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Energy Systems—The Broader Context*

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ABSTRACT

Energy and energy systems are fashionable subjects, and this has generated a lot of papers, apparently beyond the carrying capacity of the subjacent methodology.

In this written version of a presentation at IIASA Third Energy Status Report, various examples serve to show the highly unsatisfactory situation, pointing especially to the internal contradiction of results. Some hints are given about the potential of an analysis based on information theory and the negentropy concept, and about the significance of a search for precise methods of forecasting.

On the occasion of the Third Energy Status Report, 24–26 January 1978, I was asked to present some comments on the methodology of energy systems analysis and synthesis, taking as a guideline what information theory and the negentropy concept can say about systems in general.

The scope of this attempt is to provide a more abstract gauge that may serve, if only heuristically, to evolve efficiently the methodology in question and to provide transfer mechanisms for results obtained in conceptually similar structures in other branches of science, such as biology.

My presentation is the last, and it should constitute a sort of counterpoint to the others before the final discussion. I have been asked, in fact, to sit on a blimp and watch the struggle from above to see if somebody is winning and why.

From this vantage point, I would say that the statement ''muddling through to year 2000,'' which was used during the general introduction, appears to me somewhat ambiguous, because if I look at the energy system as such I have the feeling that it really works very well. If I want to buy one ton of oil to warm my house, the ton of oil is there; and if I want to fill the tank of my car, I can fill it everywhere. And if I do it throughout the year, then I get a calendar and a bonus from the man at the pump.

On the other side, if one looks at the efforts of those trying to understand how an energy system works, one really has the feeling that we are ''muddling through''—and I have the impression that we have to muddle through for a while before seeing light.

The fundamental weakness of our representation of an energy system through modeling becomes evident when we see that each model produces its own path for the future. The fact that there is only one past is perhaps a good reason, if not a sufficient one, to see whether we happen to have only one future: that is, to investigate in what measure the future can really be foreseen, and to what point it is predetermined.

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*Adapted from a presentation at the IIASA Third Energy Status Report, 24–28 January 1978.

Figure 1 shows what Jerry Weingart and Nebojsa Nakicenovic [1] have carefully put together for the predictions on energy demand and solar energy market penetration in the United States according to various models. As you can see, the number of futures is as large as the number of people who are looking into it. And that is not an extreme case. It seems really that people doing modeling never look at each other's results.

So from time to time I ask our Project Leader what he thinks of that, and he once gave me a very astute answer. He said: "That's not forecasting, that's modeling; it's preparing for the future, and the fact that no two people can get together means that the future is full of choices. And that's an example of the richness of choices that the future has in reserve for us."

I am originally a physicist, a bit of the Bridgman school, and I always try to find an operational description of certain statements. The best operational description for our case is that of Alice in Wonderland who sees flowers and flowers, picks them, and then sees better flowers, so she throws the old flowers away, and so on.

But the question now is who picks the flowers. Well, it's the "decision maker." In our slang a decision maker is an obvious person. But who are really the decision makers? Well, I am not a decision maker. I have examined my life carefully, and in a sense I never took a real decision. I saw things coming, and I tried to do the best. If I had to describe myself, I would say I am an optimizer.

I looked at the next level: perhaps politicians, or the heads of large companies, are decision makers. Well, I had long discussions with them and a lot of them say: "We *seem* to be decision makers but we are so strongly conditioned that finally we don't recognize any decision in our decisions. We are just *optimizers*."

So I thought perhaps we are in a very large boat and we have only one big decision

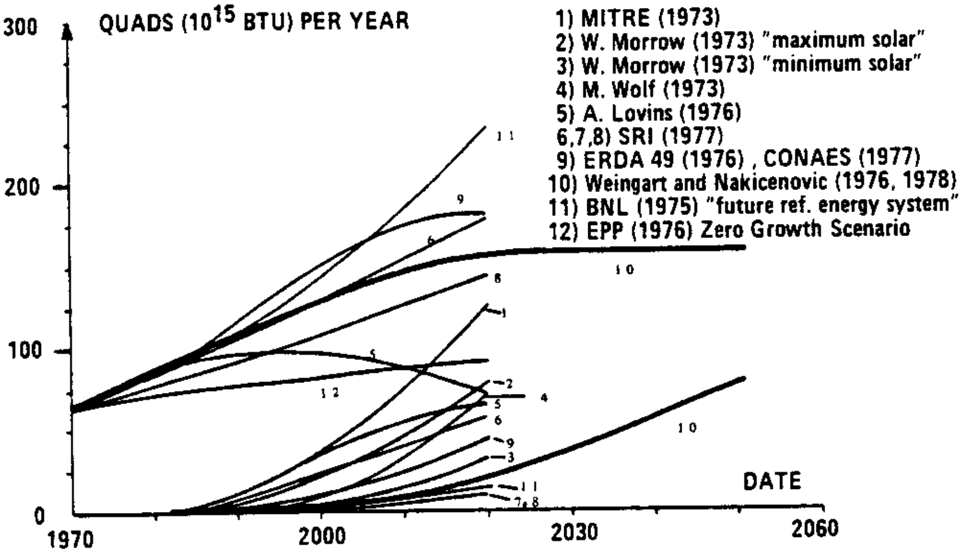

Fig. 1. Scenarios and projections of total energy demand and the share potentially available from solar energy (United States) [1].

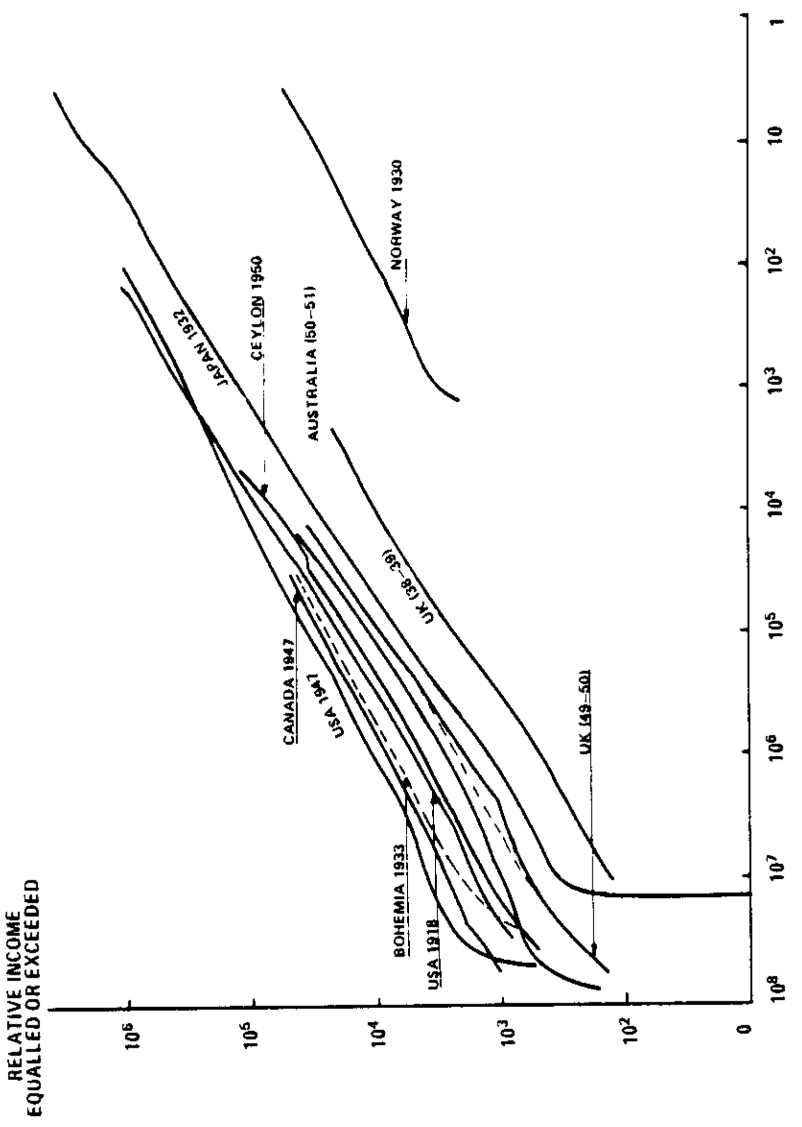

Fig. 6. Income distribution—Pareto's original observations.

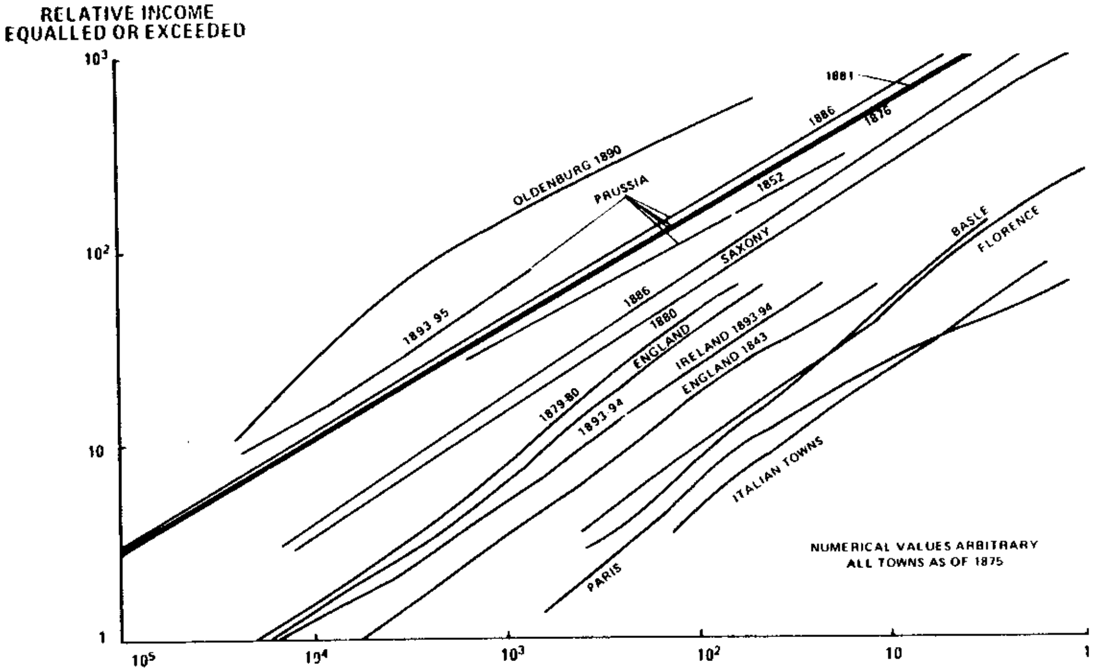

Fig. 7. Income distribution—Pareto's law.

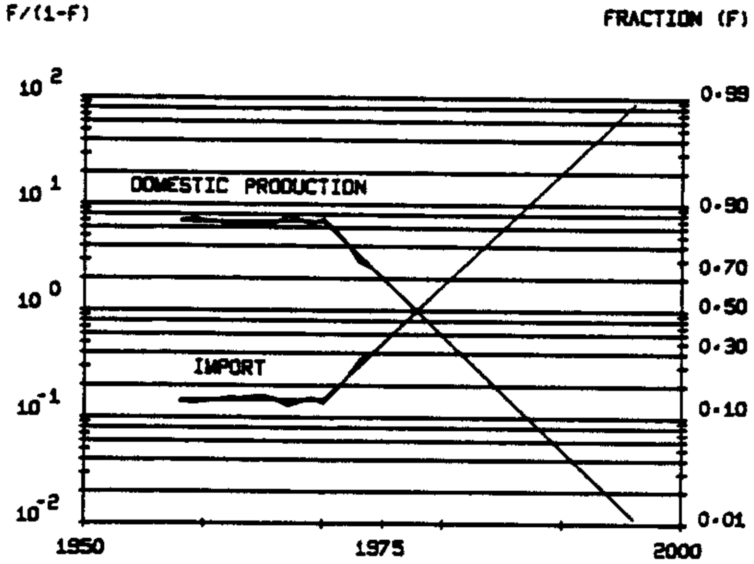

Fig. 2 United States—oil production and import (*F* is the market fraction) [2].

maker, and the big decision maker is—well, for instance, the head of the most powerful state in the world. So I thought, let's look and see, as the Chinese say.

As we are talking about energy, I can't resist showing you a graph on the evolution of a certain aspect of the energy system in the United States (Fig. 2). It is plotted in the usual way for market penetration, but this is not relevant; it's just a way of representing data. The graph shows the relationship between imports and production of oil in the United States in the last 20 years. Now it happens that in the years before 1969—that's before the famous oil crisis—there was a law saying that the quota of oil that could be imported was a fixed fraction of consumption. So we have two beautiful parallel lines under the constraint of the law. The fact that the quota was always met, however, shows a certain pressure on the system. When the quota was lifted in 1970, imports did start growing as you can see, and on the other hand a grandiose "energy independence" project was conceived and promulgated by our supreme decision maker.

Now the data in the graph stop in 1975, but the 1976 and 1977 points, perhaps by pure chance, fall in a straight line we can draw through the points 1970–1971–1972. For 1977 the imports have in fact constituted about 50% of the consumption.

To render this with an image, it seems that the most powerful man in the world looks like Napoleon in Russia, sitting on a white horse and pointing East while the Army is going West; and that's not the best image for decisional power.

So who is going to make decisions? Perhaps the system is making decisions. That is the central point of my presentation and of my analysis of energy systems in a broader sense.

Let us assume the contrary of what our Project Leader said in a certain context—that the future is not predictable. This would be a very strange statement out of context, because we would be sawing the branch on which science has been sitting for at least a hundred years. And if the future is not predictable, it is very difficult to explain how the time of landing of the American spacecraft on the moon was predicted to within a few seconds. So the statement must be qualified when out of context: "The future is not predictable with infinite precision." There are many reasons for that. Some physicists think that the principle of indeterminacy is the most important reason for the inability to predict the future, but quantum physics actually just displaced determinisms from one set of variables to another.

For complex systems, such as molecules in a volume of gas, there are ways of predicting with different levels of precision; and the limitations, most unexpectedly, are in the level of calculation. As I will say in a moment, to predict, one has to calculate; to predict with great precision, one has to calculate with great precision, and calculation costs negentropy and negentropy costs energy.

And so the process of predicting with more and more precision cannot be performed beyond a certain level. This is one of the very interesting statements that has come from a study of the fundamental limits of computers that is under way at IBM [3].[1]

A social system and an energy system can be seen as composed of many small parts that move in a more or less stochastic way; what we finally see is an envelope, such as the energy statistics for the world, for one nation, or for one particular fuel. By simple and brutal analogy, one might say that one could try the same techniques that physicists use for reconstructing the macrovariables of a system from the microscopic ones. Now, the branch of physics that is doing that is thermodynamics, and thermodynamics historically has developed in two ways: by trying to find relationships between the macrovariables of the system—for instance, temperature, pressure, volume, and things like that, which are of very general significance—and by trying to reconstruct these macrovariables starting from the basic law that governs the molecules or subsets of components.

In principle, the two conceptions can be considered as logically completely independent; in practice, and historically, there has been a continuous exchange of ideas, of suggestions, of information between the two representations of the same system, and that suggests that also in our case the two things should if possible be kept together, or kept working together.

It must be clear that the second way, that of constructing the macrovariables from the microscopic, is the more difficult one which has taxed the ingenuity of the best minds in physics for at least a hundred years. We are starting only now, perhaps in the last 10–15 years, to work on social systems or energy systems or the like using LP models or similar things; and we should not expect instant success.

We have to work for a while before achieving a degree of self-consistency and harmony with the external world such as has been obtained in the case of physics. That the thing can be done becomes evident from Fig. 3. It shows a very important fact: that a kind of macroscopic description of the system, the market penetration model, reveals an important characteristic of the system itself that I would call holographicity. From a very small part of the data that constitute the macroscopic description of the system, we reconstruct a very long tract of data, back and forth in time. This can be seen as the revelation of a deep-seated and very stable organization pattern inside the system, which gives meaning to the effort of searching for it. Obviously, this research may fail, but heuristically it's a very strong suggestion.

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[1] *Editor's Note:* see also Simon, J. C., Complexity Concepts and the Limitations of Computable Models. *Technol. Forecast. Soc. Change*, 13, 1–11 (1979).

Let us assume the contrary of what our Project Leader said in a certain context—that talking of energy, probably the best instrument (or the most obvious) to analyze its operation is thermodynamics.

What can thermodynamics do? Thermodynamics can do essentially one thing: it can say, if you want to do something, what is the best way, in principle, of doing it. And that may or may not help in practice, but it certainly gives a logical matrix and a paradigm against which what happens can be compared and evaluated. So it gives essentially a system of values and a metric.

Now one of the astonishing consequences of an elementary thermodynamic analysis is that if we take all energy uses together, we see that in the developed countries the total second-law efficiency for energy use is about 5%, a shockingly low figure. It means that there is a long way to go in improving our efficiency and getting the same results with a much lower primary energy input.

One of the facts in that direction that leaves people astonished (I made some experiments) is how much the Americans increased their energy consumption in the last hundred years. I made my checks with generally very well-informed people, and the answer was between a factor of 10 and a factor of 50. Now the real case is a factor of 2. Why only a factor of 2? Because in the meantime all the processes that lead to a certain final objective, sometimes called the "useful energy," have improved their efficiency with time, compensating for a substantial part of the increase in the demand for final energy.

If we could find for each single process the rules that govern the evolution of this efficiency, we would have a precious input for our modeling effort from the bottom up.

Figure 4 shows the evolution of efficiencies of various more or less important processes, plotted in the form that makes logistics appear as straight lines. This is due to the hypothesis that the approach of actual to theoretical efficiency is a learning process. The analysis shows two things I think important. One is that the efficiency increases in time;

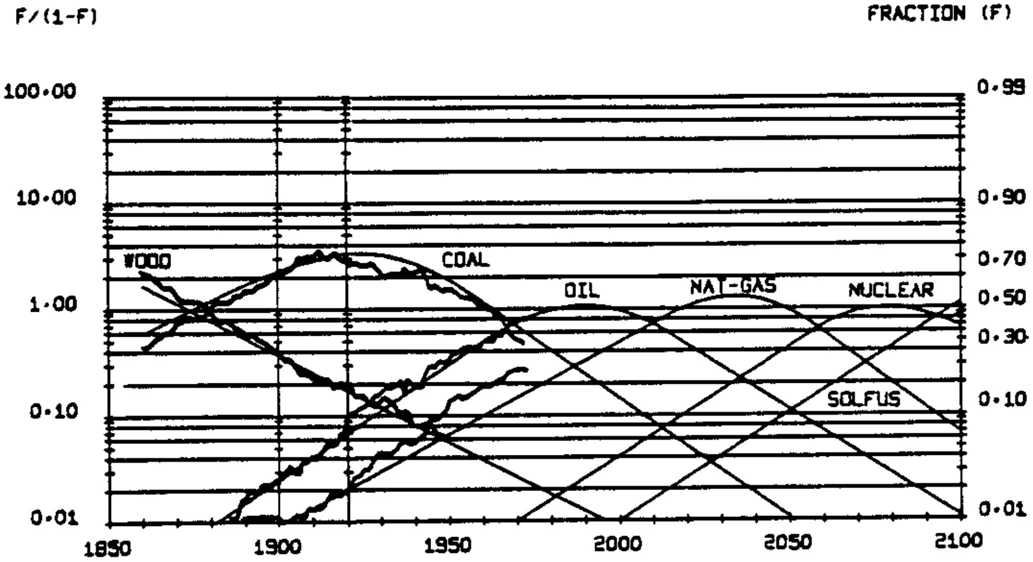

Fig. 3. World—fractional substitution with short data base [1].

the second, that this increase is extremely regular. There is a kind of internal clock in the evolution of technology, and the existence of this internal clock again points toward a deep-seated and stable organization in the operation of the human system—or a human subsystem, because we are now referring to a particular subsystem, that of technology.

I think this is a most important result, and this kind of analysis should be extended to all processes having some weight in the total energy budget. The fact that the evolution is so stable over a long time span may lead to long-term prediction, which, if not 100% precise, can be considered dependable.

I want to give now a tiny electric shock to the economists. This evolution has very little to do with the price of energy. I will give you an example where this is explicitly and clearly true.

In the case of computers people are increasingly looking toward efficient computers, in thermodynamic terms—and I am referring to central processing, not to the peripherals. This may sound funny because the cost of electricity to run the central unit is really negligible against everything else.

What happens, in fact, if the computer is inefficient—and thermodynamic efficiency of computers now runs in the range of 10^{-10}, 10^{-11}—is that it generates relatively large amounts of heat for a certain calculation. Now with the introduction of integrated circuits, computing devices tend to become smaller and smaller and the heat dissipation problem may become a constraint to miniaturization. Miniaturization is what economics strive for, and energy saving in the computer is its consequence, but in a very indirect way having nothing to do with the price of electricity.

More generally, there seems to be no connection between the fluctuating prices of energy and the very regular evolution of efficiency in particular technologies.

Similar trends can be observed for the system that uses the particular technologies. Figure 5 shows the secular trends in efficiency for the world electric system, and for the steel industry in the United Kingdom. If the technology itself seems to proceed on its own power, in the second case one can see here the effects of small local perturbations like World War II, leading to an overall reduction in the (thermodynamic) efficiency of the U.K. steel industry. It is, however, interesting, though perhaps accidental, that the curve again joins the previous trend.

At this point I would like to make a further step in the direction of a more abstract and fundamental description. Logical thermodynamicists, like Myron Tribus [4], suggest that heat is not a really necessary concept and can be thrown overboard like ether and phlogiston, and that the real thing is information, or negentropy, in more thermodynamical terms.

The concepts of information and negentropy permit one to see energy systems and systems in general with new eyes and I will describe an illuminating "Gedankenexperiment." If we take a gas, the energy in the gas is defined only by its temperature. One has free molecules, and their kinetic energy defines the energy of the gas. That means that at the same temperature a compressed gas has absolutely the same energy as an expanded gas. So the concept is the following: take a thermal gradient machine operating in the ocean, a so-called OTEC plant that uses the temperature gradient between the surface water of the ocean and the middle ocean waters, and we run an ammonia engine and use it to compress a gas (e.g., air). Because the compressed gas has no more energy than the original gas, no energy is extracted from the ocean when one sends it away in a pressure bottle or through a pipeline going ashore. This means that all the famous heat is left in the ocean, although with different spatial distribution. The compressed gas could then be introduced into a city and one can run machinery with it, one can make electricity, make hot and cold fluids with heat pumps, run ventilation, and do anything you can imagine. *But* if the compressed gas carries no heat, or no energy, then the heat balance of the system that relies on this compressed gas is again zero.

So we have a system where heat is locally circulating but there is a zero heat balance in energy generation, energy transportation, and the consumption: let us call it heatless energy. What happens in fact is that one has destroyed a certain structure, the layered structure of the sea, and has extracted and preserved a certain amount of something—let us call it information—in having a gas in a less probable state than before; and finally this information is used to organize a city. Now from this example the energy system is clearly an informational system. Everything runs, but there is no heat.

If we concentrate on the informational aspect of our energy system, the next question is how much information we need to run our socioeconomic system. This may bring us one step forward with respect to the plain thermodynamic description of an aggregate of processes. An umbilical link is left, however in that information is a physical thing and the bit of information has an energy equivalent of $KT \ln_2$, where K is the Boltzmann constant $K = 10^{-16}$erg/°K.

This conception is fascinating but not so easy to apply. Dr. Thoma, a consultant to IIASA, made an experiment trying to measure the amount of information that goes into the design of a steam or diesel locomotive, somehow counting the number of bits necessary to describe their blueprints. The figures that come out are deceptively small in terms of energy equivalent, so one might think we are dealing with phenomena somewhat beyond the realm of our preoccupations. But the situation is actually more complex. First, what we are really looking at is the superminimum that can still make our system tick. This might actually be very small. Second, Shannon information may not be the right thing to measure after all.

That we operate as informational systems is to me absolutely clear, and everyone can accept it at least heuristically. So the next move consists in looking at parallel branches of science struggling with similar problems.

One of them is biology. Molecular evolutionists have made great methodological strides in the last 10 years or so, and the patterns of how a Darwinian system thrives on information flow are becoming clear. The question is then how to formulate our problem in a compatible language so as to profit from their results.

They also have the problem of the very small amount (in energy terms) of Shannon information necessary to specify a living thing. For man only something like 10^{10} bits, or about 10^{-10} J (at 300°K) are required. Were four billion years of evolution worth that tiny result?

The answer is simple and fairly satisfactory. To go from structure A to structure B that better fits the external constraints, as with the diesel versus the steam locomotive, one can only proceed through stochastic exploration of possible configurations, and proper selection. In going from A to B then, the flow of information necessary is orders of magnitude larger than the difference in Shannon's information content between A and B, because of the great number of "failures" that have to be discarded.

In a fundamental paper by Manfred Eigen [5] of the University of Göttingen, a methodology is given to calculate the *minimum* amount of information that has to be shed in the process. The importance of the criterion resides in the fact that we start seeing here the beginning of a metric similar to that which thermodynamics provides for more "mechanistic" systems, and consequently have a reference by which to measure where we stand and how we progress. Incorporating these concepts into the modeling effort could perhaps bring it to new life, or better, nearer to life.

The other branch of science operating in this realm is that of computers. They are rapidly becoming as complex organizations as living organisms and have to face similar problems. Computing has to be based on physical operations, and the striving for higher efficiency imposes a deep revision of the principles. Biological systems have gone a long way in this direction, at least for fundamental processes like, DNA replication, perhaps because they were established during the Primeval Soup period when energy, or better negentropy, was at a premium.[2]

With central computing units operating at efficiencies of 10^{-11}, DNA replication operates at an efficiency of 10^{-1}.

Are social systems, and the underlying energy systems, amenable to such treatment, or are we not tampering unduly with our cherished "free will"? We have already commented on the free will of the decision makers. About the sophisticated order of complex social systems I would like to report here two suggestive examples.

The first (Figs. 6, and 7) refers to the distribution of income inside various human "sets" like nations or regions, or even cities at different historical times. These regularities—I would call them laws as they are so precise and stable—were first observed by Pareto, an engineer turned economist.

It turns out that, as the study of living organisms has revealed, the hierarchization of the system, the necessary mechanisms to deal with complexity, is in itself a sufficient concept to interpret the Pareto regularity. But one may object that this is just an accidental regularity, as in the case of market penetration, and from now on free will and government support will change the world from A to Z. So I want to give another example, where it is possible to look at the machinery inside and examine how free will does in fact create predictable futures.

The city of Athens (Greece) has grown from a tiny core to an agglomerate of about two million people in about a century. It grew essentially through a rim of squatters that was progressively assimilated by the city proper. No planning has ever been attempted, as is obvious if one looks at the city from one of its hills, the Acropolis or the Licabettus. But the mess works gorgeously for the people living in it, and that induced the researchers of the Athens Institute of Ekistics to do a major study in community operation.

A city can be considered as infrastructure for providing jobs and services to its inhabitants. They cover a wide spectrum, from the pub and the grocery shop to the mayor and the opera house. The scholars made a long list of these services and found that the city can be divided into small communities defined through the common use of the most basic facilities.

The first unexpected result is that the amount of energy, measured in man-kilometers to use the facilities, is the same for all communities. If the density of one of them increases, and so proportionally the man-kilometers, new facilities are created and the community splits. A balance is struck at any moment (with some viscosity) between the energy for moving and the cost of new facilities.

One can walk longer, however, for facilities that one seldom uses, and so above the communities there is a next hierarchical level of services, present in one community every

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[2] *Editor's Note:* see Marchetti, C., From the Primeval Group to World Government: An Essay on Comparative Evolution, *Technol. Forecast. Soc. Change* 11, 1–8 (1978).

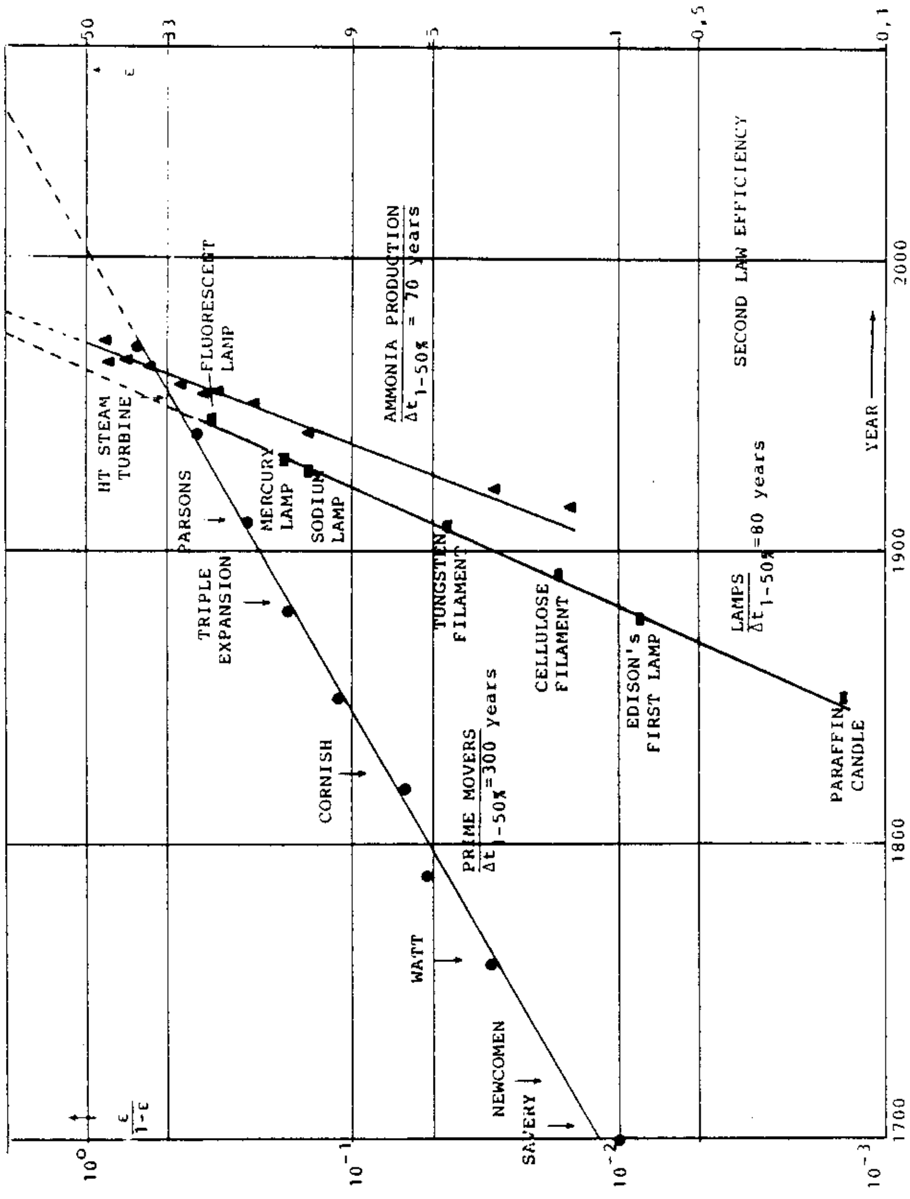

Fig. 4. Historical trends in efficiency ($\Delta t_{1-50\%}$ is time necessary to evolve from 1% to 50% efficiency; ϵ is second law efficiency).

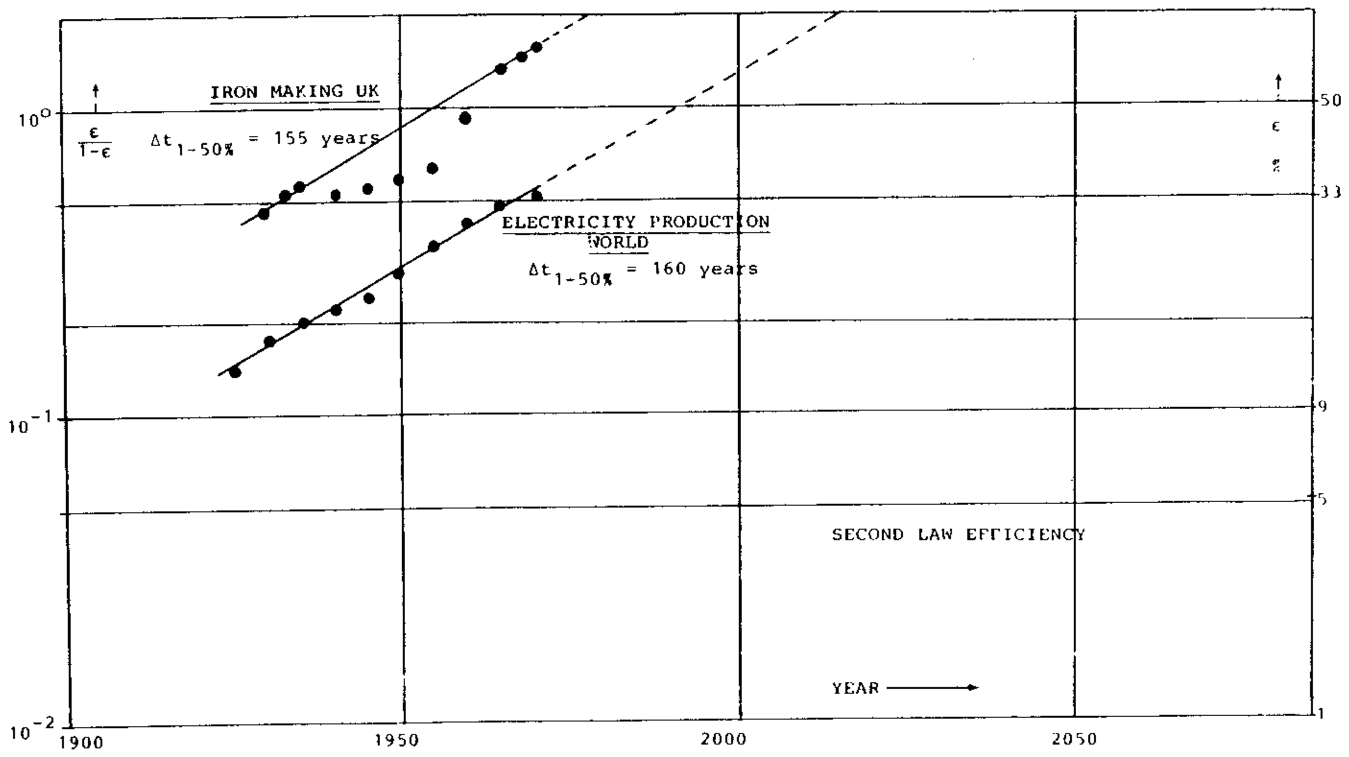

Fig. 5. **Historical trends in efficiency ($\Delta t_{1-50\%}$ is time necessary to evolve from 1% to 50% efficiency; ϵ is second law efficiency).**

seven and serving also the six peripheral ones. This hierarchization continues upward; the city as a whole has five levels of hierarchy, with the magic ratio of seven from one to the next.

As we have seen, energy expenditure versus cost of the facilities was the optimizing concept at the level of the basic community; what happens at the level of the city? Virirakis [6], who has written an extremely efficient and simple model (it looks much like mathematical physics), has calculated the energy cost for two deoptimized cases: (1) all facilities concentrated in the center and (2) facilities distributed at random.

In the first case, which seems to hold some fascination for "rational" planners, energy consumption would increase by a factor of 6 and in the second case, by a factor of 15. One should read Virirakis's papers for all the details, but I would like to make a few comments.

The example shows that a simple optimizing principle creates a highly ordered and mathematically describable structure without touching the holy totem of free will. Any member of this community *can* buy bread at any grocery in town but he most probably *will* buy it at the nearest one. And that does the trick.

Coming back to our grandiose problems, I hope I have conveyed to you the doubts about the state of our model making and the hints for a more successful round.

Waiting for more insight, I would suggest not underrating the built-in wisdom of the system. As Nakicenovic showed, a "natural" phase-out of the old primary energy sources, and a phase-in of nuclear and perhaps of a new source around year 2020, may provide a smooth transition, with no muddling whatsoever, to the year 2030. The real constraints appear to be not in the realm of physical resources, but in that of international cooperation. There perhaps decision makers (optimizers!) should concentrate their action.

As so many of us tend to focus on the technological side of the energy problem and pretend to find there all causes, effects, and solutions, I have tried to redress the balance a little by overstressing the importance of the frame, and I would like to condense my observation in a warning: *Don't forget the system, the system will not forget you.*

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