NUCLEAR ENERGY AND ITS FUTURE

C. Marchetti
International Institute for Applied Systems Analysis,
Laxenburg, Austria

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INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
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Foreword

The study of energy systems was a major subject at the beginning of IIASA in the 1970s, and a number of innovative solutions were found for modeling energy markets in time and space. Although the project practically came to an end at the beginning of the 1980s, in the meantime there has been a trickle of occasional and contractual work, deepening a lot of questions encompassing legislation, media coverage, accidents, etc., concerning nuclear energy in particular, which is still in the limelight.

This paper, written at the invitation of the Editor of the journal *Perspectives in Energy*, condenses and organizes the results of Dr. Marchetti and his colleagues' explorations on nuclear energy during the last 20 years.

Peter E. de Jánosi
Director

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Nuclear energy and its future

Cesare Marchetti
International Institute for Applied Systems Analysis, Laxenburg, Austria
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Abstract. In this paper I have extensively applied the model of cultural diffusion (a) to the market penetration of nuclear energy at the level of the world and of single nations; (b) to the interaction with and the reaction of the media to nuclear events; and (c) to legislation related to ecological matters.

The result of this analysis is
(a) that the stasis in nuclear construction is due to the approaching end of the Kondratiev cycle;
(b) that opposition to nuclear plant construction may have important qualitative, but not quantitative effects;
(c) that media coverage of nuclear construction can be modeled and has no effect on market penetration although it might have on accidents;
(d) that nuclear power station construction will probably restart during this decade on a grand scale.

A scenario is drawn for a final configuration, with nuclear energy as the sole primary energy source.

1 The substitution of primary energies

Paraphrasing an old statement of the philosophers of idealism, nihil est in sensu quod pria non fuerit in intellectu, we assume that personal and social actions are basically generated from the diffusion by imitation of social models (action paradigms). As Hägerstrand (1967) and others have empirically demonstrated, these cultural diffusions proceed through personal contact networks which are very stable in time and can be modeled with the mathematics of epidemic diffusion. We have extended the mathematical tools to the case of multiple diffusion (Nakićenović 1979), which is a special case of the general competition model as codified in the Volterra-Lotka equations (Montrell et al 1971). The essential elements of the methodology are outlined in the appendix. In this paper most of the results presented are those obtained from the simplest solution of the diffusion equations, ie the logistic equation in the Fisher-Pry notation that makes the solution appear as a straight line (Fisher and Pry 1971).

Our classic example of multiple competition in the area of energy is that of market shares of primary energies at world level expressed in terms of caloric equivalents (figure 1) (Marchetti and Nakićenović 1979). The extreme parsimony of the model is shown by the fact that the whole life cycle for each primary energy source can be described by a fit of two numerical parameters only. Taxonomically this system reveals an astonishing stability over very long periods of time. This is not an isolated case but a generic systemic property as thousands of analyses have consistently shown. The model appears to represent and quantify a fundamental mechanism in the functioning of a social system and could be applied in any situation we explored, from transport to banking, or from research and development to weapon sales.

If the great stability of the dynamics of the system is a boon to a self-consistent description, then it is also a key to long-range forecasting. The classical example I have used to show this is again that of figure 1 where the parameters are fitted to a short database (1900-1920) (figures 2a and b). The equations so constructed are then compared with actual data outside the database (figure 2c) (Marchetti and

Nakićenović 1979). This experiment shows that forecasting 50 years ahead with a precision of a few percent may be possible.

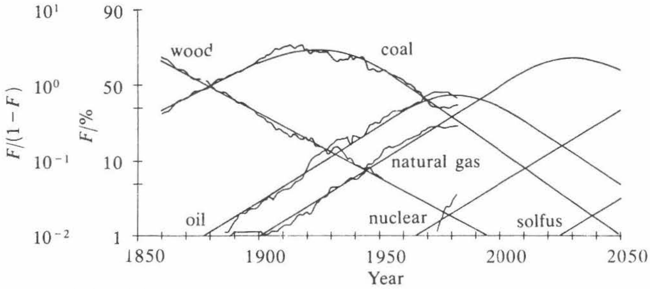


Figure 1. IIASA analysis of primary energy substitution at world level, originally done in 1974 and adjourned in 1984. A stable secular substitution, mapped with multiple substitution logistic analyses (smooth lines), is shown. The chart shows the market fraction (F) in energy terms. Starting about 1975, coal and natural gas proceed horizontally and show no substitution dynamics. This appears to be as a result of a set of laws and regulations forbidding the use of natural gas in power plants. These rules are now in a phase of relaxation and a surge of very efficient (up to 60%) natural gas power plants should be expected during the present decade and will, presumably, lead to a pickup in the use of natural gas and a drastic decrease of coal consumption. The solfus code (solar-fusion) is intended to include the possible use of solar energy, although the dilution and modulation of solar light makes it a poor candidate for large-scale energy production. Source: Marchetti and Nakićenović (1979).

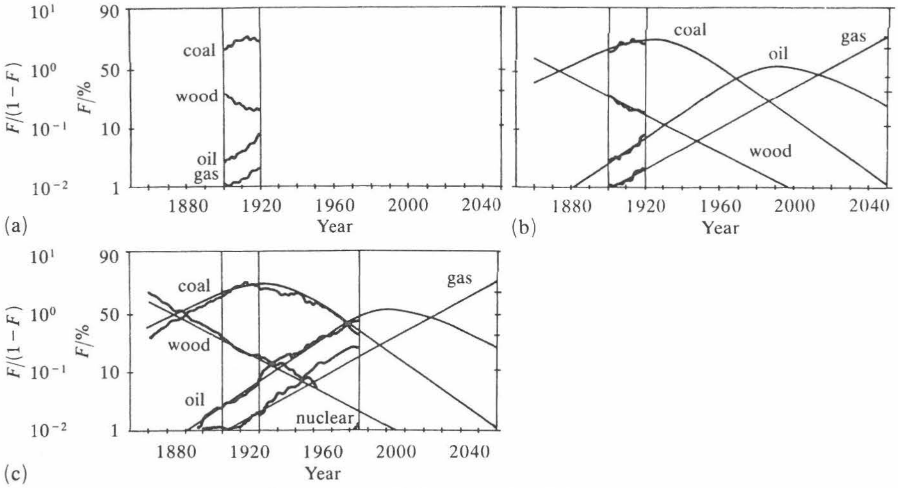


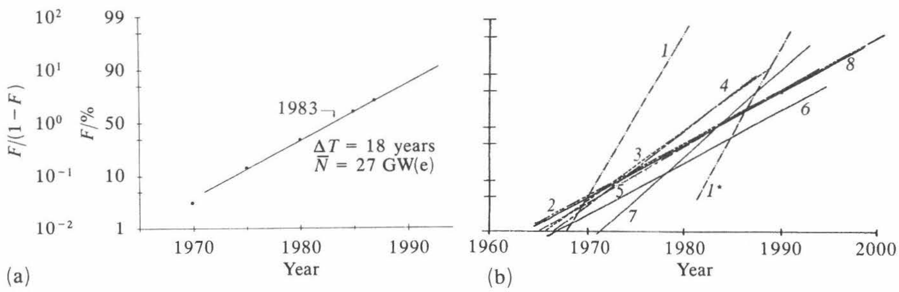
Figure 2. The most impressive feature of the analysis of figure 1 is the amazing long-term stability of the substitution process. Contingent facts, such as crises, wars, extended strikes, or whimsical regulations, appear as fluctuations that are later reabsorbed. This stability is a general feature of substitution processes as we could verify in thousands of cases. This stability is also the base for robust forecasting, and our classical example is reported here. The equations used to provide figure 1 require only two parameters each, to be extracted from a fit to a time series of statistical data. Because of considerable noise, the fitting routine requires a string of perhaps 20 years. The exercise takes a base of 20 years of data between 1900 and 1920 (a) and fits them to the substitution equations (b). The results are checked with the full set of data (c) showing that forecasting 50 years ahead can be quite robust. This procedure does not reveal the possible entrance of new competitors (eg, nuclear energy), but another procedure at a more abstract level (Marchetti 1980) also allows that prediction. According to this methodology nuclear energy should have started in 1970 (F = 1% of the market) and fusion is forecast for 2025 (F = 1% of the market).

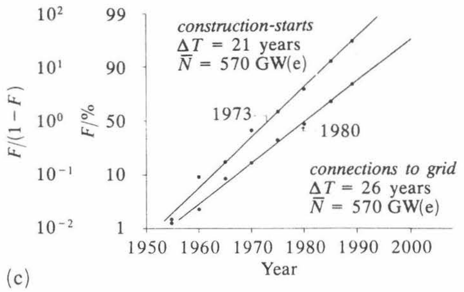
2 The penetration of nuclear energy

The rules of multiple competition as described in Nakićenović (1979) state that the last competitor grows according to a simple logistic as if it had no competitors. This may be true only taxonomically in the sense that the actual values of the parameters of the logistic may be influenced by the other competitors. But this is not important if we just want to describe the process of growth.

Applying this principle to the diffusion of nuclear energy in a certain country, we can then look, eg, at the gigawatts of nuclear power connected to the grid. The case of Germany (FRG) is examined in figure 3 (Marchetti 1983). The model fits the data very well. There is no trace of the continual arguments over the pros and the cons of the use of nuclear power. The level of nuclear power saturates at 27 GW(e) around 1995, a date which corresponds to the formal end of the present Kondratiev cycle and most things saturate in resonance as will be shown later. Some will restart with the next cycle, beginning formally around 1995.

The case of Germany is not isolated, and I have in fact examined most of the states that have developed a nuclear system (not just a couple of reactors which have then been shut down, as Italy has done). All of them have one diffusion curve saturating around 1995 (figure 3b). We can also look at the world as a single unit.





Curve	Region	$\bar{N}$/GW(e)	ΔT/a
1	USA	52	6
*1**	USA	58	8
2	Canada	16	20
3	Japan	30	15
4	Sweden	12	14
5	Germany (FRG)	27	18
6	USSR	70	20
7	France	70	12
8	Western world	315	19

Figure 3. The most recent competitor in the energy market can be represented with a simple logistic (Marchetti and Nakićenović 1979) and we profit from this simplifying rule by showing the penetration of nuclear energy for various countries. (a) The analysis for Germany (FRG) in terms of GW(e) connected to grid, $\bar{N}$. The evolution matches an unhampered diffusion process, showing that the flow and ebb of opposition had no impact on the outcome, ie, the activation of nuclear plants. The saturation point of 27 GW(e) is calculated by an iterative best-fit, and it is an asymptotic value. ΔT represents the rate of penetration, showing the time to go from F = 10% to F = 90% of the asymptotic value. (b) The same analysis as (a) for most of the Western countries where nuclear energy is used. Only the saturation point and time constant ΔT are reported. Data points are omitted to avoid cluttering the chart, but the quality of the fit is always good. The USA has two pulses of penetration. All pulses saturate during the present decade, an effect of Kondratiev cycles as explained in the text. (c) The analysis of construction starts and connections to grid [in GW(e)] at world level. Source: Marchetti (1988, 1991).

The penetration of nuclear energy in term of GW connected to the grid is reported in figure 3c, where also the cumulative construction-starts are analysed in terms of GW. They could also be analysed in terms of number of reactors, as we will see. The only exception to a single saturation is the USA which has two pulses of growth. The second one saturates again around 1995. The analysis of connections to grid in terms of GW(e) for the USA is reported in figure 4. The peculiarity of two pulses will be put to profit later, as it gives an extra degree of flexibility in interpreting possible connections with other phenomena, eg, response of the media to nuclear facts.

From a purely taxonomical point of view the two pulses for the USA are remarkably similar and the saturation points (calculated) are of similar size. The analysis was done in 1985 and the 5 years to 1990 came out almost exactly as calculated then, in spite of the numerous events that might have had an influence.

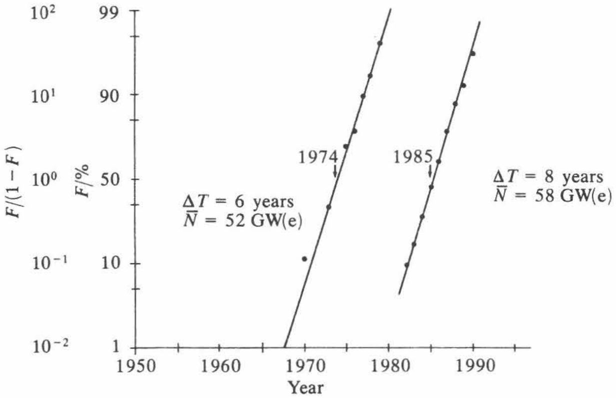


Figure 4. Connections of nuclear power to the grid for the USA. They come in two pulses and the second pulse saturates in the 1990s. These pulses are useful in identifying a connection between events linked to nuclear energy, such as media coverage. Incidentally, the two pulses have very similar saturation points and time constants. They are spaced by 11 years at the central point ($F = 0.5$ saturation). The second logistic sits on top of the first, so that the total final power installed in the USA during the present Kondratiev cycle will be $52 + 58 = 119$ GW(e) (asymptotic value). The present (1991) level of nuclear power plant connected to the grid in the USA is 102 GW(e). Source: Marchetti (1990).

3 Nuclear energy and the media

Let us now look at the interest of the media in the subject of nuclear power plants. In the USA the media are routinely monitored for their content and consequently we can afford detailed quantitative analysis over a long time series. I think that media reporting is also a good measure of public interest and public opinion. In order to survive in the hard competition for readers (and buyers) editors have to have sensitive antennae on what people want to hear. This means to perceive their opinion. I have analysed coverage by TV, dailies, and the periodical press (Marchetti 1990). In this paper we will concentrate on the last, as it provides a more long-term balanced view.

The counting of articles related to nuclear power comes from the *Readers Guide to Periodical Literature*(1) and in spite of the vast base over which the statistics are done, it should be considered a sample. On the other hand, as we will see, monitoring a single journal can be enough to track the trends. The result of the analysis of the periodical-press coverage in the USA is reported in figure 5a. From a taxonomic point of view it is very curious that again we have two pulses, practically identical, with an eight year

(1) *Readers Guide to Periodical Literature* is published by H W Wilson, Bronx, New York.

time constant and with the center-points spaced 7 years apart. However, they differ strongly in the number of articles at saturation, with 255 for the first pulse and 1200 for the second.

If we compare this media coverage with the actual connections to the grid (figure 4), the taxonomic link is not very strong, apart from the double-pulse characteristic. On the other hand, most of the fuss comes when the decision to start building a new reactor is taken and the construction of the object per se is, for the journalist and for the public, a much more important item than the actual power of the machine, which is an important subject only for the specialist. The analysis of the cumulative number of nuclear power plant construction-starts in the USA is reported in figure 5b. Again, we have two pulses and the taxonomic link with the periodical press coverage is now striking. Construction-start pulses have their center-points seven years apart (as for the periodical-press coverage pulses) and construction center-points precede by five years the center-points of press coverage (1967 → 1972, 1974 → 1979). The only difference is that the press coverage is spread over a longer time than the construction pulses (8 years versus 4 years). For direct comparison the construction-start pulses and the periodical-press coverage pulses are reported together in figure 6.

Although this fine meshing is not a proof per se, the suggestion that the noise of the bulldozers activates the collective imagination much more than the actual operation of the reactor seems inevitable. In order to give the reader more elements to construct an opinion I present a similar analysis for Germany (FRG). The long-term coverage of nuclear energy problems by the German periodical *Der Spiegel*, measured by the cumulative number of articles on the subject, is given in figure 7a. Long term

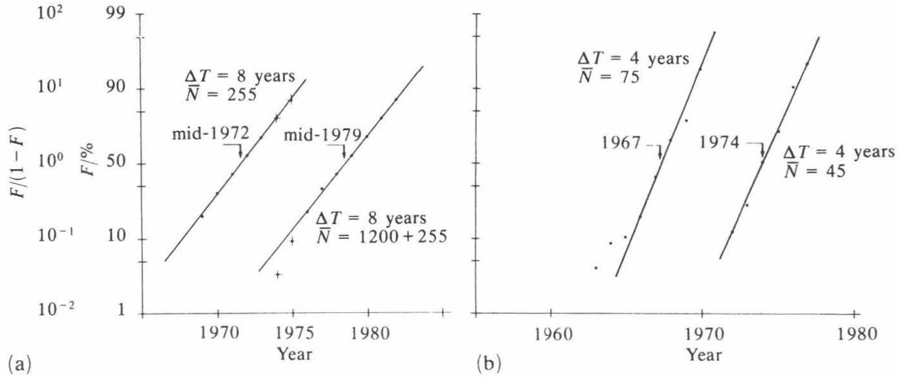


Figure 5. (a) The coverage of the nuclear energy problem by the US periodical press can be measured by counting the number of articles per year on this subject. This is done routinely in the *Readers Guide to Periodical Literature*. There are also figures for TV stories and the daily press which I have analysed (Marchetti 1990) but not reported here. The chart shows a fit with logistic equation (see Appendix) of the cumulative number of articles in the periodical literature ($\overline{N}$) and shows two pulses clearly delineated, one centered in 1972 and the second in 1979 with, respectively, 255 and 1200 articles at saturation. The time constants are identical with a ΔT of 8 years. Such precise matching of contingent phenomena, such as magazine articles, to long-term envelopes is remarkable and is not a result of large-scale aggregation—it also works for a single magazine as we shall see in the analysis of *Der Spiegel*. The two pulses are morphologically identical and spaced 7 years apart. (b) The two pulses of reactor completion and connection to the grid are mirrored in the cumulative construction-starts ($\overline{N}$) reported in this chart. Also in this case we have two pulses morphologically identical, with a time constant of 4 years and spaced 7 years apart, as in the press-coverage pulses of (a). Thinking that the reactor per se interests the public and the press, and not so much an 'abstract' entity such as the GW(e) installed, we counted here the cumulative number of reactor construction-starts. Source: Marchetti (1990).

means that short bursts of articles, which are in the analytical indexes under special keywords like Chernobyl or Three Mile Island (TMI) have been subtracted. We will come back to these bursts in detail as they show the taxonomy of the emotional reaction of the system to a major accident. A fit of the long-term coverage of the subject again shows a neat adherence to the diffusion paradigm. The fitting logistic is centered in 1979 with a time constant of 10 years.

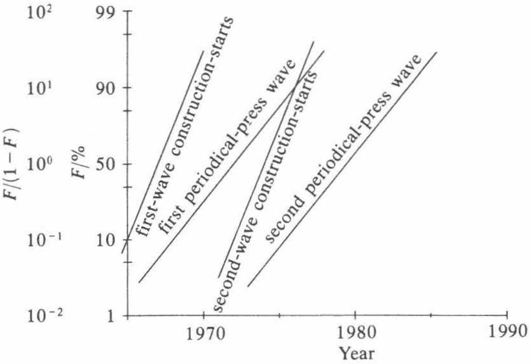


Figure 6. The charts of figure 5 are superposed to show the 'resonances' between ground-breaking and paper-printing activities. The press waves follow the construction waves with a delay of exactly 5 years for both construction waves, and have time constants twice as large in both cases: 8 years ΔT for the press wave versus 4 years ΔT for the construction-starts. Although this is not a proof of a cause-effect relation, it provides hard evidence for a study in that direction. The figures are not exhaustive but cover more or less the same journals, so they are comparable. In the first wave 75 reactors got 3.4 articles each, in the second 45 reactors got 26.7 articles each.

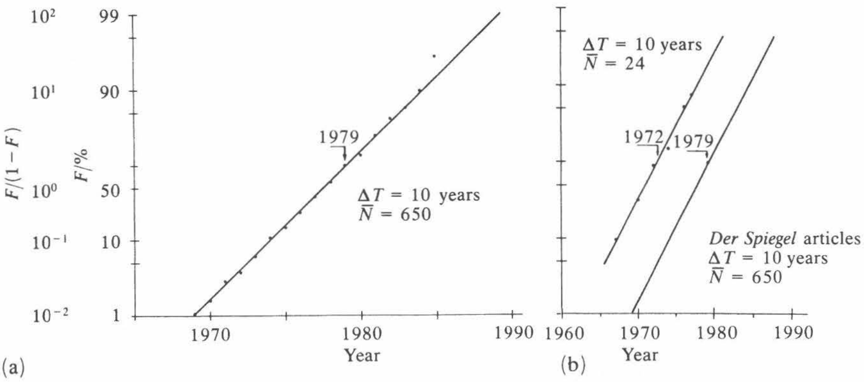


Figure 7. (a) The exercise of relating press articles and reactor construction-starts is repeated for Germany, counting the articles from a single magazine, *Der Spiegel*. The count was done with a subtraction of a couple of 'spikes' (ie 76 articles) such as the ones connected with Chernobyl, easily separated owing to their very short time constants of a few weeks (see figure 9b). The long-term interest shows a single pulse with a time constant (ΔT) of 10 years and saturating at $\overline{N}$ equal to 650 articles. (b) Construction-starts of German nuclear plants. A logistic fit centered in 1972 has a time constant of 10 years. The long-term coverage in *Der Spiegel* of (a) shows a taxonomic identity. In comparison with the USA, the distance between the pulses is longer (7 years versus 5 years), but the time constants are the same, 10 years. Germany has only one reactor construction-pulse and one press-coverage pulse. There are about 27 articles per reactor, as for the second American pulse, but in this case from a single periodical. Source: Marchetti (1990).

The construction-starts for Germany (FRG) are reported in figure 7b with the *Der Spiegel* logistic already superposed. In this case the time spread of the starts and of the articles is the same, 10 years (which is the time to go from 10% to 90% of the saturation level). The distance between the center-points of the pulses is 7 years. For the USA it was 5 years. To summarise, it can be said that the media appear to follow the action and do not seem to influence it.

4 The media and the nuclear accidents

If we come to nuclear accidents, the reaction of the media is most interesting. We will examine in some detail the case of TMI and Chernobyl, by counting the number of articles directly referring to the accidents themselves. For TMI, US TV-coverage is analysed in figure 8a and US periodical literature in figure 8b. Note the brevity of the attention pulse, just a few weeks, even in the more thoughtful periodical literature. The reactions to Chernobyl are reported in figure 9a for the US periodical literature and in figure 9b for *Der Spiegel*. Again public interest seems to fade out in a few weeks.

Looking into the sequence of accidents per se and plotting the set of major nuclear accidents in the USA—the definition of 'major' comes from the IAEA—we get the chart of figure 10 showing that they are not random but follow fairly well the usual penetration paradigm. A comparison with the periodical-press coverage of nuclear affairs, reported on the same chart, now shows curious coincidences. The fact that the two diffusion curves are parallel is not a proof of a direct connection. They could only have the same cause. But the fact that TMI, the accident perceived as the largest credible, occurred when the intensity of the press coverage on nuclear energy was at the highest level raises some suspicions. Operators are the main causes for accidents,

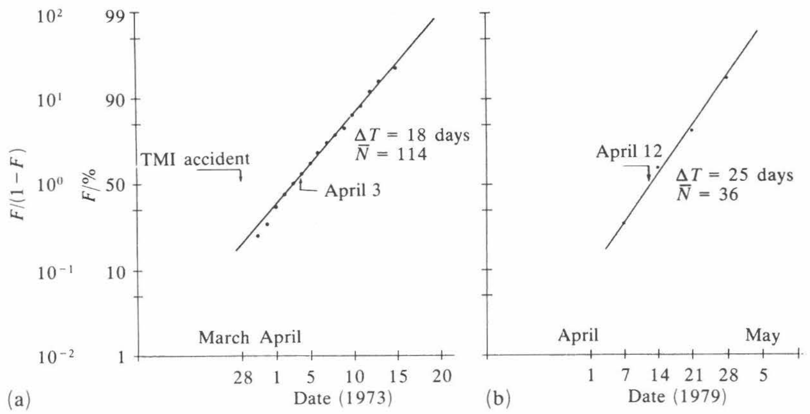


Figure 8. In the imagination of nuclear operators the shock waves of a major event like TMI or Chernobyl will keep reverberating for ever in the minds of people. The media, which in my opinion are the best mind-readers on the market, give quite a different image of the situation. The public does not seem to be able to concentrate its emotion for a long time on the same subject. Even for big events like TMI or Chernobyl the time constant of the attention wave in the periodical press as in the more pervasive TV can be measured in weeks. (a) The chart here shows US TV-coverage on TMI, measured by the entries in the evening news $\bar{N}$. The usual diffusion model fits the data very well. The first day was clogged with reports and in fact this alone accounted for 12% of the total number of reports. If we look at the same phenomenon as reflected by the more thoughtful periodical literature (b), we find very similar results. Here the time constant is a week longer, which is trivial. Clearly, the attention span of the readers was short. Source: Marchetti (1990).

not in the sense that they provoke them, but because they can lose control of the runaway chain of events that lead to the accident. To dominate these chains requires imagination and swiftness of decision. People get nervous when they are under scrutiny, and the press may just channel the emotional load that society directs toward a particular category. That said, we only report these results for further reflection and analysis.

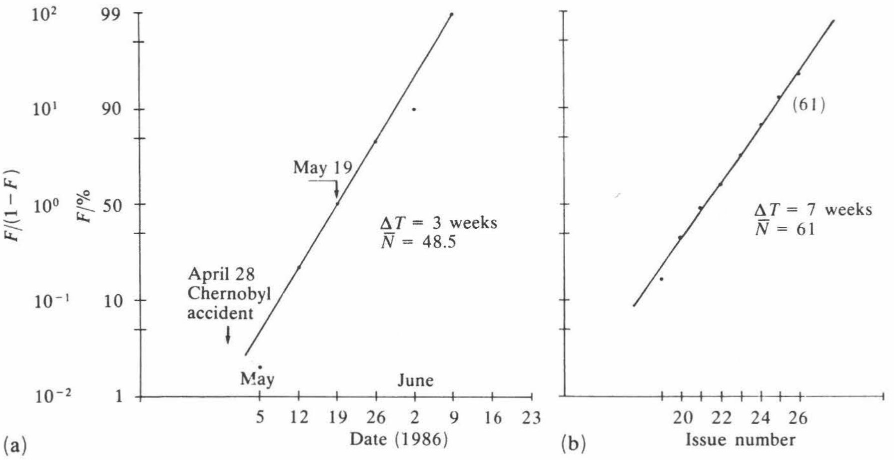


Figure 9. Press coverage of Chernobyl, an event intrinsically much more damaging than TMI, where all the events occurred within the reactor's container, yet with a very similar result. For the US coverage the time constant is 3 weeks and again indicates a brief public-attention-span, even on very tragic events (a). (b) On analysis of the *Der Spiegel* data one finds a longer time constant, 7 weeks, similar to the US coverage. The parallel case for long-term attention of the press on nuclear facts is reported in figure 7. Source: Marchetti (1988).

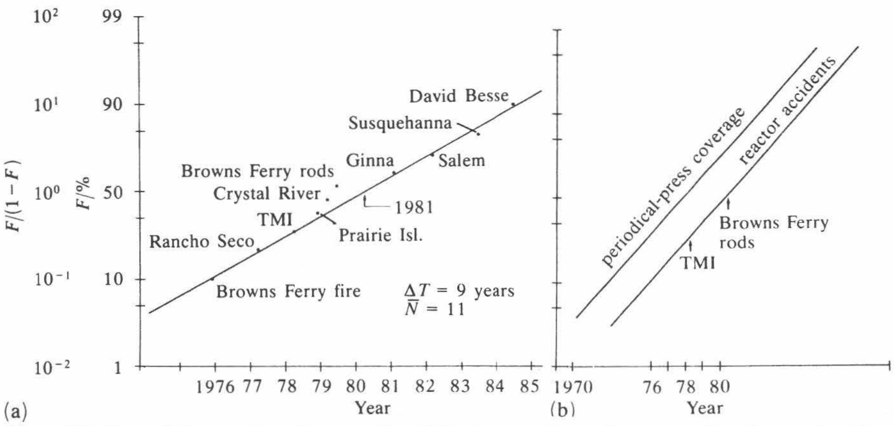


Figure 10. One of the most curious results of the taxonomic analyses was the observation that nuclear accidents do not seem to be random (a). Their cumulative number ($\bar{N}$) can, in fact, be fitted with a logistic, giving the series precise functional connotates. We find a time constant of 9 years and a central point in 1981. This particular behaviour is characteristic of an epidemic. It might be some kind of attitude that spreads between operators. The pressure of public opinion as measured by the media shows strange coincidences and parallels with this epidemic (b). To give an example, the maximum conceivable accident as perceived by the media was the TMI accident. It occurred at the center-point of the wave of attention of the media, when public opinion pressure, as mirrored by the media, was at its maximum. Source: Marchetti (1990).

5 Nuclear energy and Kondratiev

The next step of our analysis will be in the direction of clarifying why all construction of nuclear power plants has come to a practical standstill. As the case of Germany shows, opposition to nuclear energy appears a poor candidate. The connection-to-grid curve of figure 3 is a splendid example of self-consistency. All evolution is coherent with a logistic deployment in view of a given saturation point. The same can be said for all countries we have examined (figure 3b). The single countries are moving consistently with the world mean to saturation in the 1990s. The discordant lines refer to the USA, which has two pulses, but as we said before, the second saturates again around 1995. People opposed to nuclear power could say that the world is a single object, and the antinuclear dogma has become effective everywhere. The sad point, however, is that almost every productive activity is going to saturation in the 1990s, from steel production to air traffic to car ownership, and will lead the

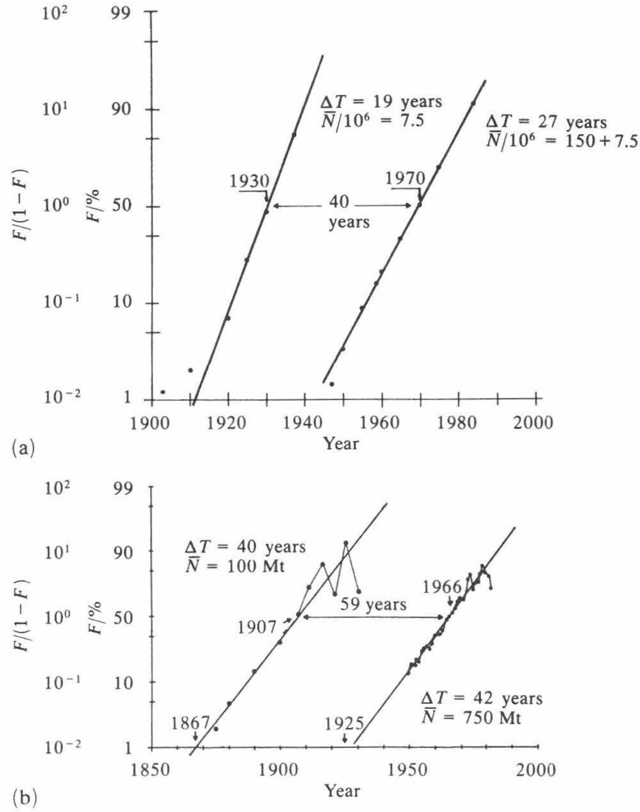


Figure 11. As I have shown in previous work, the Kondratiev cycles pervade all of society. What happens is that most markets saturate toward the end of the cycle (formal reference dates for the end of the last two are 1940 and 1995). The phenomenon can easily be identified in a study of, for example, the possession of a certain good, or the production of a certain commodity. The case of car ownership in Europe during this decade is shown analysed in (a). The two pulses are sharply interpolated by logistics saturating around 1940 and 1995. The same can be said for world production of a basic commodity, such as steel, shown in (b). The hundreds of cases that we have examined make it highly probable that the present saturation in nuclear plant construction is just an effect of the Kondratiev cycle. Source: Marchetti (1988).

world into a deep recession; to attribute all this catastrophe to nuclear opponents would presumably give them too much credit. The economy of a general theory makes it more reasonable to try and find why or how everything is going to saturation, and add nuclear power plants to the batch.

In the mid-1920s a Soviet economist, Kondratiev (1926), trying to interpret the downturn of world economies in the 1880s and again in the 1920s, proposed the idea of a long (about 55 years) economic cycle with expansive economy during the first half of the cycle, and the other half with reflective, recessive, and possibly depressive economy. His theory has had a troubled history, but it has been recently revived and revalued. In our institute, and with the same kind of taxonomic analysis employed in this article, I examined hundreds of cases of economic activity, showing beyond doubt the existence of these cycles, their synchronisation at world level and the stop-go character of their terminations. These crucial ends can be located around 1830, 1885, 1940, and 1995. As the last two are more interesting for our argument, we report here a couple of cases for exemplification. A larger set can be found in the references (Marchetti 1983, 1988; Nakićenović 1987, 1990; Grübler 1990).

The first case I report is that of car ownership in Europe (figure 11a). The two pulses clearly terminate in 1940 and 1995. The two logistics are in sequence and sit one over the other. The case of world steel production is reported in figure 11b and world air-traffic (in Gt km a^{-1}) (including passengers) is reported in figure 12a. Going to more abstract levels, the cumulative number of laws related to the environment is reported in figure 12b for Italy; a similar behaviour is noted for most US states and

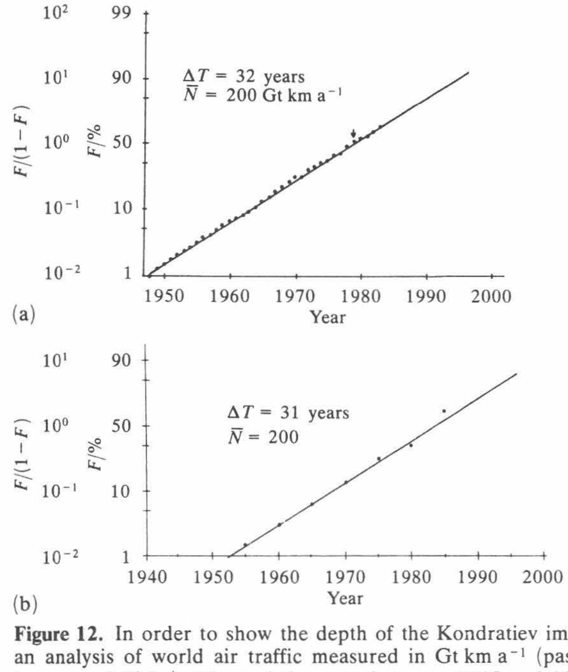


Figure 12. In order to show the depth of the Kondratiev imprint on all sorts of human activity, an analysis of world air traffic measured in Gt km a^{-1} (passengers at a standard weight, with luggage, of 90 kg). The logistic spans between 1945 and 1995 where it approaches saturation. Incidentally, it is remarkable that there is no effect on world traffic as a result of the oil shocks of 1973 and 1979. In (b) a completely different subject is shown: the cumulative number of laws in Italy on the subject of environment. All other countries of the EEC and the USA have a parallel behaviour which shows saturation around the end of the cycle. Source: Marchetti (1984, 1988).

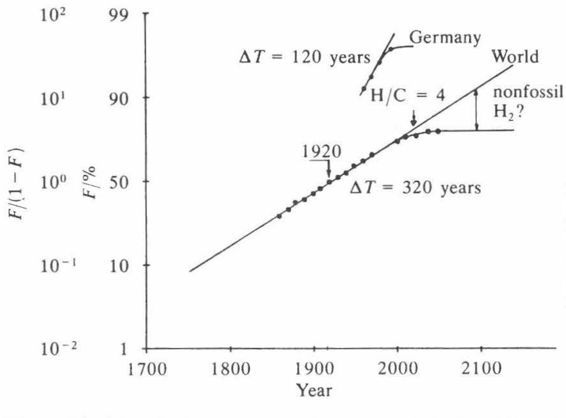
the EEC. Also here the platoon marches in compact ranks to saturation points located in the mid-1990s. The details of the analysis with the inclusion of the data points, suppressed here for clarity, can be found in Marchetti (1990).

The samples reported here, and the larger set contained in the literature, suggest that the slowdown in nuclear start-ups and construction-starts is simply a result of the effects of Kondratiev cycles, a very plausible hypothesis.

6 Nuclear energy and natural gas: a promising synergy

As said before, nuclear primary energy must penetrate beyond the area of electricity production. The logic is simple and clear. On the assumption that asymptotically electricity production will absorb, eg, one half of the primary energy resources, the other half will keep growing, presumably at the rate of 2.3% per year as in the last 200 years (Marchetti and Nakićenović 1979). This means a doubling approximately every 30 years. In other words, the introduction of nuclear energy will serve only to delay, by 30 years, all the problems related to the use of fossil fuels. All that circus to buy 30 years extra time is certainly not worth the entrance ticket.

The only way out of this problem is to penetrate the primary energy market completely or almost completely. There is time for that, but the technical keys to this penetration must be developed now. A glimpse of what the market may demand in the future in terms of fuel quality can be extracted from the chart of figure 13 which shows the progressive movement of primary fossil fuels toward hydrogen. The ratio H/C reported in the figure is calculated by weighting the energy market shares of figure 1 with the H/C ratios for different fuels reported in the chart itself. The bend, when extra hydrogen from water decomposition using nonfossil-fuel energy will be in demand, starts in the 1990s. Our original idea then, and a possible final solution to the problem, will be to use nuclear energy to split water into hydrogen and oxygen—back to square one. In fact, this was the solution that the biosphere found three



Fuel	H/C
Wood	0.1
Coal	1
Oil	2
Gas	4

Figure 13. The historical evolution toward fuels richer in hydrogen is well known, going from coal to methane. Oil refineries raise the energy value of crude oil by producing a spectrum of lighter compounds by distillation and hydrogenation. The evolution toward lighter primary fuels is quantified by a plot of the ratio of hydrogen (H) atoms to carbon (C) atoms [$H/C = F/(1-F)$] during the last 100 years or so for the mix of primary fuels at world level [note $F = H/(C+H)$]. The chart is interesting because it shows a logistic substitution of carbon with hydrogen. If we assume that the trend will continue, even beyond the ratio of 4 characteristic of methane, we must assume the introduction of hydrogen from water-splitting with nonfossil primary energies. The ratios H/C used for the calculation are also shown. The low H/C ratio for wood is because cellulose is not a hydrocarbon, but a carbohydrate where H_2O has weak bonds with the carbon skeleton.

billion years ago when chlorophyll evolved to tap solar light. But now we can use nuclear energy. Hydrogen is an extremely useful and flexible fuel and could be used for almost everything that fossil fuels are being used for now (Marchetti 1973). Sets of chemical black boxes, where one introduces water and heat and takes away hydrogen and oxygen, have been devised (Marchetti 1973) and are under development, albeit at laboratory level, in Germany and Japan. These black boxes operate with chemicals in closed cycles. Their regeneration complicates the flow sheet and loads the costs, but there is a short-term way out of the impasse: a process with relatively limited final capacity but fairly simple chemistry and interesting costs—the reforming of natural gas using nuclear heat with a process developed by Einzelspaltrohr Versuchs Anlage (EVA) at the Jülich Nuclear Center (Barnert 1988).

The process of steam reforming is endothermic and consequently transfers energy from the nuclear system to the hydrogen fuel product. Efficiencies above 50% are achieved with present designs, which can be greatly improved upon when the process is adapted to the peculiarities of the nuclear heat source, the very large size of the plants, and the low grade of purity required for fuel uses.

This reforming can be seen as an open-cycle water-splitting process. In fact, 50% of the final hydrogen in the reaction

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

comes from the feed water. From the energetic point of view, however, only a quarter of the energy in the final hydrogen comes from the nuclear energy, the rest issuing from the oxidation of the carbon atom.

This process also generates, in separate form, CO_2 which is considered a pollutant by ecologists and a valuable raw material by the oil industry where it can be used profitably for tertiary oil recovery. In order to have this synergy of interests in operational form, I proposed at the 1988 Hydrogen Conference in Moscow (Marchetti 1989b) to locate the first natural gas refining facility somewhere in the Western Ukraine, where gas pipelines moving methane to Western Europe converge and where a set of very old oil fields could profit from CO_2 injection. However, locating the plant elsewhere, eg, in Czechoslovakia, and piping liquid CO_2 to the sites may not change the economic attractiveness of the proposal by much. Expanding this refining technology to the gas produced in the world, in a progressive way (up to 50% in 50 years), we should be able to stablise CO_2 emissions at around 440 ppm by 2030 (Marchetti 1989b).

7 HTRs, military plutonium, and natural gas: a possible synergy?

The reactor type most adapted for the reforming of natural gas is the high-temperature reactor (HTR) in any of those configurations which produce hot helium gas at temperatures above 800 °C. This reactor type should have deserved much more success because of its good operating characteristics, particularly in terms of intrinsic safety. But it is known from history that new technologies have the greatest problems in penetrating their potential markets if the old ones are sufficient to match the demand in quality and quantity. The jet engine was invented and patented before World War I, but was implemented toward the end of World War II, when piston engines, then at the end of their technical evolution, could not satisfy the increasing demand in power by heavier and faster fighter planes.

The latest proposal for HTR coming from Kern Forschung Zentrum (KFZ) in Jülich and the German industry was for small power units [300 MW(th)] factory-made and almost absolutely fool-proof. This proposal was probably a reflex reaction to the very emotional demand for nuclear safety, which does not seem really to have much physical basis as nuclear plants to date appear as the form of energy with the lowest specific rate of casualties (coal comes first). But beyond the emotional screen the real demand will be for cheaper nuclear plants, ceteris paribus. The simplest way of achieving lower specific costs is by making the plants larger, naturally respecting all boundary conditions. One of these conditions is to have the technology at hand, obviously, but a more stringent one is to have a market with sufficient spatial density of electricity consumption to avoid excessive transportation costs for electricity. The problem has been thoroughly treated by economists in the central place theory. One of the consequences for electric generators is that their size is precisely determined by the spatial density of electricity use and the cost of its transport, as an analysis of the size of generators in the USA since 1900 clearly shows (Marchetti 1973).

If we remove the limit of distribution costs by placing the thermochemical plant on the same site as the reactor and provide an energy carrier with high transportability, such as hydrogen, then we can remove the limit of a few GW(th) that derives from the present structure of the electric system in western countries. Some years ago at KFZ in Jülich, some configurations of the HTR using toroidal cores and pressure vessels were studied. In these configurations, the power capacity per plant could be up to 100 GW(th) (personal communication). This can be very important for the long-term penetration of nuclear energy into the market of cheap fossil fuels. When the cost of nuclear plants was still transparent, it was proportional to the square root of the plant size (as for oil tankers). Thus, a 12 GW(th) reactor should have a cost per kW of about one half that of a present-day 3 GW(th) reactor. Four such reactors could provide energy for the reforming of 10^{11} m^3 natural gas, which can be considered a ceiling for the present configuration of gas pipelines crossing the area of the Western Ukraine cited in the above proposal (present throughput around 5×10^{10} m^3).

The second quality that makes HTRs attractive is that they can burn weapons-grade plutonium. Now that Russia and other countries are trying to beat swords into ploughs, these HTRs could be attractive incinerators. Incidentally, plutonium from nuclear power plants is also piling up, or stays in the spent fuel rods, with no sizeable buyer in sight.

8 A long-term configuration: the energy island

In the frame of this broad-brush and very long-term description of nuclear energy development it is very natural to look into what configuration nuclear energy (of any description) will finally land. At IIASA we asked ourselves this question about 15 years ago, and we came to a scenario that is still plausible today, a record of durability for a scenario built in the 1970s.

The first constraint is that in the long run we must leave aside fossil fuels. Our technological substitution analysis indicates about 150 years as the final term (figure 14). It also indicates that substitution is not resource driven and that substantial resources will remain in the ground. We have already a good example in that the world's forests keep shedding perhaps 100 TW of biomass, when humanity consumes only 10 TW for its energy needs (1 TW is roughly equivalent to burning 1 Gt of coal per year). And the scarcity in coal was not a drive to move to oil.

The analysis presented in figure 13 indicates an increasing demand for hydrogen-rich fuels that may finally end in the use of pure hydrogen. Space launchers and hypersonic planes are the most obvious uses, but fuel-cell plus acceleration-battery cars, which are in experimental stage at present, may draw more, in terms of quantity. In fact, a detailed analysis of final energy uses showed that hydrogen, if available in a pipeline network, could penetrate efficiently and conveniently practically all sectors of industry and home, substituting in some cases for electricity itself (Marchetti 1973).

So we created a scenario with a dozen energy centers at world level (energy islands) to produce hydrogen for export in liquid form. The primary energy would

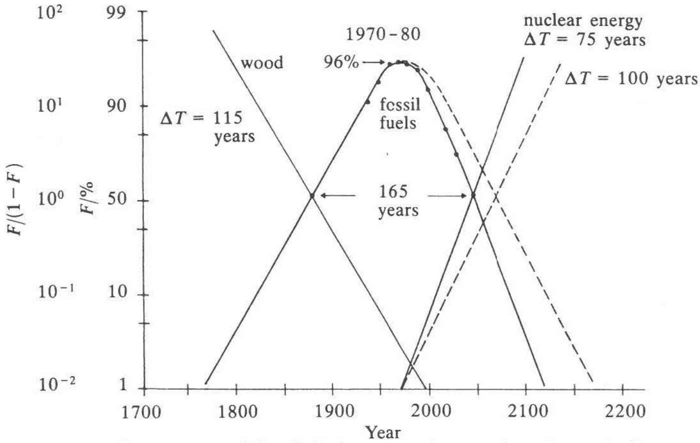


Figure 14. The amount of fossil fuels counted as market shares in figure 1 can be combined to construct the fossil-fuel grand substitution. The only parameter which is open to speculation is the long-term rate of penetration of nuclear energy. The regularities in the penetration time constants of coal, oil, and gas would point to a penetration constant for nuclear energy of around 80 years. Until a more stringent logic to restrict the range of this parameter is known, two values are given, with time constants of 75 years and 100 years. In both cases the time left for fossil fuels to end their cycle will be around 150 years. The total cycle time should be of the order of 350 to 400 years. Source: Marchetti (1988).

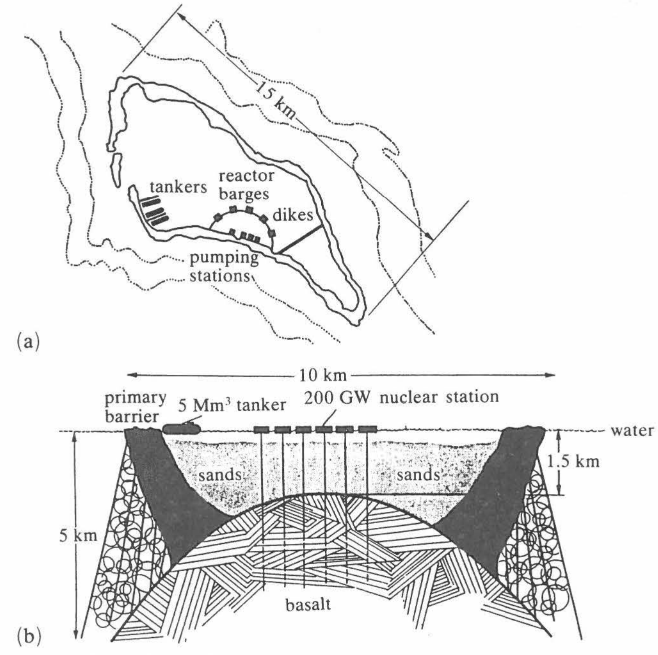


Figure 15. (a) The 'final configuration' scenario envisages an energy island where very large nuclear reactors mounted on barges feed a thermochemical process to decompose water. The hydrogen produced is shipped in liquid form with cryogenic tankers. The cooling water is pumped from the depth where it is cold and released at surface temperature to minimise ecological impact. The figure shows a scheme developed by IIASA in 1978, with the atoll of Canton Island in the Pacific as a container. (b) A schematic cross-section of a typical atoll sitting on a basalt mound. The lines descending under the nuclear stations are sink holes for fission products from irradiated-fuel reprocessing. With sufficient concentration (>30%) of these products in the containers, the decay heat is sufficient to melt the basalt so that the containers can sink to a depth of 10000–15000 m). If the reactors are breeders or quasi-breeders, the cooling water carries enough uranium to refuel them, in fact ten times the uranium fissioned. Recovery can be made with solid absorbers.

come from very large reactors [eg, 200 GW(th)] and the uranium could be extracted from the cooling water. The seawater used for the cooling actually carries about ten times the uranium fissioned in the reactors. The island or even the reactor itself would contain all the nuclear processing and waste disposal machinery. In the configuration shown in figure 15, it would export indefinitely an amount of energy equivalent to that provided by the Middle East at present. This energy island scheme, where we chose Pacific atolls to locate the reactors, geographically decouples populated areas from nuclear plants and permits supreme concentration of skill and high technology, drawn from the whole world.

The hydrogen would then be distributed by pipelines, with the same energy throughput of present-day natural gas pipelines, and be used in a comparable way. For electricity we had two configurations, one where all base-load was covered by a network of nuclear reactors, and the variable load generated locally with hydrogen. The electric network would compensate for all the point pulses of production.

The other way would be to distribute hydrogen and progressively substitute natural gas, the dominant fuel for the next 50 years, and leave the system to adapt.

Conclusions

This discussion, mostly taxonomic, into the evolution of energy systems and the penetration of nuclear energy, leads to a number of simple conclusions:

—Nuclear energy in some form is unavoidable. The rules of the technological game show a promising future as a primary energy source. Natural gas and nuclear energy together will dominate the energy market for the next 50 years.

—The present stop of nuclear construction is linked to the end of a Kondratiev economic cycle.

—The opposition to nuclear energy measured through media coverage shows the classic love-hate ballet of opinion that occurs when a new technology is introduced. It has no effect on the actual outcome (eg, the dynamics of GW of nuclear power linked to the grid in Germany).

—The restart of nuclear construction will come when society moods, modulated by the Kondratiev cycle, will permit the propagation of positive signals. The system should achieve criticality in a few years (the reference date for the start of the new Kondratiev cycle is 1995).

—A long-term final configuration of the nuclear energy system seems to have an attractor that strongly resembles that of the biosphere about three billions years ago. The new machinery of chlorophyll was used then to split water using solar energy. Hydrogen carried the reducing power that ran the biosphere. In our case we propose the same thing but with the use of nuclear energy. Sunlight seems too dilute for human society's energy needs in general.

Contrary to what has been said during the last 20 years, the destiny of humanity will not be determined by an energy scarcity. Energy availability is only a problem of ordered development.

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APPENDIX

Mathematical methodology

The mathematics used in this analysis is extremely simple. The basic concept, that action paradigms diffuse epidemically, is condensed in the epidemic equation:

$$\mathrm{d}N = aN(\overline{N}-N)\mathrm{d}t\,,$$

which states that the number of new adopters ($\mathrm{d}N$) during time $\mathrm{d}t$ is proportional to the number of actual adopters (N) multiplied by the number of potential adopters ($\overline{N}-N$), where $\overline{N}$ is the final number of adopters and a is the constant of proportionality.

The integration of this equation gives

$$N = \frac{\overline{N}}{1+\exp[-(at+b)]}\,,$$

which is the expression of a logistic S curve well known to epidemologists and demographers. We apply it to ideas.

In the diagrams in this work the logistic equation is presented in an intuitively more meaningful form. N is measured in relative terms as a fraction of $\overline{N}$ (ie $F = N/\overline{N}$), and the S curve is 'straightened' by plotting $\ln[F/(1-F)]$ (Fisher-Pry transform).

$$\ln\left(\frac{F}{1-F}\right) = at+b\,.$$

The time constant ΔT is the time to go from $F \simeq 0.1$ to $F \simeq 0.9$. It takes the central part of the process (80%), and the relation between ΔT and the a in the equation is $\Delta T = 4.39/a$. The central date T_0 is defined as b/a. The final number of adopters, $\overline{N}$, is given in the figures.