The Long-Term Dynamics of Energy Systems and the Role of Innovations

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1. Innovation: A Driving Force or a Driven Force?

I am personally an innovator, and it would be reasonable to expect me to say innovation is the mother of progress. But I am also a systems analyst turning stones into the history of things. It is clear that no innovation can propagate if the "times are not ripe", i.e., if there is no demand in the context. As we will see in the case of the electrical system, the main driving force for innovation is the increase of spacial consumption, kW year/km^2 or something like that. More in general, this is also the case for primary energies. Certainly there is also the drive of "better if cheaper" but this leads more the refinements in conception and production than to breakthroughs.

Electric consumption per capita is still increasing even in the richest economies like the US, and world population is imploding into the cities. These dense human settlements will then be the hotbeds for nursing innovations like cryocables, zero emission power plants and dispersed generation, jut to quote what comes first to my mind.

2. The Innovation Waves and the Kondratiev Cycle

Most of my work during the last 20 years is based on the assumption that the dynamic of our social and economic system is due to the injection of innovative ideas, be them organization schemes or clever machines, which diffuse progressively into the system following an epidemic course. As many studies on the detailed mechanism of innovation acceptance show, acceptance comes basically through personal contacts like the diffusion of flu, and a similarity in the mathematical equations should then be expected (see Appendix). In 20 years of research at IIASA my colleagues and I have analyzed about 3000 cases of diffusion, and the paradigm works beyond expectation, even when one cannot imagine a person-to-person contact mechanism behind it.

In 1979 I examined the case of basic innovations as described by Mensch in his book *Das Technologische Patt.* He dates the start of an innovation by the time the object was first marketed. Mensch observed that basic innovations do not trickle down all the time but they come in waves. I tried to analyze these waves assuming they were diffusion processes and the result is given in Fig.1. I am the first to say that it is not clear what diffuses as every object in the list is a different one. Perhaps what diffuses is the more abstract idea that the times are ripe to accept innovation. Seen through the model, the system appears incredibly organized. Over tens of years new innovations come up in perfect tune. No trace here of "Genie und Unregelmäßigkeit".

This organization refers to the internal structure of each wave. But also the set is organized. The central points of the waves when innovation is at a maximum are spaced about 55 years apart. This is not due to chance. If we observe the deviation from the secular trends of primary energy and of electricity in the USA, we find the same 55-year periodicity (Fig.2). Energy is a synoptic indicator of social activism and a straight connection can be done with the ups and downs of Fig.2 and the ups and downs in the *rate* of growth of Western economies as described by the *Kondratiev cycles* quantified in the Twenties by the Russian economist Kondratiev. The raising branches in Fig.2 can be associated with periods of economic boom, and the descending branches with periods of recession and depression. Incidentally, the lowest point is in 1995.

If we locate the centerpoints of the basic innovation waves on the energy consumption synewave we find an interesting synchronization (Fig.3). These centerpoints lie 2 or 3 years before the minima. In other words, innovation is activated during recession and reaches its maximum when things go worse. It continues, however, also during the rising branch of the synewave, i.e., during the first part of the boom. The introduction of these innovations in a way or another *leads to a reorganization of the productive and the social system* as Schumpeter has clearly stated in the Thirties and the Forties. However, as the Bible already observed, human mind is very viscous and these revolutions move at glacier speed. A good unit for measuring them is 50 years.

3. Primary Energies as Technologies: Their Penetrations and the Innovation Waves

When in 1974 I was given the task of finding a global logic in the evolution of energy markets for the last two centuries, I solved the problem neatly by de-emphasizing the almost metaphysical importance of energy. I said, let us look at primary energies as various brands of gin competing for markets. The idea is coarse but it works (Fig.4). Primary energies penetrate the energy market and go out of it in elegant orbits of outmost mathematical simplicity. Only two parameters are necessary to introduce one. Adding the rules of interaction the system is set. For a century ahead. Human minds are viscous as the Bible said. The description of the primary energy market through a sequence of diffusion bouts, incorporates the technological improvements linked to the use of certain primary energies, but gives no hints about the basic innovation of introducing a new one. In the Twenties, scientists predicted that radioactivity may become a source of energy for humanity, but nobody dared to say when and guessed how.

Primary energies seen as a basket of new technologies should obviously be classified as innovations. So a comparison between Fig.1 and Fig.4 may give some new information about the introduction of new energies. They are superposed in Fig.5. It is clear that every innovation wave holds in its basket a new primary energy. The innovation lines represent starts of diffusion and the primary energy lines represent actual diffusion into the energy market. Oil, gas, and coal, on the other hand, were known since antiquity. The technologies of extraction and processing were to a point known, but their markets were minimal. Being difficult to insert them properly into the innovation waves using Mensch's definition, we can take 1% penetration of the market as an arbitrary but indicative date for the start. We can then state that *primary energies are introduced very early during each innovation wave*, for the three cases examined. We may take this as a heuristic rule and see what happens.

4. Who is Going to Come Next. Nuclear Fusion as No.1 Candidate. When Will μ-sion Come?

Nuclear energy can be quantified in Mensch's terms because there is a No.1 commercial reactor. On the other hand, the present wave of innovations can be calculated using the internal regularities of the three basic invention and innovation waves that are described historically by Mensch. These forecasts are reported in Fig.6 up to the year 2100, i.e., with three extra innovation waves. I must say I have found traces of 55-year cycles since 1500, i.e., for 500 years. Going 100 years ahead is not so daring after all. The first observation is that *nuclear energy* commercial start-up *fits well with the start of the present innovation wave* calculated using our rules (Marchetti, 1980). This is encouraging. According to the chart in Fig.6 the next innovation waves will start around 2025 and 2080. What can we guess as primary energies to be started commercially at such dates?

The first prejudice to be dealt with is that the change is driven by exhaustion. This was a thesis very popular at the time of the oil shock. Fossil fuels are on the verge of exhaustion, let us use solar energy which is meant to last another few billion years and keeps flowing like river water in any case. It seems obvious in retrospect that oil was not introduced because of a scarcity in coal and gas because of a scarcity of oil. It must be clear that world forests are shedding about 100 TW in form of biomass when humanity is consuming *now* about 10 TW of primary energy. In spite of the numerous sarcastic comments one can offer, however, Greens and otherwise serious professionals still stick to the idea.

My hypothesis is that economy of scale is the driving force. Because the technologies linked to a certain primary fuel have different economies of scale, when total consumption and *spacial density* in consumption increase, the technologies with higher economies of scale are favored. It looks reasonable then that fusion which has a very high economy of scale would be favored against solar which has almost none. The date 2025 ± some years comes down from the metaphysics of system selforganization. In such cases it is good to look for converging (or diverging) estimates. Speaking with my colleagues working in the area of fusion I got very converging estimates about *when* fusion power plants may become commercial and so I stick to 2025 as a reference date waiting for new arguments to challenge it.

In a first approximation electric generator size grows with the level of consumption. In a finer approximation it grows faster because higher spacial consumption provides the market for higher capacity, i.e., higher voltage lines. Transport becoming cheaper, the generator then "sees" a larger area. Let us say in 2025, 5 GWe generators may fit well the system.

About 20 years ago I started circulating the idea that hydrogen may run parallel to electricity in transporting secondary energy (from nuclear). Because hydrogen has higher transportability than electricity (on top of storability), fusion generating stations making electricity *and* hydrogen may well have powers up to 100 GWth. *So the engineers designing fusion reactors may have free reins concerning size.*

As we have now taken some familiarity with metaphysics, we can ask what next. Meaning what kind of primary energy may come into the picture around 2080. In 1980 I was giving the "Gregory lecture" at CERN in Geneva, telling the physicists there that they should start thinking to repay society for the extravagant expenses in fundamental physics by inventing some new way of milking energy from more or less elementary particles. A voice from the floor said: "If only protons were a little more short-lived". I caught the ball saying that the long life or uranium had not been an obstacle. Clever physicists invented a "*catalyst*", *the nuclear reactor*, to shorten it. And it could be shortened so much as to make bombs. Coming to brass tacks a laser can be seen as a catalyst to shorten the life time of excited atoms inside a cavity, and the laser represents a very general concept. If somebody in his spare time will concoct a very shrewd machine for lasing the decay of protons, he and humanity will reap enormous benefits.

5. The Electrical System and Innovation: Energy Density as the Driving Force

Electrical energy started its penetration through two applications:

- Illumination via electric arcs first and then filament lamps. Special effects could be reached thanks to the high temperature reached by the emitting bodies.
- Transmission of mechanical power via generator and motor. The servitude of beams and pulleys was eliminated.

The second application was in my opinion the most revolutionary one as *aggregating primary movers* and *disaggregating the secondary ones, brought to a complete spacial reorganization of the mechanical power system in our society.* Penetration was slow. As usual it took about 50 years as the market substitution chart of Fig.7 shows for the USA.

Prime movers were water, right from a medieval tradition, and steam. Total production of electricity at world level can easily be plotted for the last 100 years using the diffusion model (Figs.8a and b). Splitting is necessary because the Kondratiev cycle does not spare electricity. Almost everything comes in pulses of 55 years as I said. The second pulse is about 13 times larger than the first one. And *á propos* Kondratiev, the end of the second last cycle was around 1885. The *innovation called* *electricity* came with the wave associated with that recessive period. The primary movers, water and steam, can be separated looking at the electricity generated at world level using water power (Fig.9) and fossil fuels (Fig.10). Also here the effect of the Kondratiev cycle is evident: in both cases the two pulses are neatly contained in the time boxes 1885–1940 and 1940–1995. These sets of pulses have internal regularities that permit in some cases robust forecasting as for the innovation waves we have seen in Fig.1. Because the success of new technologies depends on the general context, an effort to forecast it, at least in terms of envelopes, could pay off well.

6. On the Voltage of Trunk Lines and the Capacity of Generators

As I said at various points spacial density of use is the independent variable that moves the technology of the system, both stimulating it and braking it through the selections the system operates. I will show now some of the results of the analysis I have made for the USA. The choice of the area is uniquely due to the fact that long-term statistics were lying on my table collected in the precious book: *US Statistics from Colonial Times to 1970.* As my experience shows there should be no problem in doing the same for the various European nations. The evolution of total electric generating capacity and maximum voltage of trunk lines are reported in Fig.11. Inevitably there is a split in two waves of growth related to the Kondratiev cycles. The second one fits well into the cycle. The flex point, 1970, when growth was maximum coincides well with the central point of the cycle, 1968 (middle point between 1940 and 1995).

The previous wave of growth displaced forward (1927 vs. 1913) because it started late into the cycle (begun in 1886). However, it saturates correctly around 1940 as the second wave around 1995. A third wave should be centered around 2025 and saturate in 2050. There is still room for growth for electricity consumption obviously at world level, but also in developed countries highly electrified like the USA.

In the exponential phase of US electrical system growth, consumption doubled every seven years and generator size every 5 years. Expansion of electricity consumption will call, during the next cycle, for generators beyond 1 GW capacity, perhaps up to 3 GW or 4 GW. This would create a context favorable to cryotechnologies or to superconductivity at higher temperature. On the other hand, the technique of steam turbines may hit into physical limits in generating such powers in one or two units and feeding it into the generator. This may pave the way to a breakthrough in technology in terms of, for instance, plasma dynamic generators. The use of fusion machines as primary energy sources, may give the occasion.

7. Where Is Consumption Density Going? The Case of America

Spacial consumption density is the primary driving force as said before, and we may give a glance to its possible evolution. To the increase of spacial consumption the first contribution comes from the specific increase in consumption, and then from the densification of human settlements. Cities tend to range their sizes in a fractal sequence, both at world level and at the level of the USA. The increase in size is driven by the corresponding increase of the hierarchy of functions and made possible by the transportation technologies. The city "wall to wall" has the size of one hour travel time. It was 5 km at the time of Traian's Rome, and it is about 40 km (one hour by car) in the case of Mexico City. With the same spacial population density of imperial Rome, Mexico City will move toward 50 million people. When the Japanese will realize the Maglev Shinkansen (joining Tokyo to Osaka in one hour), we may witness a 100 million people city. These concentrations will foster all sorts of new technologies, both for transporting and distributing electricity. Cryocables at various temperatures and capacities come straight to mind.

Also transportation per se can become mostly electric. An archeological machine like the Paris Metro carries about 4 10^9 passengers per year. Maglevs – silent, smooth, speedy, very frequent and under total computer control – can become the dominant form of city transport and also substantial consumers of electricity. That quantity is not difficult to estimate as every citizen travels about one hour a day, mean, and if the Metro system is cleverly done, about half of that will be on the metro.

In my exploration of future systems, I also considered the possibility of using Maglevs in a Constant Acceleration (and deceleration) Mode (CAM). This requires operating under vacuum or reduced pressure as proposed by the Swissmetro engineers. I got some fun out of tickling Bonn bureaucrats who do not like to move to Berlin, by proposing a 5m/sec^2 CAM that would link Bonn to Berlin in 10 minutes. Or, by the way, Casablanca to Paris in 20 minutes, helping to solve very sour ethnic problems.

Developing such technology will require the genius of electric engineers, working now in the area of particle accelerators, superconducting devices, space satellites, and fast control. The best configuration for these "trains" is to move into *magnetic buckets* like particles in an accelerator (actually sitting in electric buckets). This will bring the walls of the city quite far away restructuring to a point all the systemic of human settlements. And will draw substantial amounts of electricity into the transport system. I made an estimate for the Bonn–Berlin connection that would require a couple of GWe with about 100.000 passengers/hour top flow. This assuming a regeneration of 90% which would be difficult to achieve with present technologies.

So my view of the future of electricity is bright, for the producers in terms of increasing quantities and penetration, and for the engineers in terms of sophistication. The next Kondratiev (1995–2040) will require the best brains to develop the inventions that the system will require.

8. Conclusion

I hope to have shown – if by glimpses here and there – that the structure of the energy system and technology develop in a tightly bound feedback process. The problem for the engineer, the businessman, and the inventor is to insert himself into the flux of things so as to be able to produce the right object at the right time. Electricity has so many useful qualities, and its use will keep expanding in the future requiring more and more development and striking inventions. The next 20 years are crucial for introducing basic innovation, and the problem is to identify the right ones and pursue them at the right speed. The glimpses in this paper show a methodology that can greatly help in that direction.

Appendix:
The Mathematical Methodology

The mathematics used in this analysis is extremely simple. Because historians may not be familiar with it, we add this note for illustration. The basic concept that *action paradigms* diffuse epidemically, is condensed in the epidemic equation:

$$dN = aN(\overline{N} - N)dt$$

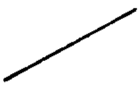
saying that the number of *new* adopters (dN) during time dt is proportional (a) to the number of actual adopters (N) multiplied by the number of potential adopters ($\overline{N} - N$), where $\overline{N}$ is the final number of adopters.

The integration of this equation gives

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

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

In the charts of the present paper the logistic equation is presented in an intuitively more pregnant form. N is measured in relative terms as fraction of $\overline{N}(F = N/\overline{N})$, and the S-curve is "straightened" by plotting $\log(F/1 - F)$ (Fisher–Pry transform).



$$\log(F/1 - F) = at + b\ .$$

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 as a number in parenthesis.

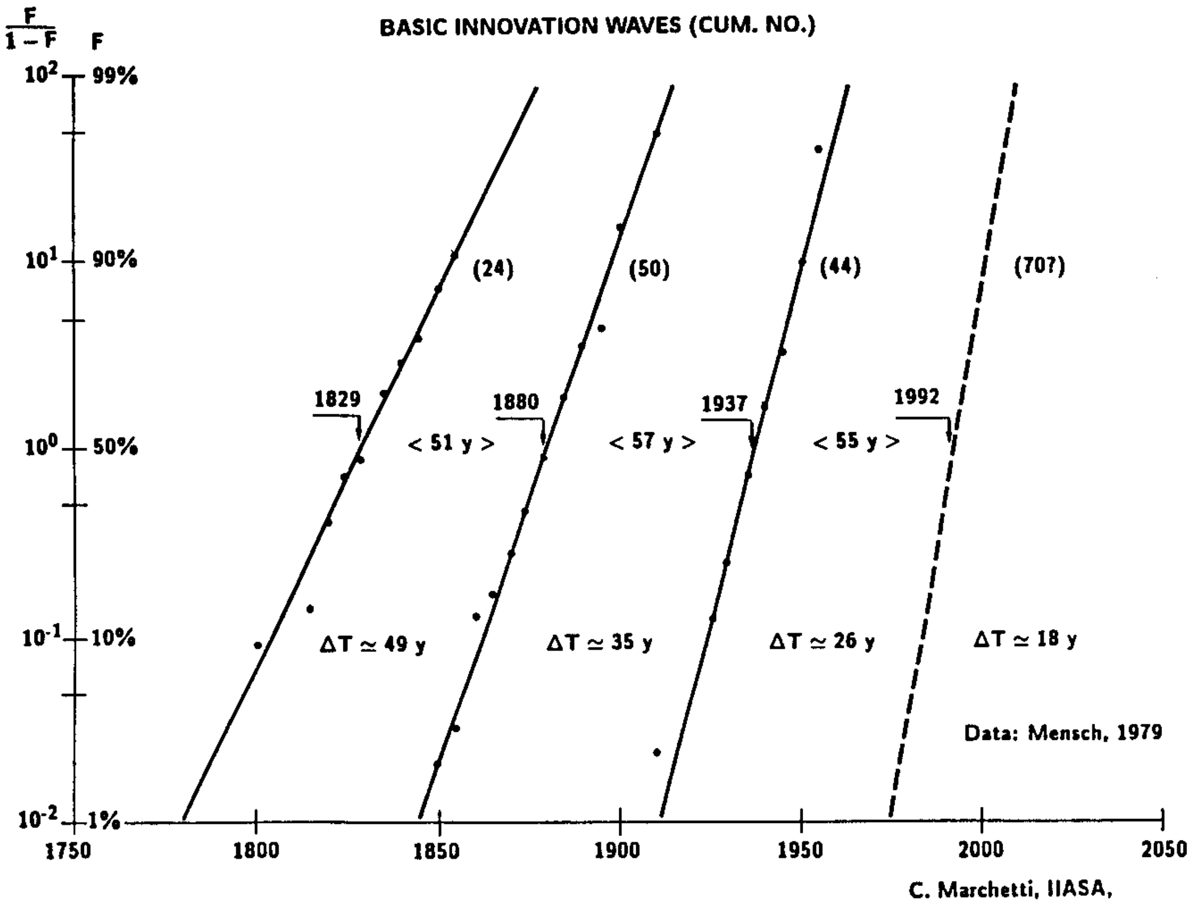


Figure 1. *Basic innovations* are here defined as inventions leading to new branches in industry. The date associated to an innovation is that of the first commercial sale. As said in the text, basic innovations do not come in sparse order but in bunches. These bunches have a high level of internal organization: The cumulative number of innovations can be fitted well with a three-parameter logistic presented here as a Fisher–Pry transform (see Appendix). Furthermore, the centerpoints of bunches or crests of waves are evenly spaced, about 55 years, reminiscent of the long Kondratiev economic cycles.

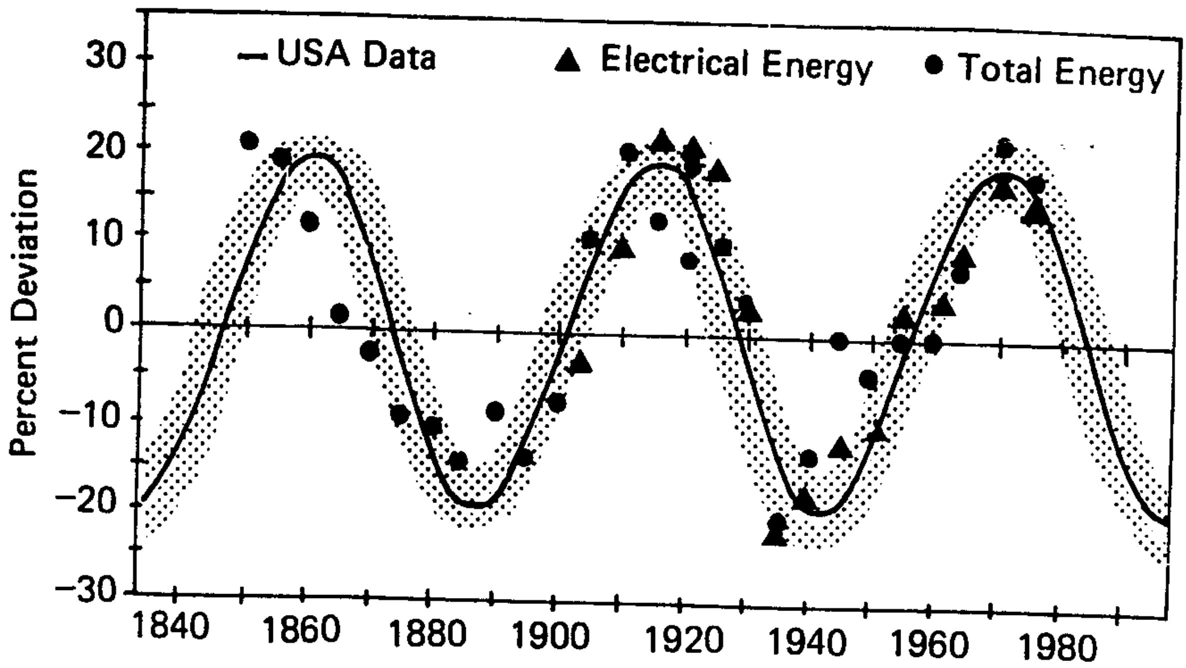
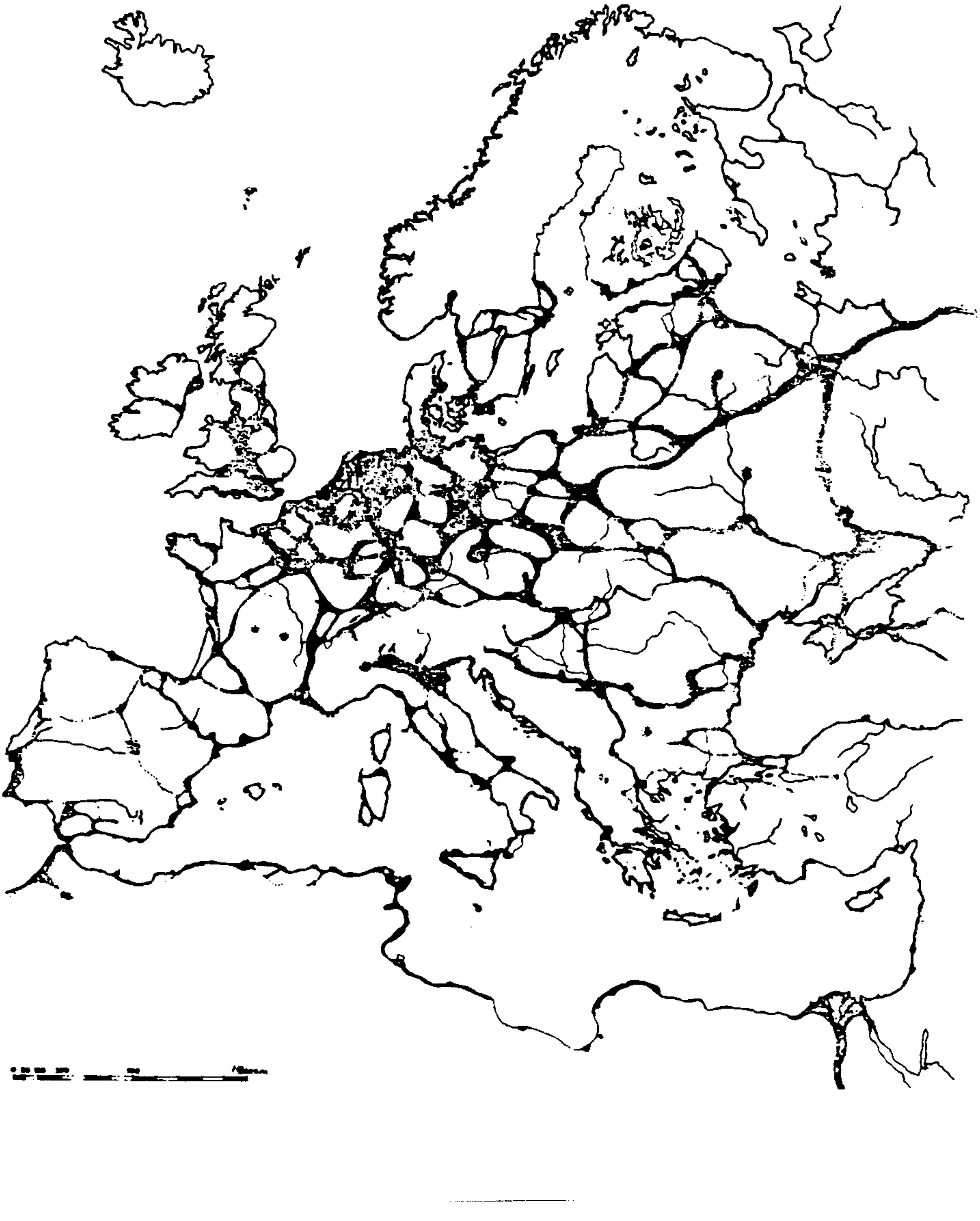


Figure 2. If we take total energy consumption or total electricity consumption, e.g., in the USA, and we try to fit their secular trend with an exponential or a logistic, we find a good long-term match, but with strong oscillations around the trend equation. By extracting the oscillation in terms of percent deviation we obtain a fairly regular sinusoid, here reported, with a period of about 55 years and an amplitude of ±20%. Energy and electricity are very good synoptic indicators or the system's agitation. In fact, the rising segments correspond to boom periods and the descending ones to recessions of various intensities.

ECUMENOPOLIS IN EUROPE



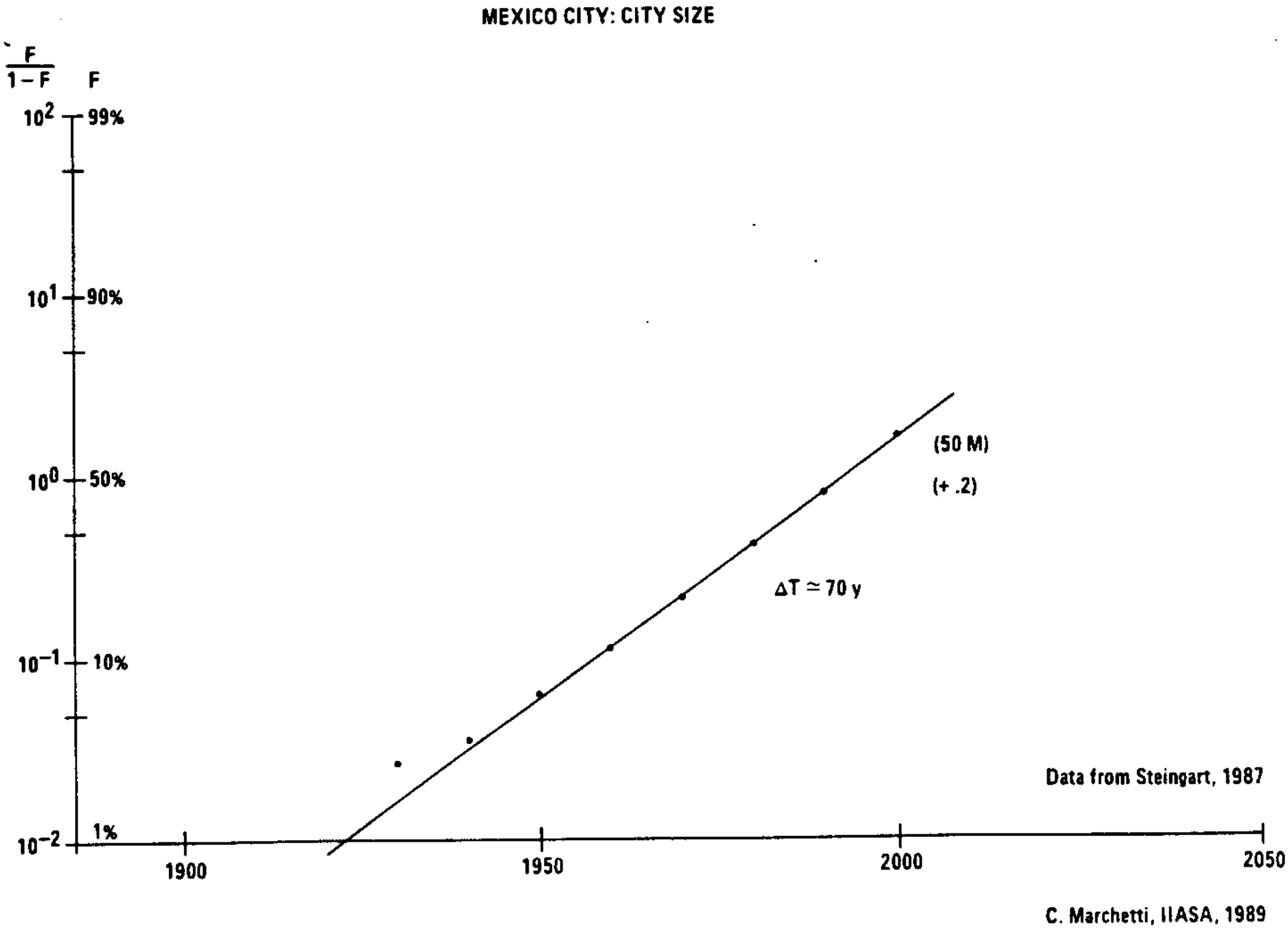
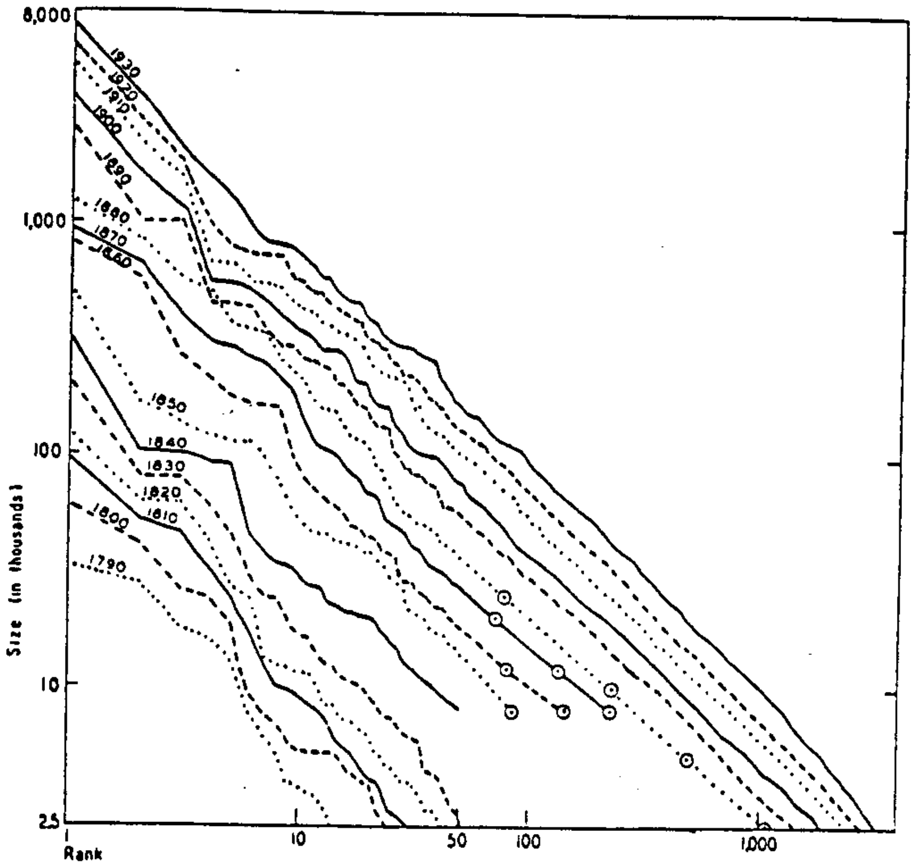


Figure 13. The maximum physical size a city can have depends on the speed of transportation available to the people living in the city. The diameter corresponds to one hour travel with the fastest means of transportation. Ancient cities never went beyond 5 km diameter (the Gürtel in Vienna!), 5 km being the speed of walking. With cars having a mean speed of about 35 km/h inside the city boundaries, we can have cities 50 times larger *in area* than Diocletian's Rome. Assuming the same population density we have the possibility of a 50 million people city. As the chart shows, this is exactly the saturation point of Mexico City. A 50 million people conurbation, with a consumption of 10.000 kWh per year per capita (US is the reference) or 500 10^9 kWh/yr, will create a very interesting problem for the electric company serving this market. Installed capacity would be in the range if 50 GW. Distributed production with *splicers* may here become very handy.



U. S. A. 1790–1930. Communities of 2500 or more inhabitants ranked in the decreasing order of population size.

Figure 12. Ordering US cities in terms of size (Rank Order), their dimensions tend to have a constant ratio, pointing to a fractal filling of space. This ratio remains constant in time. An increase in population tends to produce larger cities at the top Ranks.

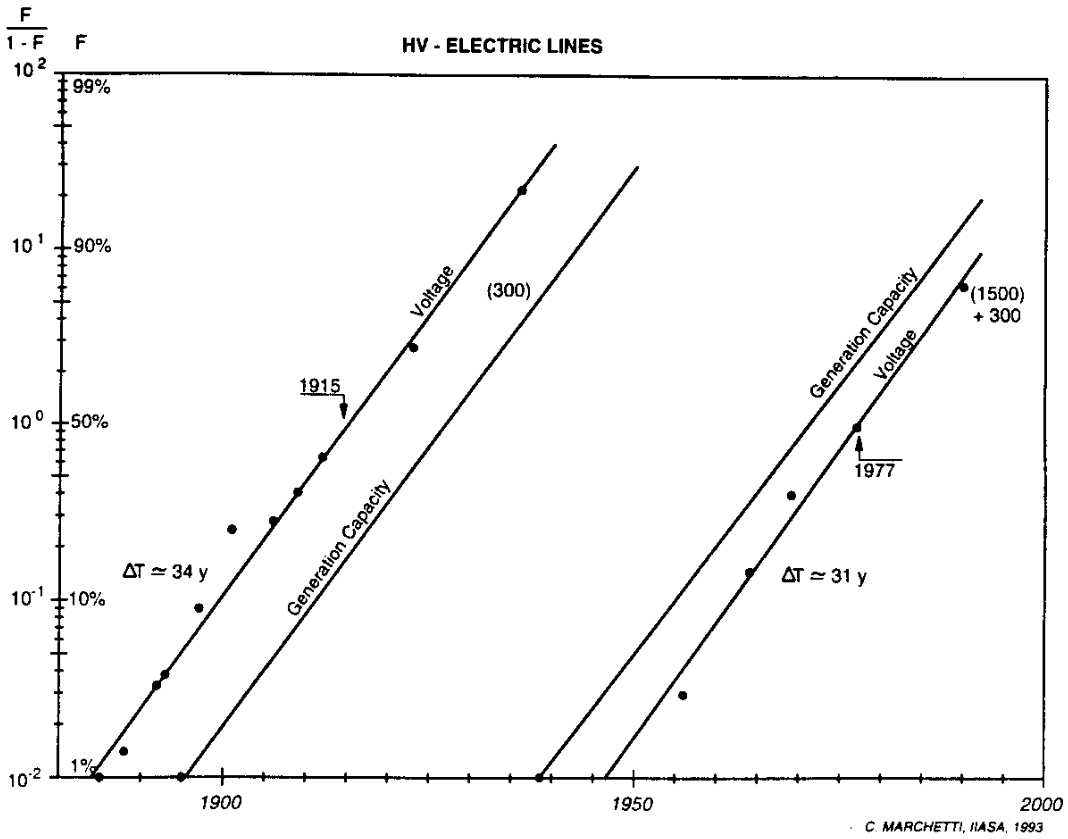


Figure 11. The evolution of US electric generation capacity and the maximum voltage of electric transport lines is reported here. Both can be represented by two logistic pulses of growth. Voltages are obviously a consequence of capacity, i.e., of spacial density of consumption as the areas stay constant.

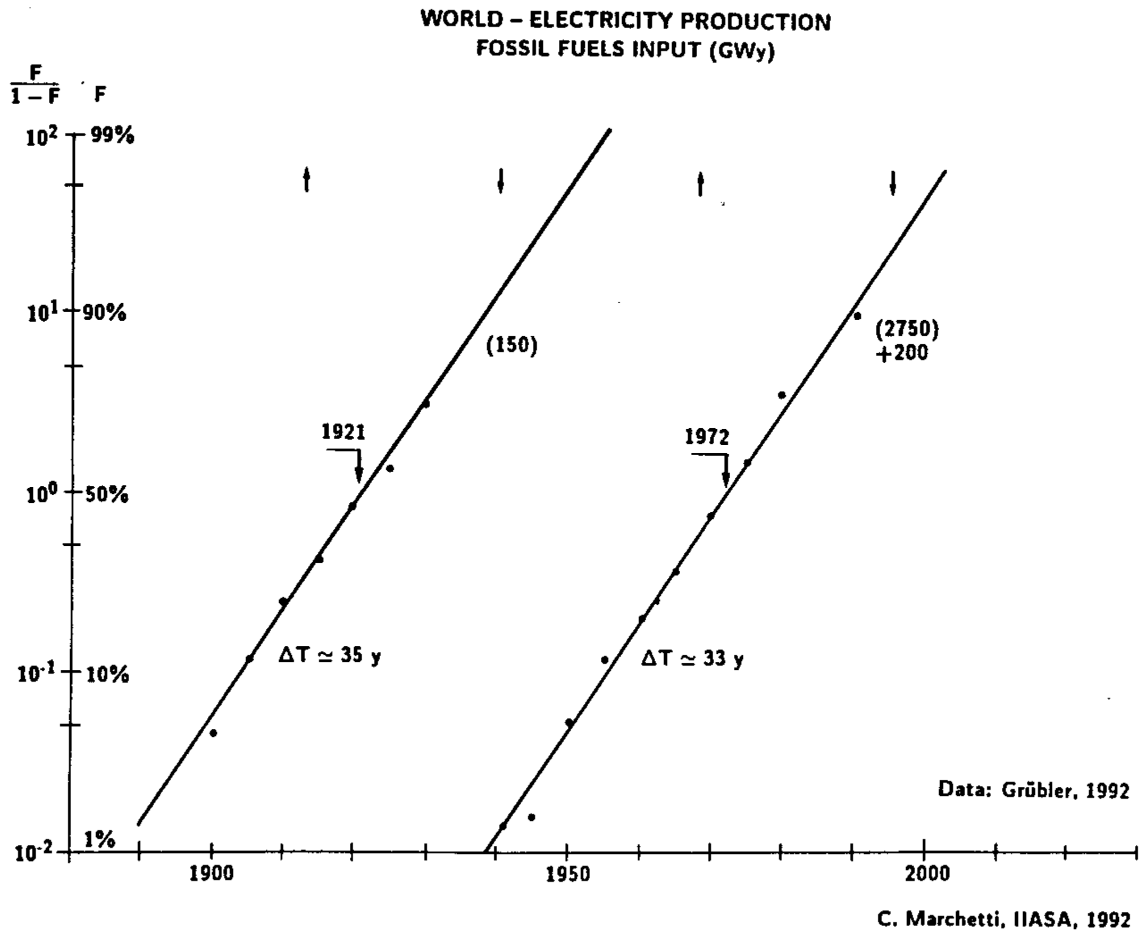


Figure 10. The production of electricity from fossil fuels at world level is analyzed in this chart. It can be modeled for a 100 years with two logistic pulses inserted into the last two Kondratiev cycles.

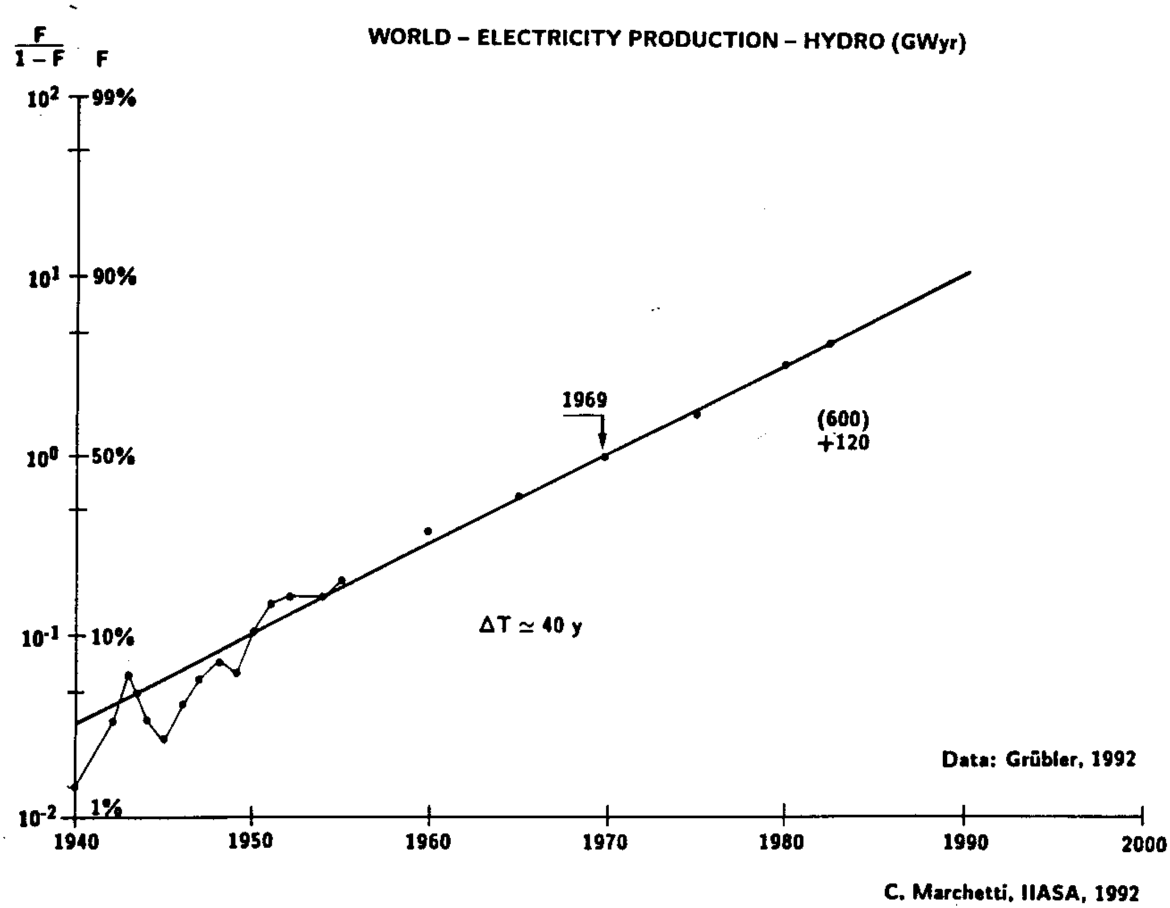
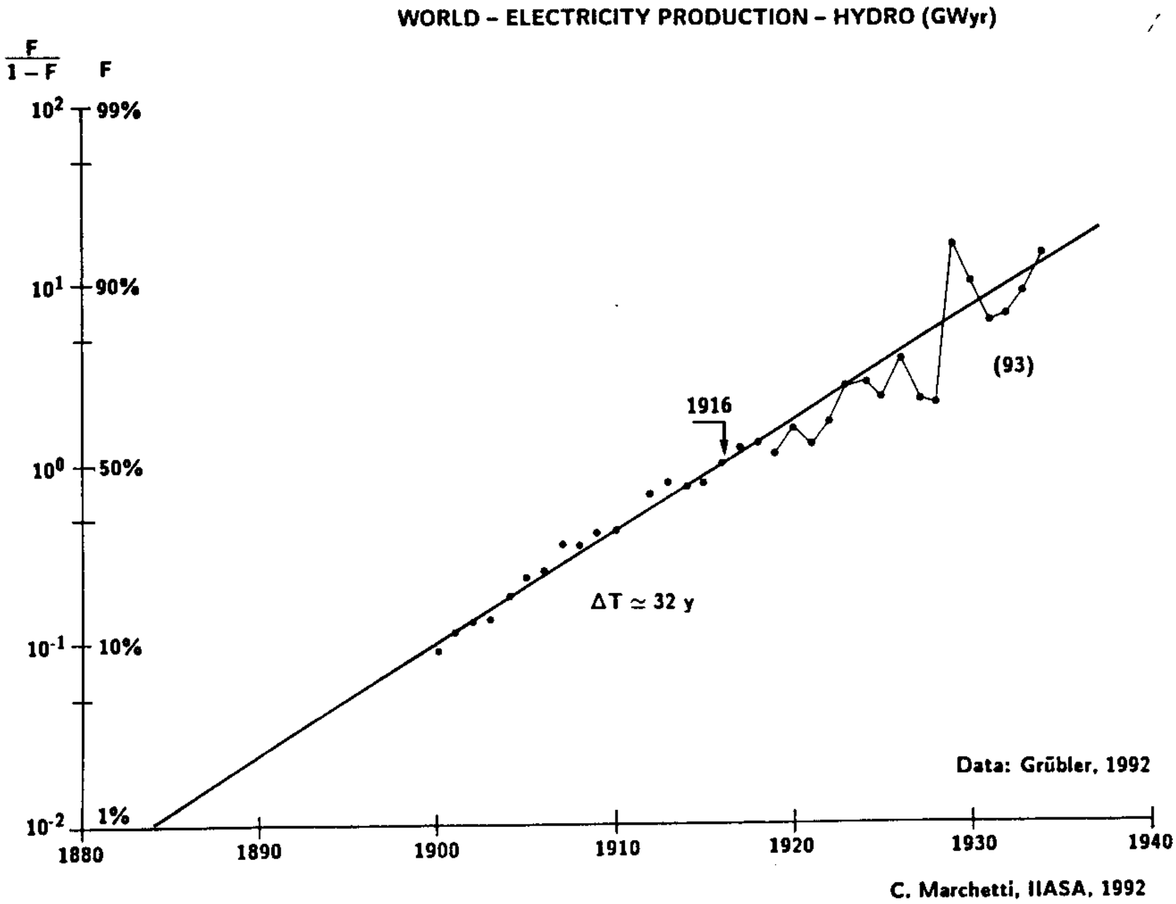


Figure 9b The electricity production pulses of Fig.8 can be split in terms of primary energy sources. We can find here the analysis for water power generation. The double pulse linked to Kondratiev appears also here.



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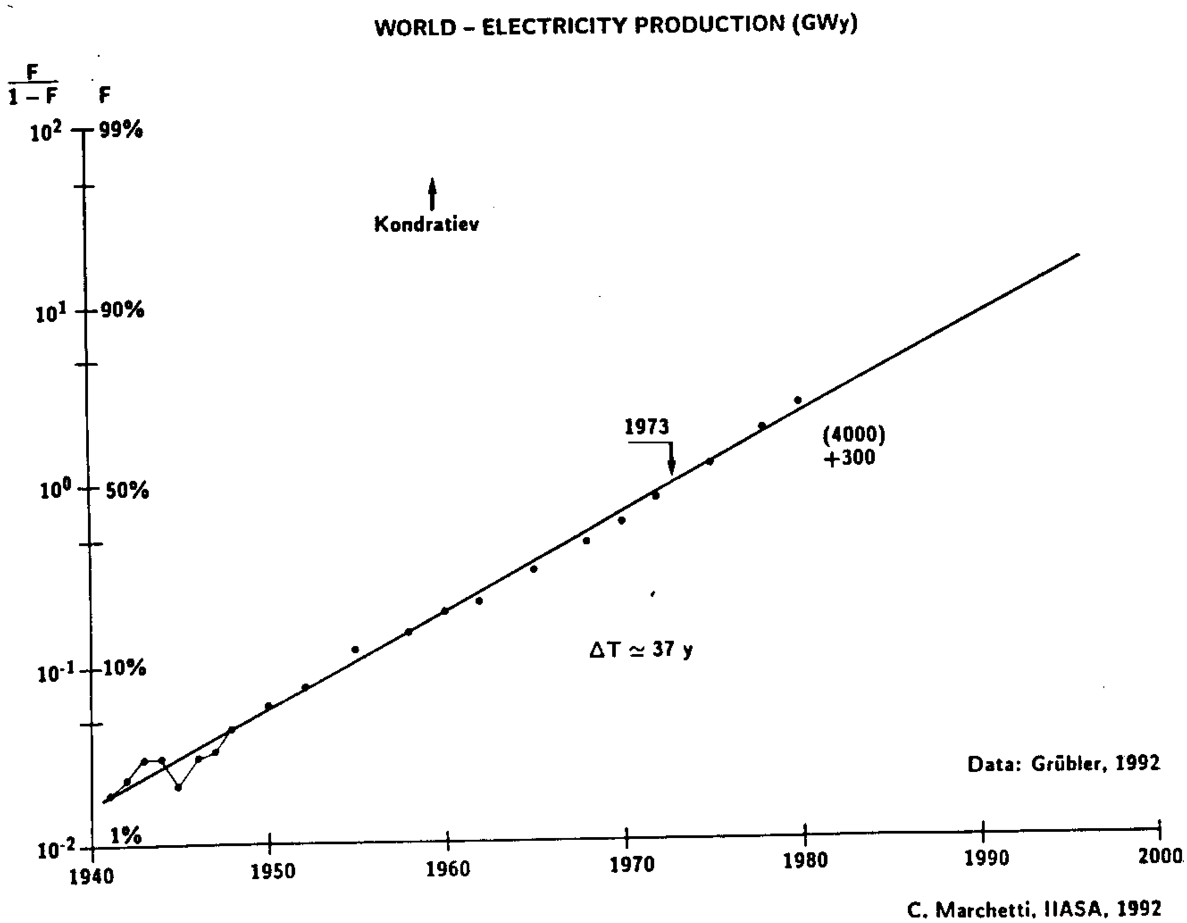
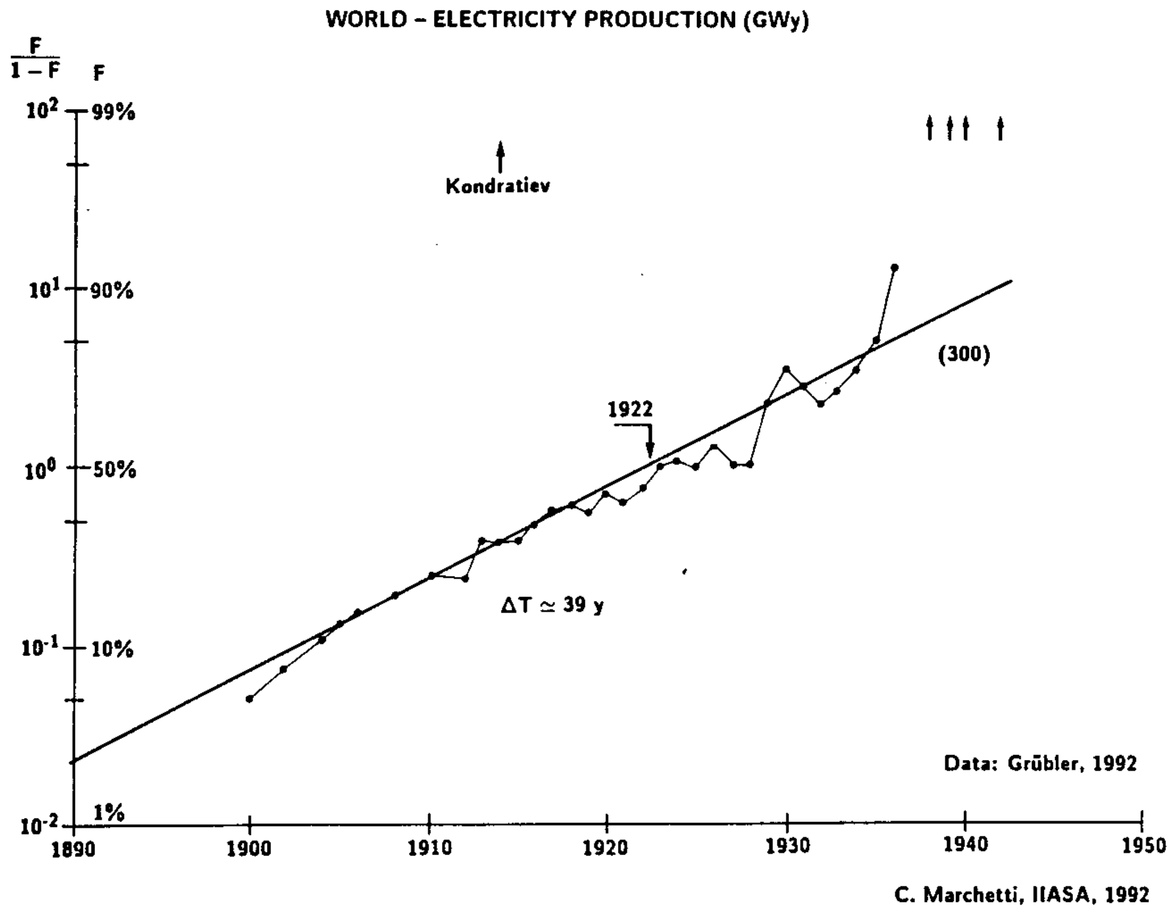


Figure 8b The penetration of electricity at world level is depicted here through two logistic pulses of growth, well inserted into the Kondratiev cycles 1885–1940 and 1940–1985. The second pulse is much larger than the first one. The next may be even larger as so many developing countries (think of India and China) enter into the industrial development game.



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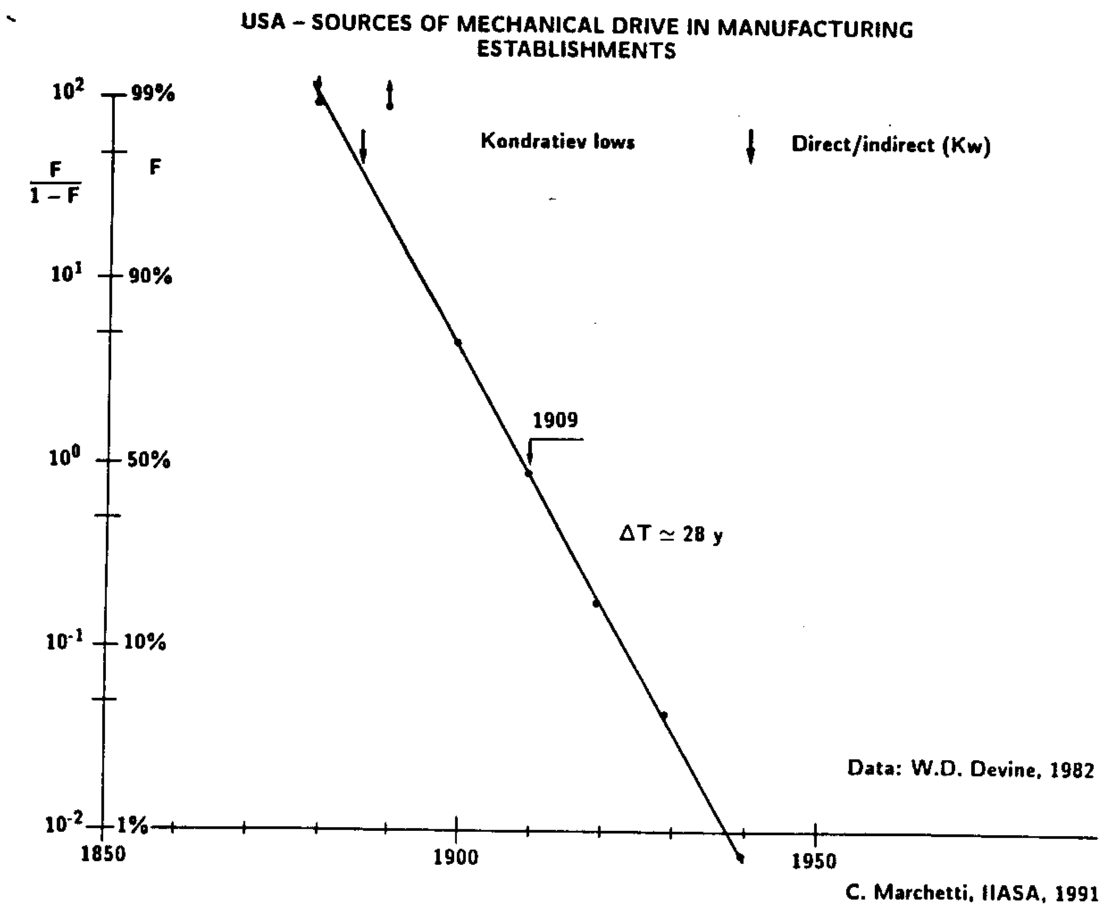
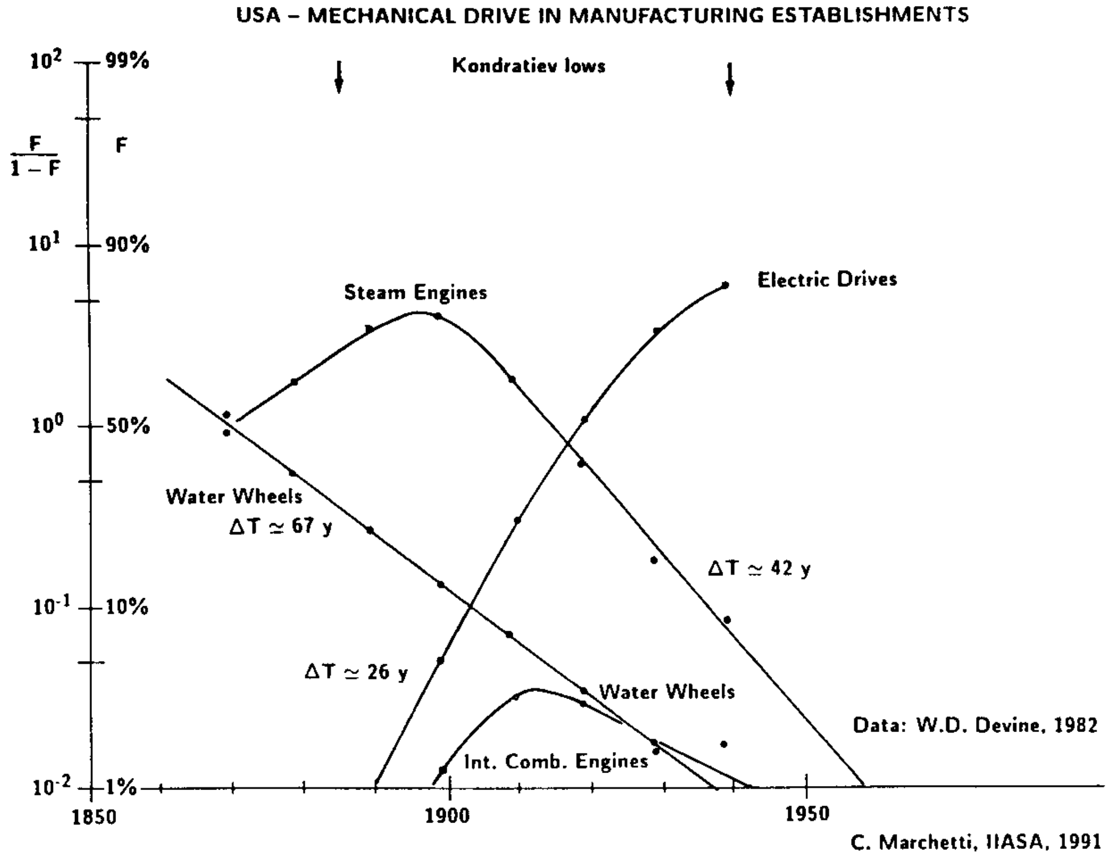


Figure 7b Innovation dynamics in the area of mechanical movers. We start from the medieval hydraulic wheel transmitting energy with connecting rods and pulleys, ending with the electric motor operating the single working machine. Although the last scheme enormously simplifies the layout and the atmosphere of the workshop, it took more than 50 years to completely substitute the previous technology.



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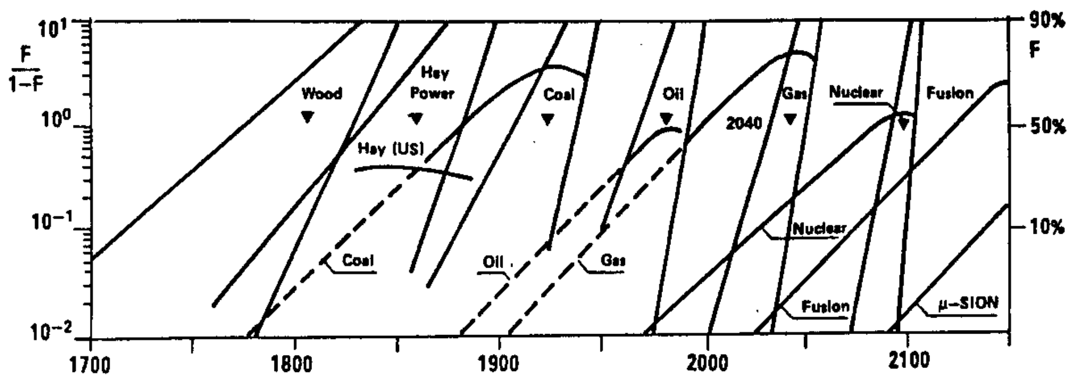


Figure 6. As I have shown (Marchetti, 1980), the innovation waves of Fig.1 have an internal order that permits to calculate the future ones. This is done here up to 2100, adding three waves. If we assume that each wave has a new primary associated with it, we also get the opportunity windows for launching them, and I take the chance of elucubrating about their nature. The first window around 1970 has already been neatly taken by nuclear energy. For the next one, around 2025, there is a good chance for nuclear fusion. The game is open for the window of 2080. I have suggested "elementary" particles as possible candidates for primary energy sources, as a third level of exploitation after chemical and nuclear.

INNOVATION WAVES AND THE START OF NEW ENERGY SOURCES

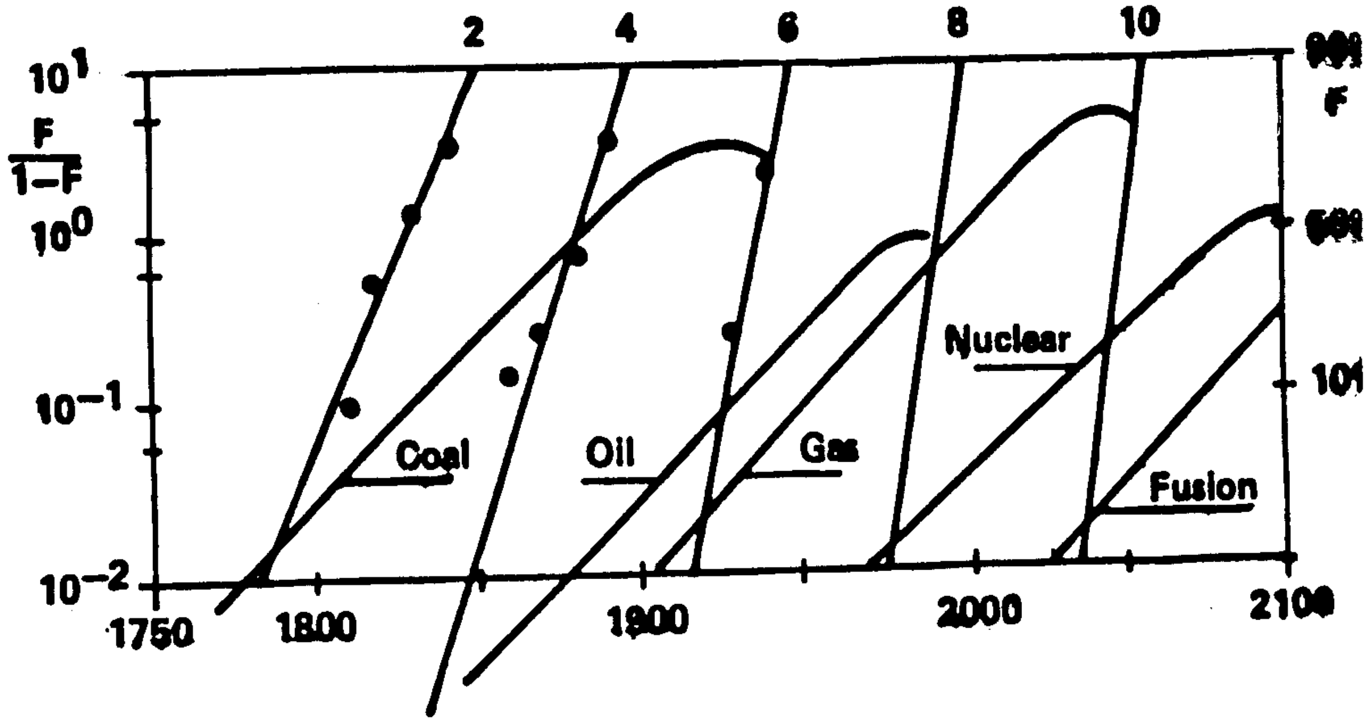


Figure 5. The interlacing between the innovation waves of Fig.1 and the diffusion waves of primary energies of Fig.4 is shown here, reporting only the penetrating branch for the energies. It is clear that each innovation wave has a new primary energy implanted at its beginning.

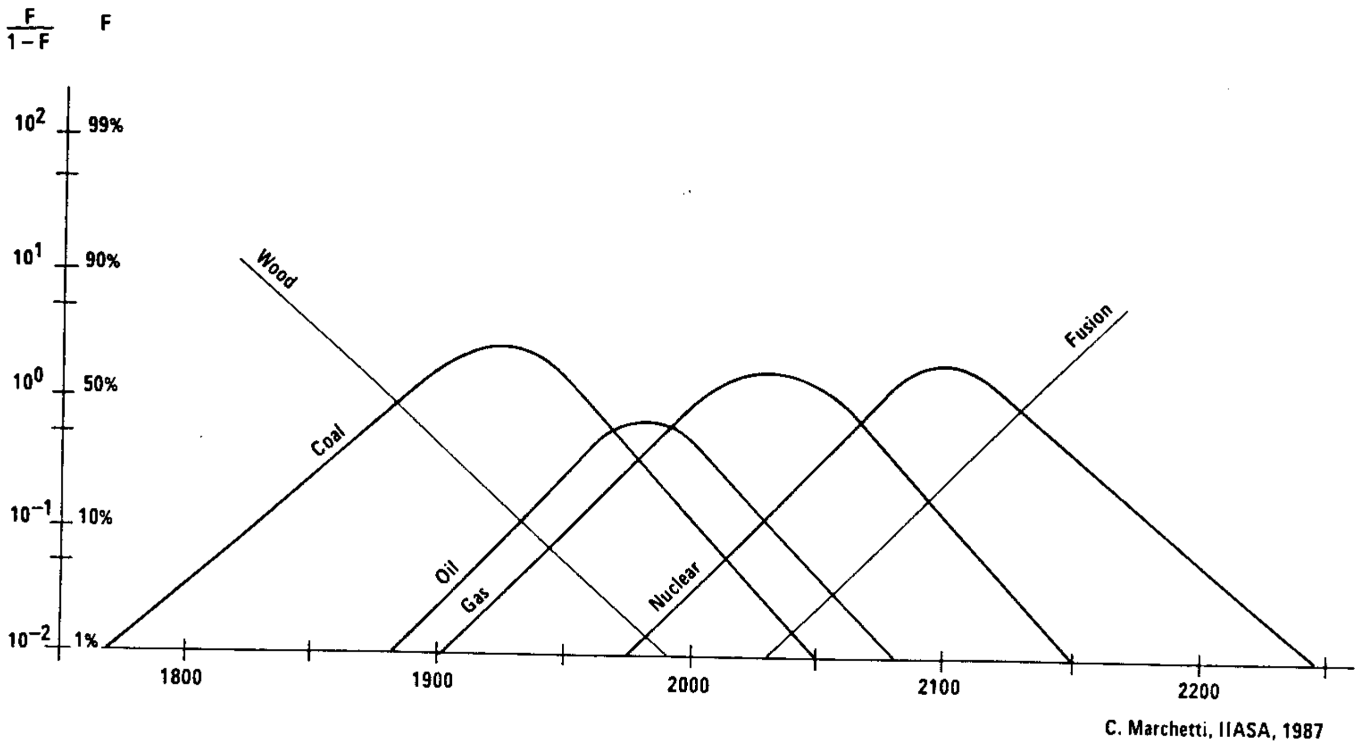
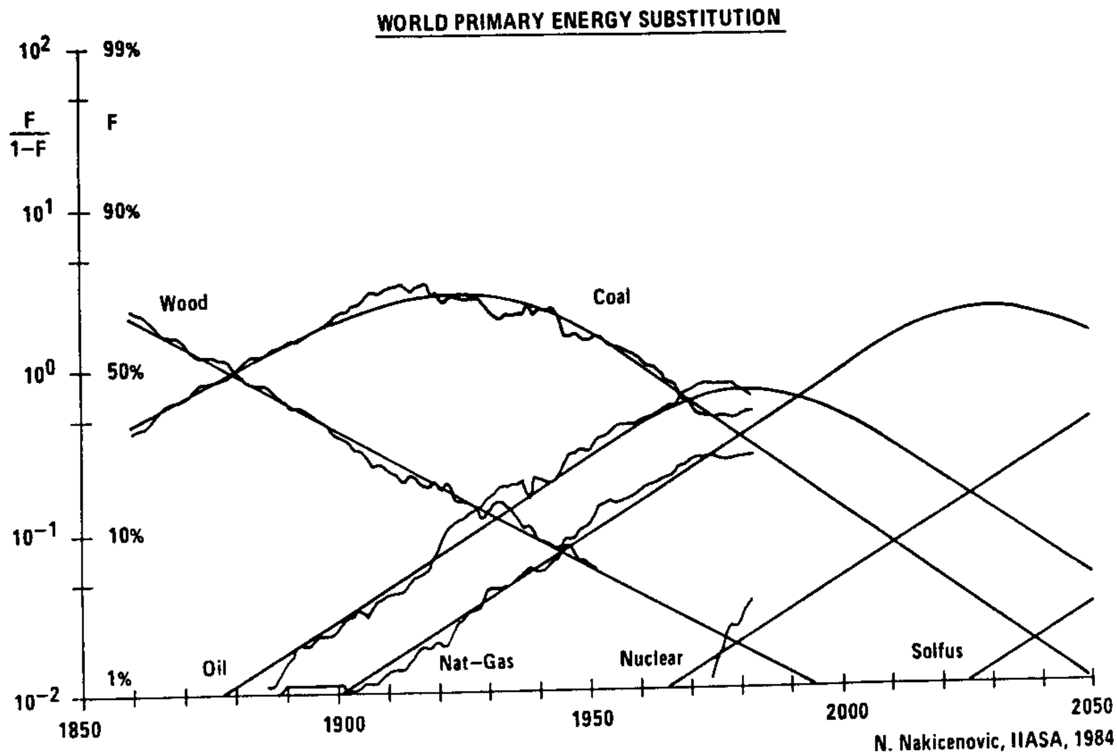


Figure 4b The immense complexity of world energy markets and energy consumption can be reduced to a simple ecological game between "commercial species", by looking at the secular dynamic of market share and market penetration of primary energies. The equations are basically two-parameter logistics. One of the characteristics of the system is the very low speed of penetration of new "energy technologies". A new primary energy can be dubbed this way since it carries a cluster of new techniques for its exploitation. Typically, they take 100 years to go from 1% of the market to 50% of the market.



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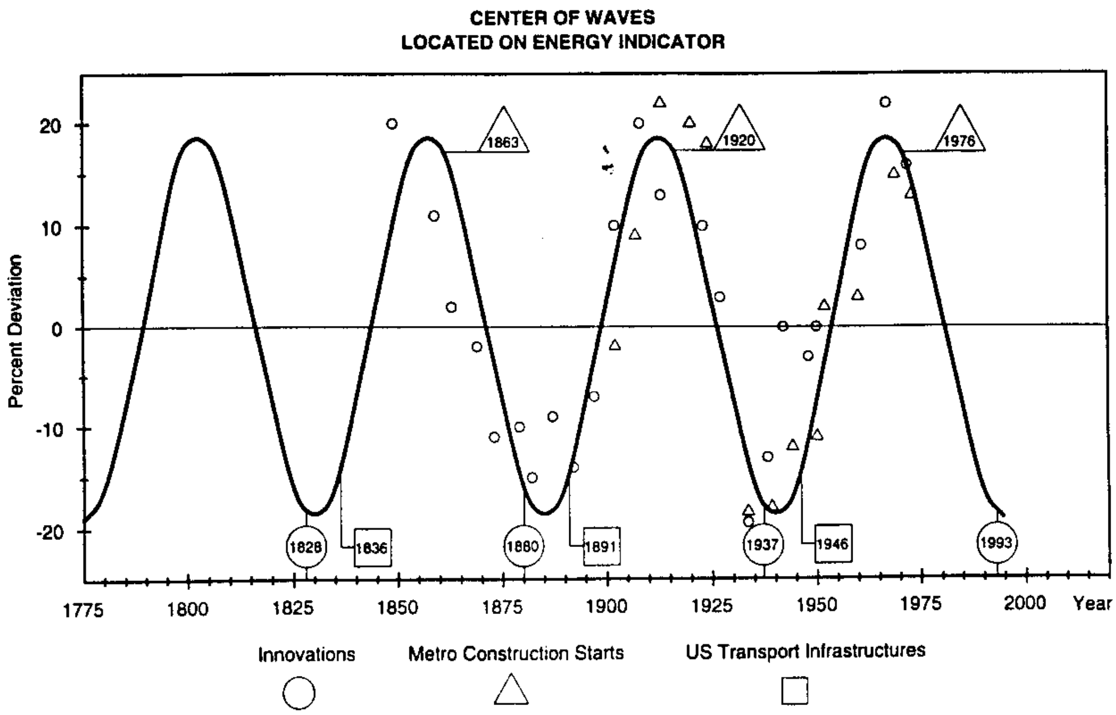

Figure 3. All activities are influenced by this "Kondratiev respiration" of Western economies and specific subsets show synchronization. The case of innovation pulses is shown, reporting here the centerpoints of the pulses. Also the centerpoints of subways start-ups at world level and of transport infrastructures in the USA are reported to show their almost perfect synchronization.