanation before accepting and using them. Nothing to say about the first two points but the third one is in principle unacceptable: laws work or they don't work, and the only reason to accept a rule as a law is because all sorts of tests applied to it show that it works.

What most model makers do, starting from elementary relations and by functional and progressive aggregations going to macroscopic variables (e.g., demand) is very similar to what is done in statistical mechanics in order to "induce", e.g., thermodynamic laws from mechanistic principles. But thermodynamics is completely autonomous from the interpretation, in the sense that its "truth" is internal to the set of macroscopic measurements from which it has been derived.

Now, putting philosophy aside, I played the game of forecasting (i.e., of backcasting) within the historical period. That is, I took the data for the U.S. from 1930 to 1940 and

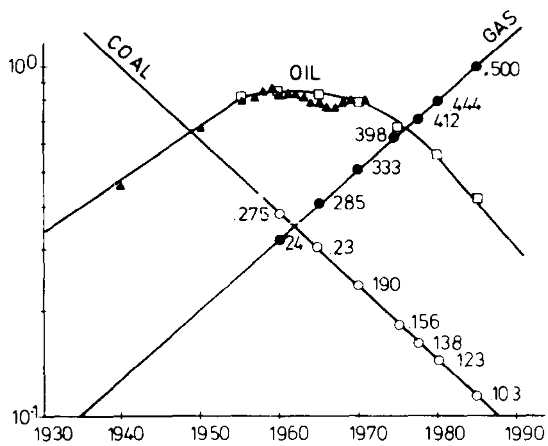

Fig. 6. Forecasting U.S. oil comsumption as a fraction of total energy consumption from 1930–1940 trends. □ calculated values, △ statistical data. Other symbols and figures represent intermediate steps in the calculation, the graph having been drawn from my notebook.

tried to forecast oil coverage of the U.S. market up to 1970. As Fig. 6 shows, the predicted values even for the saturation period fit the statistical data better than 1%, which is the minimum error that can be expected from this kind of statistics. This means that the contribution of oil to the U.S. energy budget, e.g., in 1965, was completely predetermined 30 years before, with the only assumption that a new primary source of energy (e.g., nuclear) was not going to play a major role in the meantime. As the history of substitutions shows, however, the time a new source takes to make some inroads in the

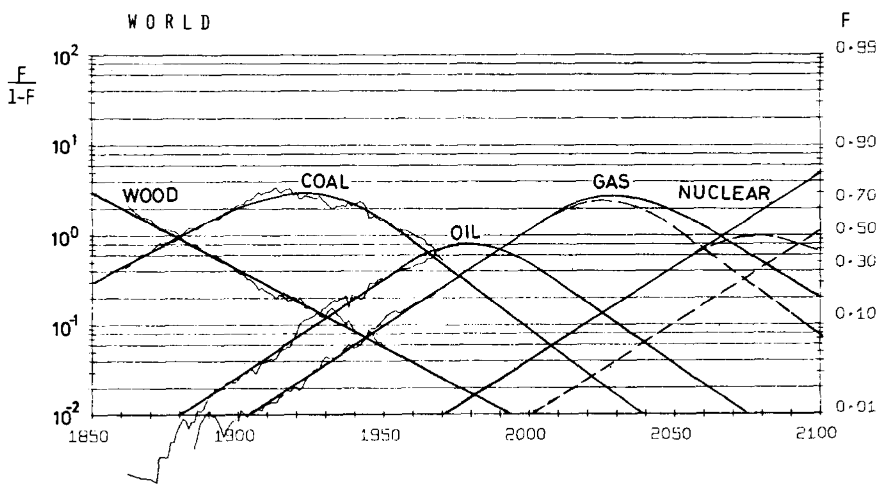

Fig. 7(a). Historical evolution of the primary energy mix for the *world*. Wriggling lines are statistical data, smooth lines computed. Some values for the actual market fractions are given on the right side of the figure. The effect of introducing a new source of primary energy (1% in year 2000), solar, fusion or else, is indicated by the dashed lines. This effect appears minimal on conventional sources, and dramatic only on nuclear, but in the second half of the next century.

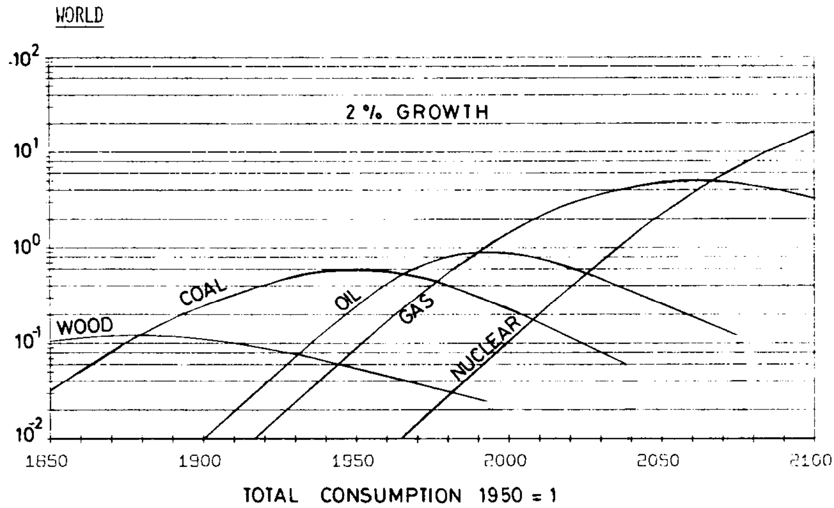

Fig. 7(b). World primary energy consumption in absolute terms (total for 1950 taken as unit). Secular growth rate assumed to remain 2%. Nuclear penetration assumed to be 4% in year 2000. Total oil consumption may be compatible with reserves but this is highly improbable for gas. A faster nuclear penetration and the vigorous introduction of a new source of energy during the next 20 years (fusion, solar?) may correct this incongruency and could be considered a demand from the market and not just an optional alternative.

market is very long indeed, about a 100 years to become dominant starting from scratch, so that this assumption also appears really unimportant for predictions up to 50 years ahead.

As our game worked so well in the last 100 years, why not make a try for the next 100 years, just to see what happens? The results are shown in Figs. 7–11, and some quite important consequences can be drawn from them.

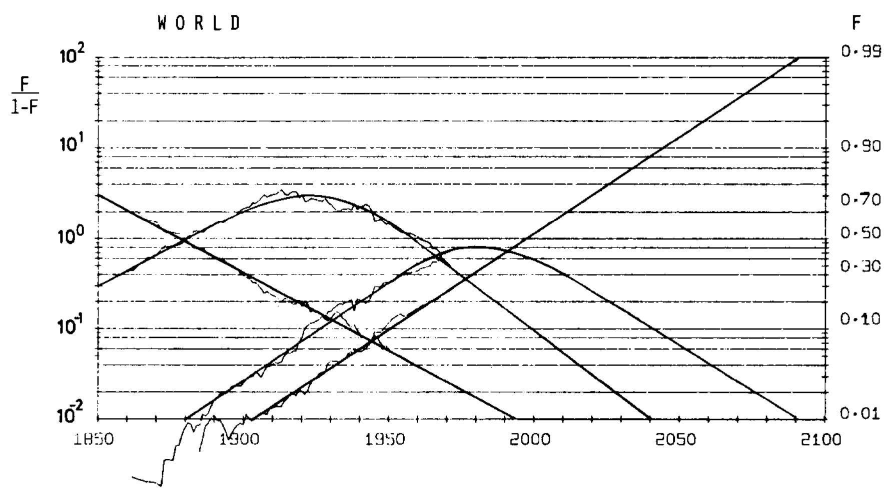

Fig. 8. The assumption that no nuclear energy, or new sources will be introduced leads to the absurd situation where all energy input will rely on natural gas.

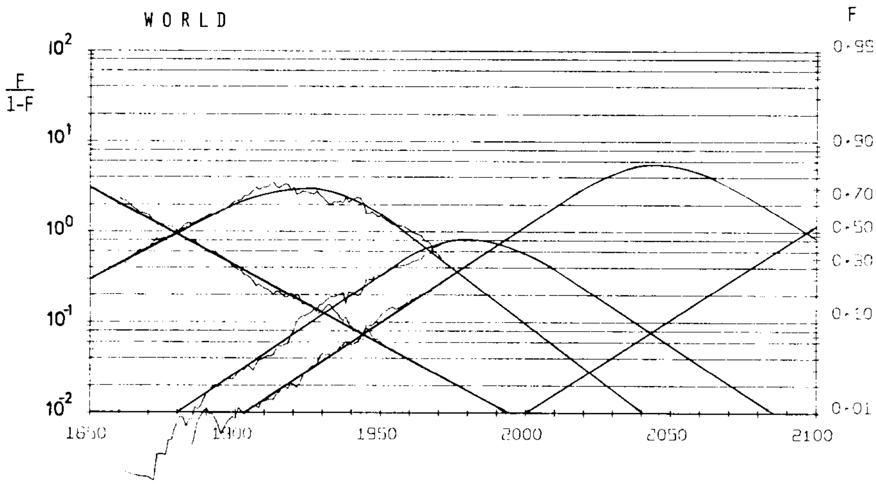

Fig. 9. Even the assumption of a moratorium for nuclear energy up to the year 2000 leads to a situation of incompatibility with gas resources. The introduction of nuclear energy appears a perfectly timed device to make ends meet.

The first consequence is that substitution has a certain internal dynamics largely independent from external factors like final reserves of a certain primary energy source. Thus the coal share of the market had started decreasing in the U.S. around World War I in spite of the fact that coal reserves were in a sense infinite.

The second is that substitution proceeds at a very slow pace, let us say of the order of 100 years to go from 1% to 50%. The "acceleration of the times" which we all perceive does not show up in the statistics. Perhaps the increasing number of changes is giving us that sense of acceleration, even if the rate of each individual change stays constant and low.

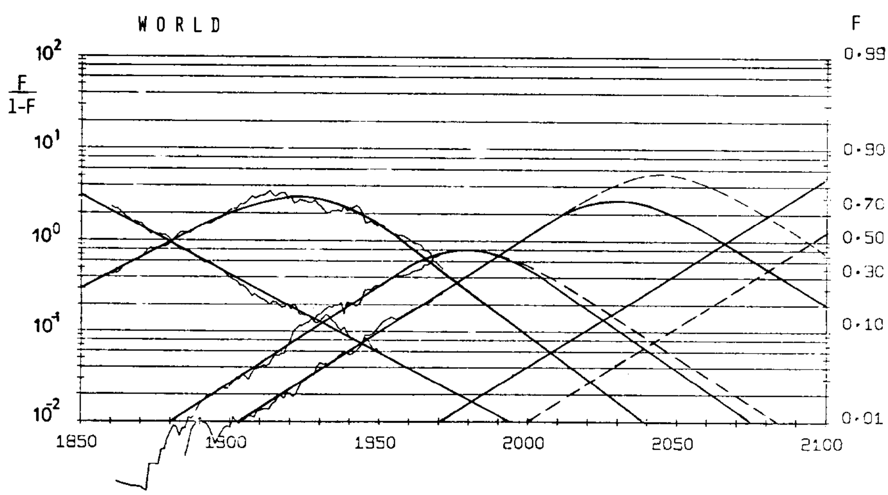

Fig. 10. The effects of the moratorium shown by respect to the base case. Penetration of nuclear energy is taken very prudently to be about 4% in year 2000.

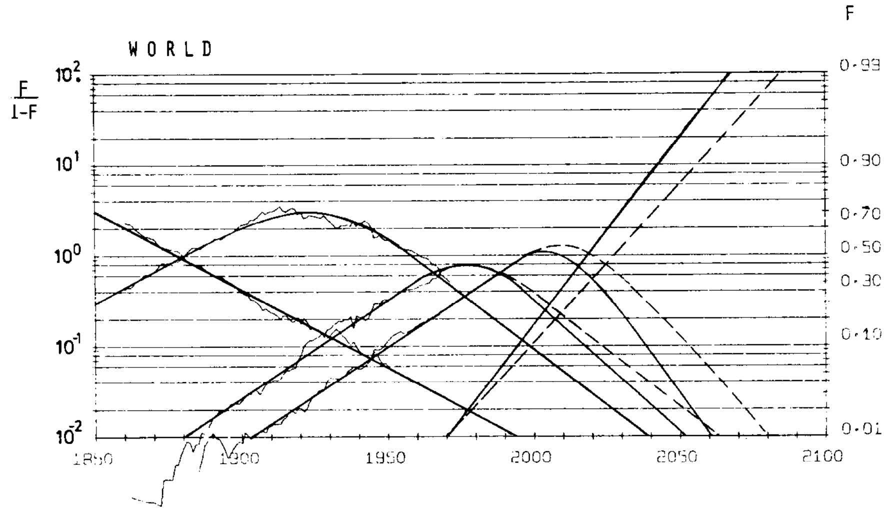

Fig. 11. Effect of an accelerated nuclear program (solid lines). Again only gas consumption appears to be heavily affected.

This fact rules out the possibility of having fusion or solar energy covering a sizable fraction of the energy market before the year 2050 and leaves us with the narrow choice: go nuclear or bust. A resurgence of coal appears improbable too, and I found very nasty reactions on that point from everybody except from coal people who appeared in a sense relieved from a mission well above their forces.

The problem, however, of how to consider a SNG plant, a coal consumer or a primary energy producer, as in fact it is seen from the market, is still an open question. This leaves some ambiguity in the interpretation of the curves in the case of important intertransformation of fuels. These curves relate to fractions. To obtain absolute values, one has to multiply them by the total level of energy consumption. Figure 7(b) gives the result for the world, using a 2% secular rate of growth. The amount consumed in 1950 is taken as a unity.

Phasing out of a source does not necessarily mean reduced production in absolute terms when the total market is expanding.

The following step is to integrate this consumption over the entire cycle of a certain primary fuel and compare it with the resources. I did this exercise and discovered that the world will not be short of oil, whether nuclear energy will keep the present rate of penetration and perhaps even if not, but that there may be problems with natural gas. As everybody has his or her own figures for the reserves, I prefer not to raise a row on this point and leave it to you to make comparisons and draw conclusions. After all, the scope of this presentation is essentially methodological.

PRODUCTIVITY VS. ENERGY

People in the world rightfully try to improve their lot, and the numerical indicator for this is GNP. So the linkage between GNP and energy consumption, and the possibility of making this linkage looser than it appears now, are of the utmost importance both in order to better understand and plan the working of our society and perhaps to better guess on the evolutionary trends.

Although I will not be able to draw final conclusions, I hope the following figures will

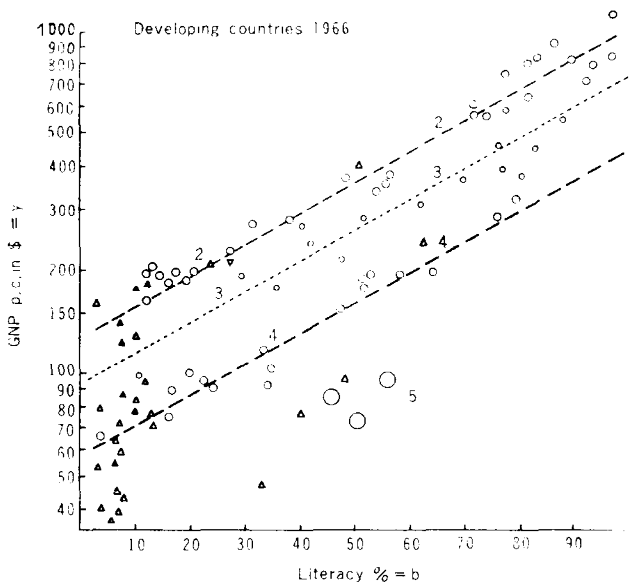

Fig. 12. Analysis of GNP vs. literacy, sediments the countries of the world into four layers. A fifth one is not included because the indicator is saturated. The proper indicator in this case is percentage of engineers in the population.

show that there is much purpose in the research and the linkage is not as rigid and indissoluble as much of the pertinent literature tends to indicate.

Apart from energy, the other inputs to a productivity function are raw materials, know-how, capital and societal organization, and one may expect a certain degree of substitutability between them. The most convincing analysis in that sense has been made by H. Millendorfer and C. Gaspari [3] amd I report here some of the results.

One of the most obvious *indicators* of the level of know-how is literacy and in fact the correlations between GNP and literacy work well, as shown in Fig. 12.

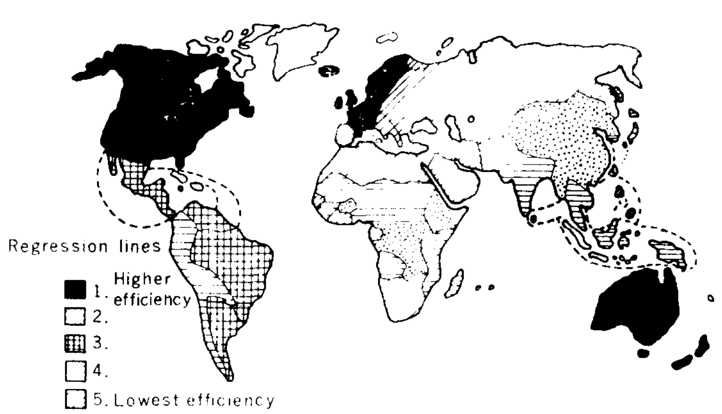

Fig. 13. World map of the regions with equal "societal organization" coefficients. The ratio of the coefficients of levels 2 and 3, or levels 3 and 4, is above 1.4. This means level 3 needs 40% more input than level 2 for the same GNP.

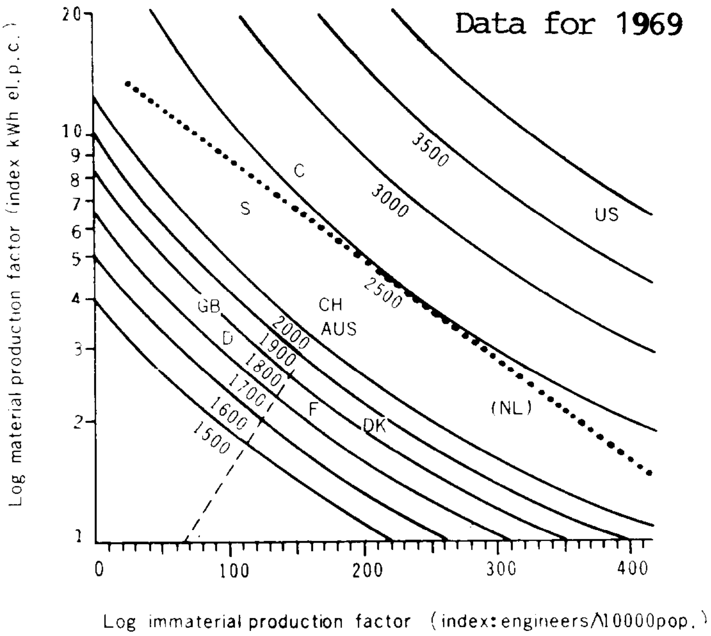

Fig. 14. Iso-GNP as a function of the two indicators for material and immaterial inputs. Dashed line indicates their balance, i.e., $m^{1/4} = e^b$. Dotted line has been drawn for $F_s = 1$ and shows the effect of incomplete substitutability of the production factors. It is very interesting to note that the U.S. and Sweden have roughly the same material index, and the much higher GNP per capita of the U.S. appears to be due essentially to a higher immaterial production factor.

The very interesting point is, however, that the nations of the world, bunched into a certain number of *parallel lines*, essentially five in all, indicated another factor at work which we may call "efficiency parameter" or "societal efficiency". The different groups are geographically identified in the following Fig. 13. Societal efficiency seems to correlate strongly with religion.

Inside each of the groups, the productivity function becomes:

$$y = C_z m^{1/4} e^b F_s + 0.8\, q, \tag{3}$$

where y the GNP per capita in U.S. dollars, C_z the zonal constant, or societal efficiency, m the *indicator* for the material input (per capita electricity consumption), b the *indicator* for the immaterial input (literacy, or engineers/10,000 population, when this indicator is saturated), q mineral resources, expressed in per capital value of production, F_s is a "stress function" indicating the noncomplete substitutability of the material and immaterial inputs. $F_s = 1$ for $m^{1/4} = e^b$ and bends somehow the iso-GNP as it appears in Fig. 14. It is fitted once for all through one parameter only, ρ.

$$F_s = \left[\tfrac{1}{2}\left(\frac{m^{1/4}}{e^b}\right)^{-\rho} + \tfrac{1}{2}\left(\frac{e^{b}}{m^{1/4}}\right)^{-\rho}\right]^{-1/\rho},$$

The results of the calculations are given in the following table:

TABLE 1

	Calc.	Obs.		Calc.	Obs.
Canada	2540	2380	Great Britain	1830	1700
Australia	1970	1970	Switzerland	2150	2310
Belgium	1770	1740	U.S.A.	3870	3670
Denmark	1850	1950	Sweden	2230	2500
France	1780	1950	Holland	(2250)	1520
W.Germany	1760	1750			

[a]For 1969–in U.S. dollars per capita.

The only real departure is for Holland. One interpretation being that it really belongs to the "Catholic" group, i.e., to the second one, with a lower societal efficiency.

The results are graphically displayed in Fig. 14 where it appears very clearly how different nations have organized themselves, and how high GNP with low material input, e.g., energy can be obtained via a high level of engineers, i.e., of know-how.

It is unfortunate for Japan to have such a low level of societal efficiency, revealing perhaps the difficulty of adapting its society to an economic system developed by a protestant society.

One might, in abstract, speculate on the consequences of trying to adapt western technology to the Japanese society, the reverse of the option taken a century ago.

Conclusion

A new approach in the analysis of the internal dynamics of primary energy substitution and of energy use is attempted. The results are very encouraging and promise a deeper insight into the subtle links between energy use and society operation.

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