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WHEN WILL HYDROGEN COME?

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WHEN WILL HYDROGEN COME?

The question expressed in the title started puzzling me since the beginning of my involvement with hydrogen as an energy vector at the end of the sixties. It was actually the driving force for me to enter into the study of the dynamics of innovation processes, and of systems analysis in general.

My first attempt was based on a classical microscopic analysis of the process. Assuming the wind blows in the right direction, it will take some time to accomplish each of the steps from conception to sales. Estimating these technical times and summing them up gives an earliest date for the implementation of the idea. The advantage of following this scheme is that it is very analytical, with all components and hypotheses clearly visible. The disadvantage is that practically it is a guesswork construction, quite useful for visualizing the things to do and their logical order, but of little help for forecasting a solid date.

The fluffy quality of the operation led me to explore the possibility of something harder even if less explicit, so that the mechanisms are not visible. An example of this procedure is thermodynamics, as opposed to its analytical counterpart, statistical mechanics, where the global result is synthetized from the elementary processes.

The approach was very successful when applied to the dynamics of energy markets, a work done under the auspices of the Volkswagen Foundation in the middle seventies [1]. A system of two parameter equations could describe the evolution of the structure of all kind of energy markets, for periods of time up to one hundred years, and with the utmost precision.

The background heuristic drive was that complex systems depending on numerous variables tend to evolve along mini-max tracks, yielding some sort of behavioral laws. In the specific case it was assumed that the market was a fighting arena, so the equations for ecological competition were tested first, and as said before, they worked remarkably well.

The case of competition between primary energy sources is reported in the well-publicized Fig.1. Market shares are there plotted vs time for the basic primary energies, wood, oil, gas, and nuclear. The cut-off level is 1% market share, and this is why hydraulic or wind energy are not included in this world case.

Competition can be studied at various levels. As Fig.1 reports the primaries for the world, Fig. 2 looks at how different fuels contribute to the production of electrical energy in Western Germany. This means the analysis in fact can be zoomed into sectorial compartmentalizations with still excellent results. About three hundred case histories were analyzed this way.

Hydrogen is an intermediate form of energy, an energy vector, and this methodology could help to find something about its penetration. The rates, e.g., can be assessed by analogy. In the case of primary energies at world level, they have been consistently of 100 years for wood, oil, and gas, and this makes the best guess for nuclear. These 100 years is the time to go from 1% to 50% market penetration, taken as a measure for the rate of substitution.

What we are looking for, however, is when hydrogen will start penetrating. The weak spot of the above analysis is precisely the fact that penetration must have started in order to fit the equations and let them go. Se we cannot apply it straight.

To find a detour that would bring us nearer to the solution of the problem, I used another heuristic trick which usually works: From the hundreds of case histories of large systems I analyzed it appears that the more complex the system is the less can a component be determinant of its behavior. Fair enough. But going one step further, that the behavior of the components is strongly limited by the boundary conditions that the system itself imposes. This is a trifle harder to accept, especially if the components are people. Even in abstract configurations like consumers or decision makers. In other words, identical seeds can produce very different effects depending on the ground that they fall on, as is exemplified in the parable. This type of reasoning leads to the search for "opportunity windows" for a certain operation, a concept very clean in agriculture, for the seed to fall on fertile ground, and astronautics, for the right time to take off.

The argument I used to find this opportunity window may appear at first sight as a curious one. We have to first find some sort of competitive process already established so that we can fit it with our equations, which finally sets or indicates some conditions making our hydrogen useful or necessary. The fact that the process is competitive is obviously not required in principle, but it must be if we want to try to solve the problem using an homogenous procedure.

It has cursorily been observed that in the course of time the market required progressively more fluid fuels, in practice reacher in hydrogen. Actually, in wood the molar ratio H/C is about .1, in coal about 1, in oil about 2, and in natural gas about 4.

That wood has so little hydrogen may seem strange at first sight. Actually, about 70% of wood is made of cellulose, i.e. a carbohydrate. As the name says it is carbon plus water, even if one writes it as H-C-OH. By heating wood we get in fact this chemical water out, and produce a black char. About 30% is lignine, with complex cyclic molecules and some real hydrogen into them. My overall .1 is obviously very rounded taking into account the great variability of the various percentages. The same should be said for the ratio of one which I chose for coal. The situation is much more clear for oil and obviously for natural gas which is an almost pure product. The first qualitative observation that there is more and more hydrogen in our fuel starts being quantified.

At this point one could argue that after all hydrogen and carbon can be seen as competitors fighting for a niche, i.e. the fuel market. Because the H/C ratio grows it means hydrogen is winning; let us see where it is aiming.

I made the analysis for the world first, and the result is reported in Fig.3. This figure is obtained by weighing the market fractions of the fuels with the relative H/C coefficients described above, in order to get the mean value of H/C as a function of time. The result is presented in the usual coordinates of Fig. 1 and Fig. 2.

The procedure is not 100% clean, but let us look at the result first; there is always time to polish and improve. The almost perfect alignment of the points shows that H/C evolves logistically in time, i.e. it follows the ideal curve for a one to one competition. Our queer proposition appears then to be at least formally correct.

In one to one competition the winner wins totally, eliminating the loser. He usually loses only to the next successful competitor. In our case no new competitior is in sight and we should conclude, with a logical leap, that hydrogen should finally become the sole carrier for chemical energy in the fuel system. The timing of the process should then be described by the curve of Fig. 3.

If we assume to stay in the fossil fuel system, then a difficulty arises, that the maximum allowable H/C ratio is that of the hydrogen richest hydrocarbon: methane. In order to go beyond that one has to introduce hydrogen from an external source, inevitably water. Because fossil fuels with lower H/C ratio are there to stay for a while, if in reduced amounts as shown in Fig. 1, this exo-hydrogen may well be necessary some time before the H/C ratio in the historical "demand" curve reaches the level of four.

All these considerations are again synthetized in Fig. 3 and the rounded appraoch to level four actually describes the influence of the mix of primary fuels with various H/C ratios.

The exo-hydrogen would then be indicated by the gap between the projection of the historical H/C line, and the one constructed by weighting and summing up the curves of Fig. 1.

The point of interest to us is when the two curves depart, indicating the starting date of the hydrogen era. It must be clear that at the beginning this hydrogen may well be used inside the fossil fuel system to improve the H/C ratio, e.g., via some kind of coal liquefaction, or of heavy oil residues mobilitation but this does not change the situation conceptually. Above the H/C ratio of four, however, hydrogen must appear as such.

I am perfectly aware that all the reasoning hangs on the assumption of business as usual. My confidence in that assumption stems from the analysis of hundreds of cases where the "system" showed an incredible perseverance and doggedness to hold its usual dynamic of change, through wars, depressions and pestilences.

If the reasoning holds, the exo-hydrogen should appear in sizeable quantities, at world level, around the year 2000. It would obviously help a lot to gain confidence in that date, if it could be defined through a completely different line of reasoning, something I will attempt in a moment.

The type of analysis used in Fig. 1 has an important weakness, as I said, in that it can predict the dynamics of the battle only after it has already begun. It cannot say when a new competitor will come in. Because the subjects I am analyzing are finally reducible to technological innovations in the broad sense, I looked into this more general area to see if these innovations have order and rules so that something could be predicted about them.

The search was very successful and the results reported in [2]. In a nutshell inventions and innovations come in waves finely organized in time so that precision predictions are possible. One such wave is reported in Fig. 4 where the line on the left describes cumulatively the inventions and the line on the right the innovations, i.e. the starting of new industries based on the inventions located in the first line. Both are expressed as percentages of the total number of items. This to read the coordinates correctly, which by the way are the same as in Fig. 1.

Now one might expect that due to the complexities of life an invention located somewhere in curve one would be realized anywhere on curve two. The curious thing however is that both sets are basically ordered, i.e.,with relatively few exceptions, the order in time of the innovations follows that of the inventions. Thus, if we are able to locate an invention, then we can give a prediction when the corresponding innovation will appear on the market.

Locating an invention means, by the definitions I used in paper [2], looking when a successful prototype worked. Because not all successful prototypes end in successful innovations, i.e. new industries, there is another if in the logic. Let us look however where the reasoning leads us to.

If the hydrogen is produced without using fossil fuels, and this comes from the definitions used in the analysis, then the primary source of energy can only be nuclear or solar, via hydraulics. Other solar applications have little chance to make any dent in the time range we are examining. This comes out from the internal logic of my analysis, and the very long time constants for the process of introducing a new primary energy source, even if successful.

Another opinion of mine is that thermochemical processes to split water using nuclear heat, the primary source number one because in its way up as shown in Fig. 1, will win over electrolysis. Then the invention to look for is a prototype plant successfully working.

One such plant could be the bench-scale Mark-13 realized in 1980 at the Ispra CCR Research Center, or, as I prefer, the CRISTINA pilot plant to be operational in 1983-84. So, if the process is going to be successful then we can draw a horizontal line from the 1984 point of line one in Fig. 5 and see when it crosses line two. This should be the starting date for exo-hydrogen from thermochemical water splitting. The date is located in the second half of the nineties, which is perfectly consistent with sizeable amounts popping up a few years later.

Analysis at world level, however, is somehow insensitive to the fine print, for obvious reasons. When something new is introduced, it happens somewhere and its surroundings show the earliest effects. In the case of energy matters, Western Germany appears to have the shortest time constants and on the other hand, it is brooding the High Temperature Reactor, the only suitable heat source to enter into the thermochemical game.

Doing for Western Germany the same analysis as for the world for the H/C evolution in time, we find again a straight line with a much shorter time constant of 120 years, and the knee pointing to the introduction of exo-hydrogen occurring about ten years earlier than for the world. The two things are not contradictory as Germany represents only a small fraction of world energy consumption and it might well represent the total source of exo-hydrogen for the late nineties. Consequently the different behavior is just a matter of amplification.

If exo-hydrogen from nuclear origin should appear in Germany at the beginning of the '90s, then CRISTINA is a little too late. The Germans, however, are pursuing a project of water half-splitting, where the hydrogen is liberated but the oxygen is left in a bound state. It has the advantage,over the full split, of using more familiar technologies and having a much higher thermal efficiency. It has the disadvantage of using a synergetic chemical, methane, in an open cycle. Consequently, the amount of hydrogen produced is limited by the availability of methane for reforming.

This is of no real consequence at the beginning if one decides e.g. to introduce methanol in the gasoline pool to reduce oil dependency and start running cars on nuclear energy plus methane.

Now it happens that the pilot plant, the "invention" according to my definition, was built in the German center of Jülich around 1970 under the nickname of EVA. Drawing the horizontal line we find the corresponding "innovation" around 1995, which fits well the other dates, year more, year less.

This beautiful convergence of dates is certainly not a final proof, but it is highly consoling. The only suspicious thing is that in my 1973 paper [3], using only dreamy guesses, I had predicted under the symbolism of an energy island the date of 1991.

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Figure 1.

WORLD PRIMARY ENERGY SUBSTITUTION

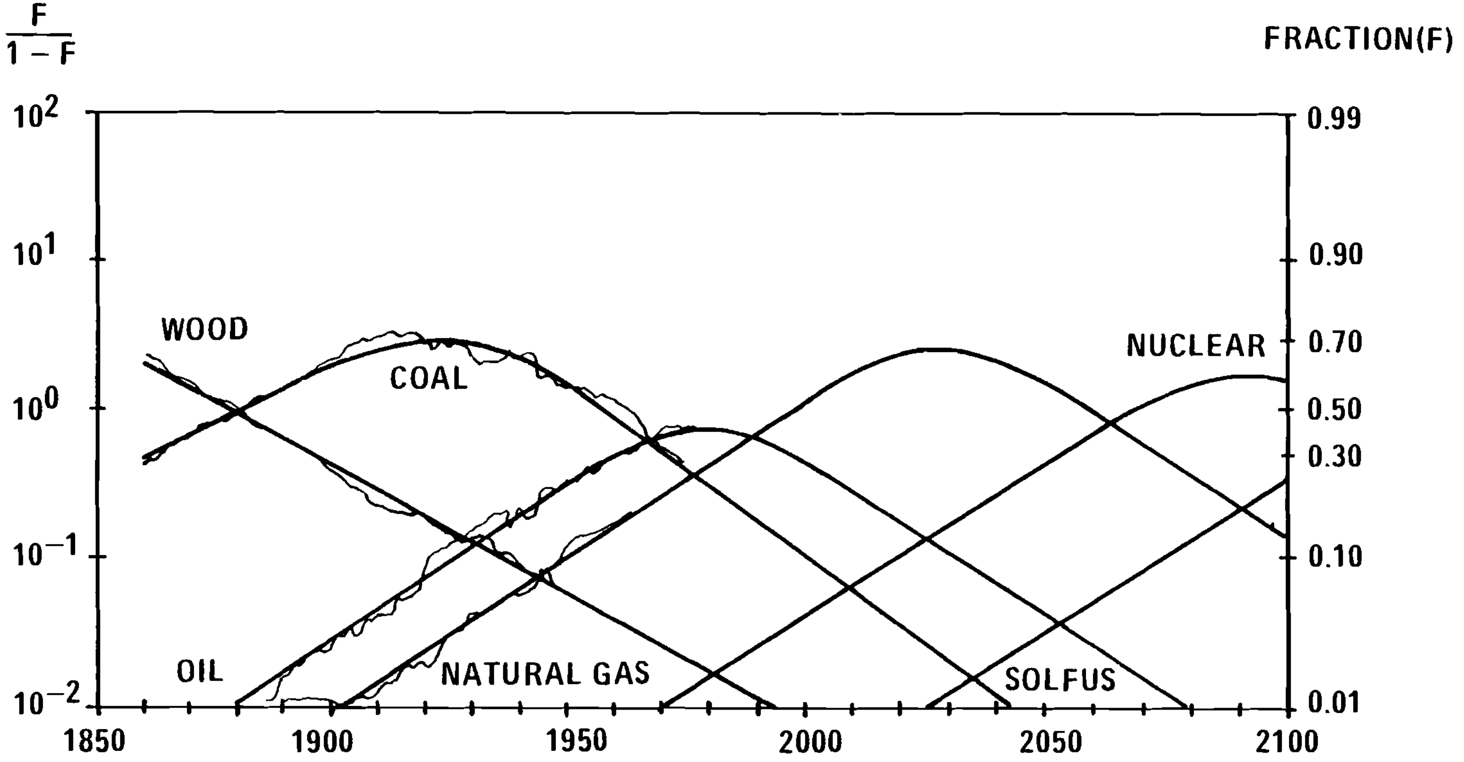

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Figure 2.

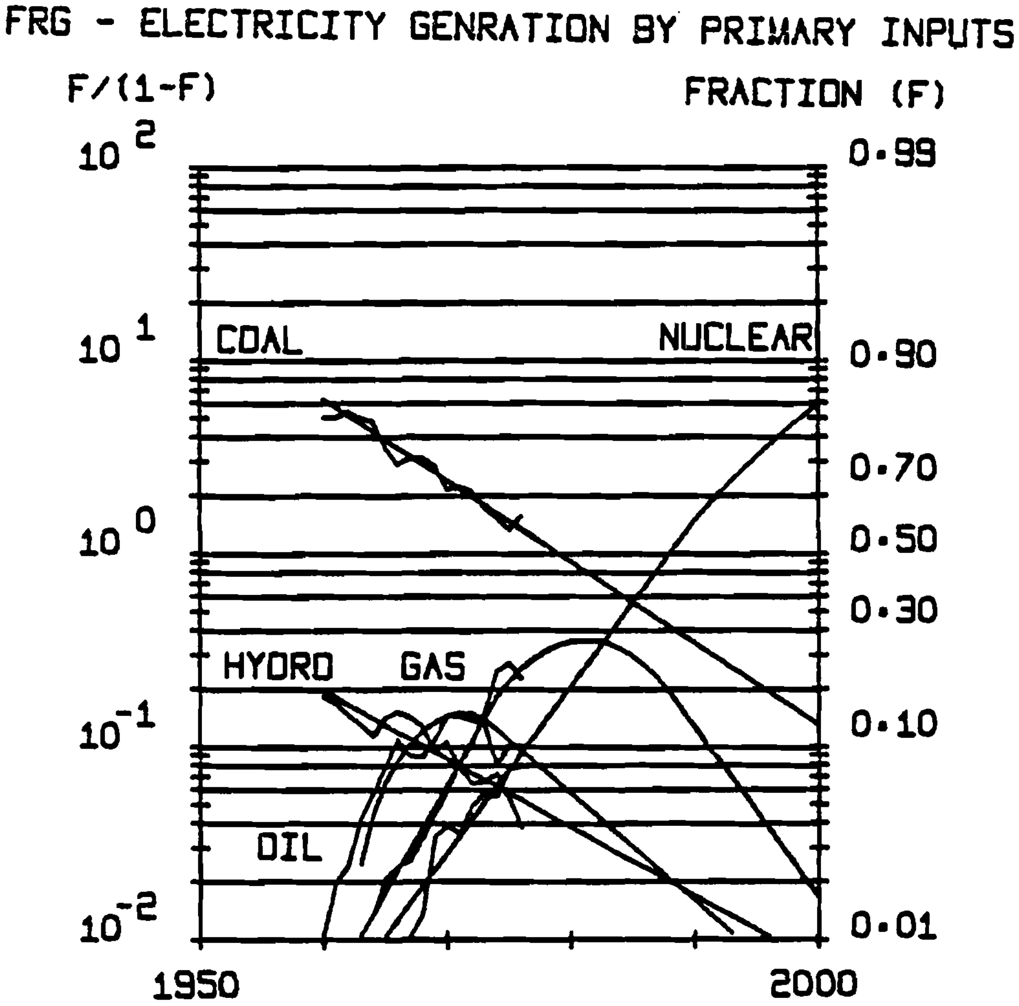
FRG - ELECTRICITY GENRATION BY PRIMARY INPUTS
F/(1-F)
FRACTION (F)
10 2
10 1
10 0
10-1
10-2
0.99
0.90
0.70
0.50
0.30
0.10
0.01
COAL
NUCLEAR
HYDRO
GAS
OIL
1950
2000

Figure 3.

WORLD EVOLUTION OF H/C IN WORLD'S FUEL MIX

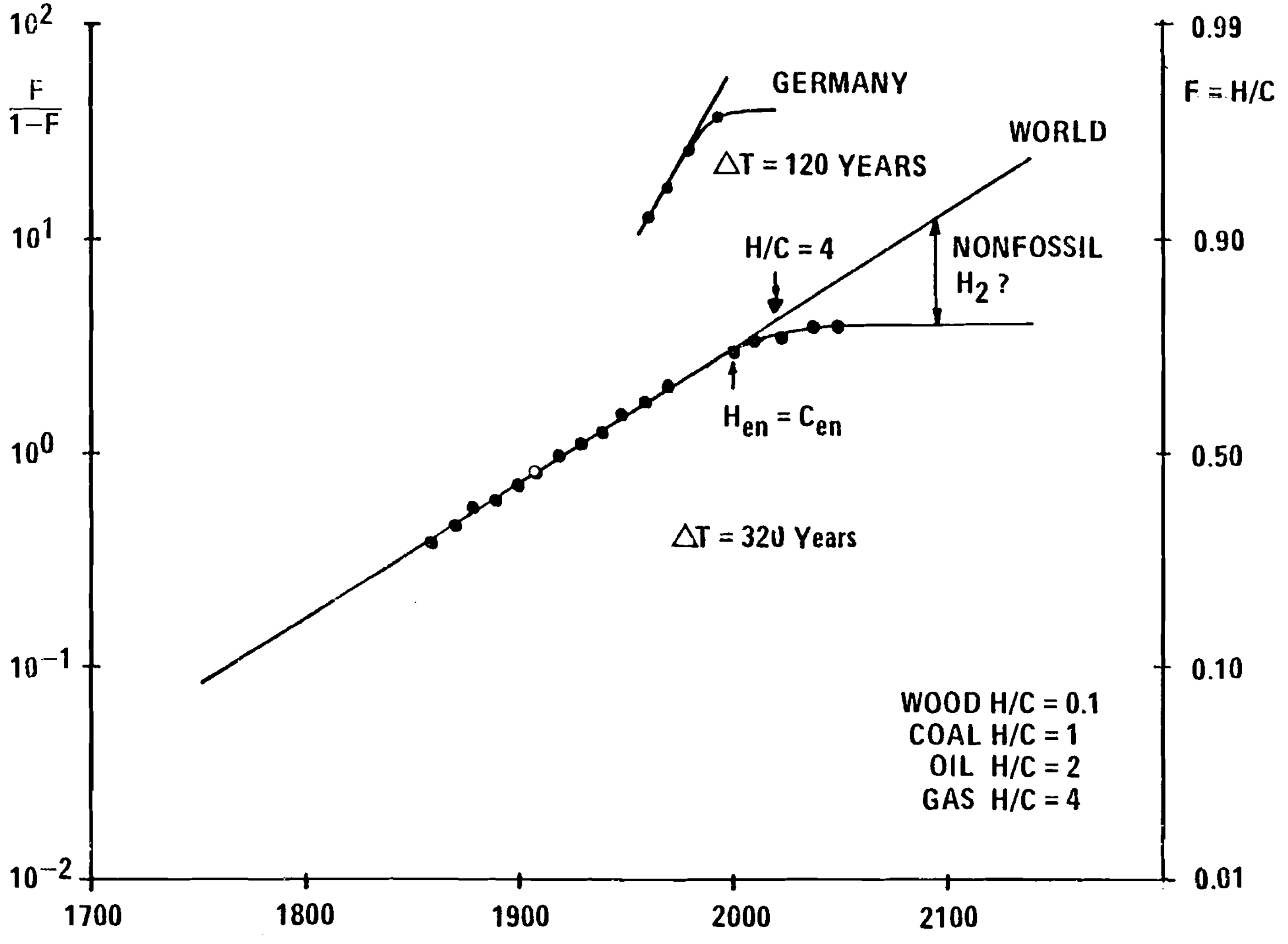

Figure 4.

THE 1922 WAVE

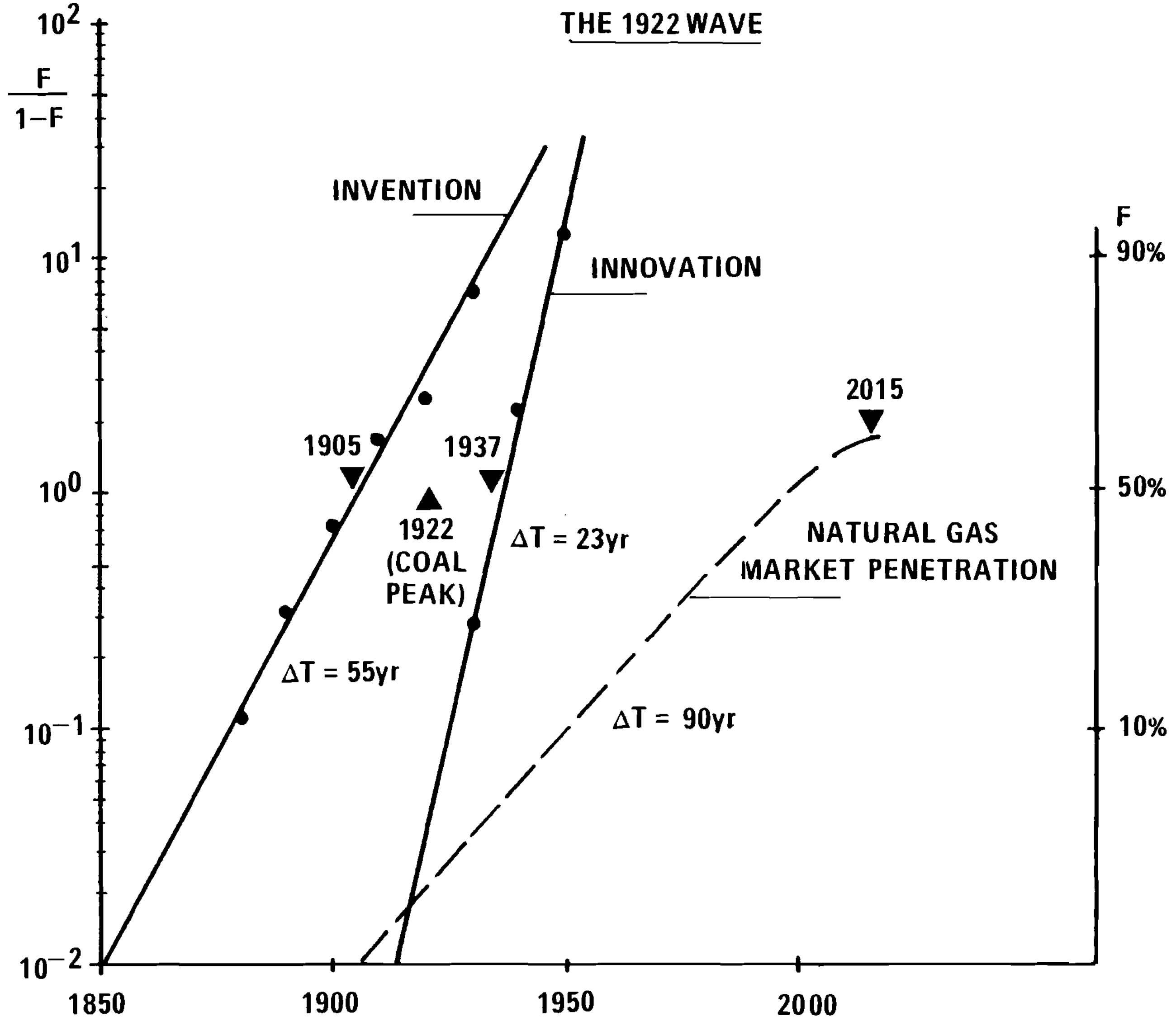

Figure 5.

IMPLEMENTATION DATES FOR TWO PROCESSES TO PRODUCE HYDROGEN