International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report IR-05-005

On Decarbonization: Historically and Perspectively

Cesare Marchetti (marcheti@iiasa.ac.at)

Approved by

Leen Hordijk
Director

January 2005

Prepared for HYDROFORUM 2000
Munich, 11-15 September 2000

Abstract

The possibility that CO_2 emitted as a consequence of burning fossil fuels may have an impact on climate stimulated a lot of research on the evolution of the emissions and the possibility of remedies.

Here we analyze first the evolution of CO_2 emission historically, by looking at the mix and quantity of fuels used. This mix evolves from wood to nuclear energies with an intermezzo of coal, oil and gas, the fossils. The intermezzo lasts about 400 years.

These fuels are made of carbon and hydrogen in different proportion and we have discovered that the ratio evolves in favor of hydrogen following a simple logistic for more than 200 years, formally pointing to a pure hydrogen economy for the end of this century.

That fact that hydrogen has to emerge as the central fuel is shown here to evolve out of the history of fuels consumption. Nuclear appears to have the quintessential characteristics to be the primary energy source.

About the Author

Cesare Marchetti started his career as a physicists, was then manager of research laboratories, and finally spent 30 years as a researcher in IIASA doing system analysis. He produced very simple predictive models, the physicist way, on the most variegated subjects, from the dynamics of energy markets to the evolution of transport systems. His papers are collected on his web site www.cesaremarchetti.org/.

On Decarbonization: Historically and Perspectively

Cesare Marchetti

When man tamed fire, perhaps a million years ago, he started interfering with the carbon cycle. Wood, in fact, is mainly cellulose, a carbohydrate that should be defined by the formula $(H_2OC)n$. By gentle heating, water is separated leaving almost pure carbon, the charcoal.

Wood and charcoal have been the staple fuels for humanity until the end of the 18th century, although the Romans knew mineral coal. The Chinese, on the other hand, could drill boreholes to reach natural gas already a thousand years ago with a technology very similar to our present technology.

In both cases the problem was to carry the energy to the final consumer and the transport systems made the mining or drilling unsuitable for the necessary large distribution. So the Romans did not develop coal mines and the Chinese used their methane only locally to make salt by boiling brines.

Trains made the difference, plus an increased consumption of energy due to industrialization and increasing wealth. Coal was used in large amounts starting from the beginning of the 19th century. Its overall formula can be seen as -(HC)-n so that the energy comes in part from carbon and in part from hydrogen reducing carbon emissions with respect to wood or charcoal. Decarbonization begins.

Oil was developed first at the end of the 19th century basically to produce a substitute for whale oil to be used in lamps. Curiously thanks to a drilling technology taken from the Chinese via their workers emigrated in the US. Its overall formula can be seen as $-(CH_2)-n$, thus further reducing carbon emissions for the same amount of energy liberated.

The final contender is methane that only recently started to extensively penetrate the market and has a neat formula of CH_4 with the maximum hydrogen content for a hydrocarbon. The history of market penetration of our primary fuels is reported in Figure 1 and the increasing ratio of hydrogen to carbon is reported in Figure 2. Both charts are plotted fitting logistic equations and using the Fisher&Pry transform. F is the market fraction for a given competitor.

So decarbonization has been intrinsic to the development of the mix of primary energies. Also increasing efficiency moves in the same direction by reducing consumption for a given task, if very slowly (see Figure 3), but increasing consumption which can be estimated at about 2% per year for the last 200 years overcompensated both, leading to a net increase in emissions.

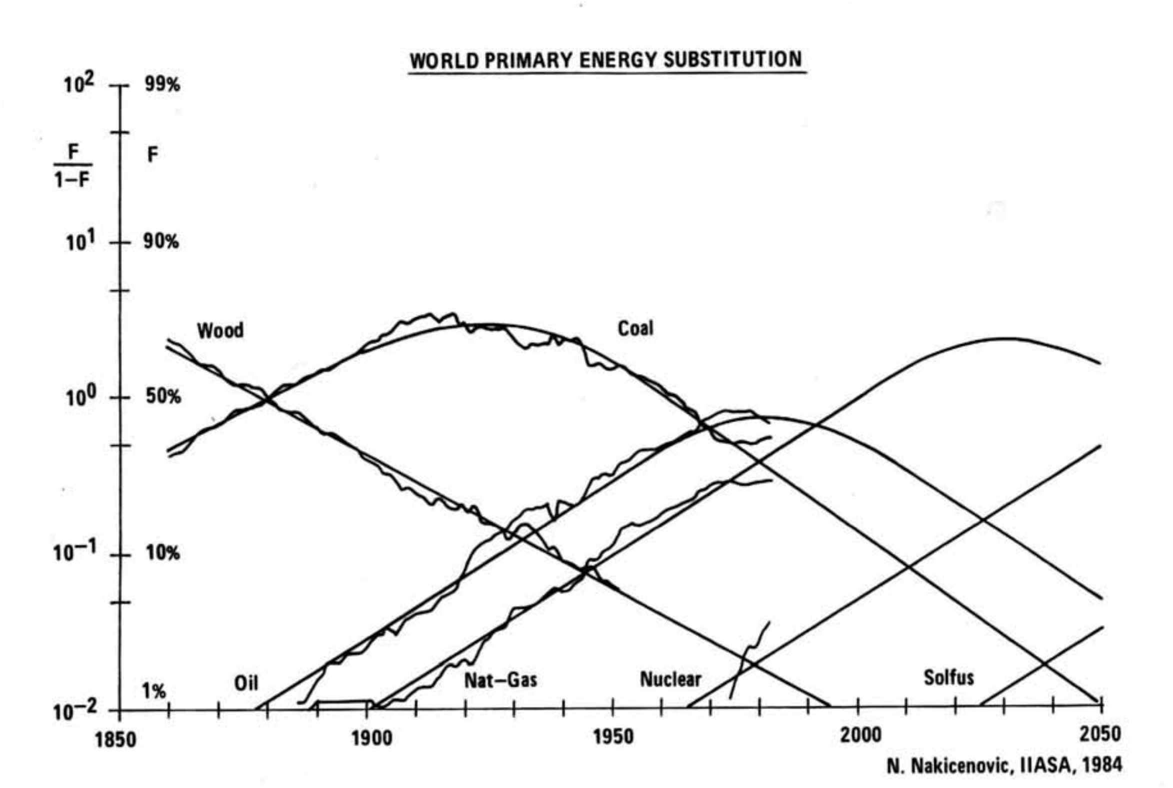

Figure 1.

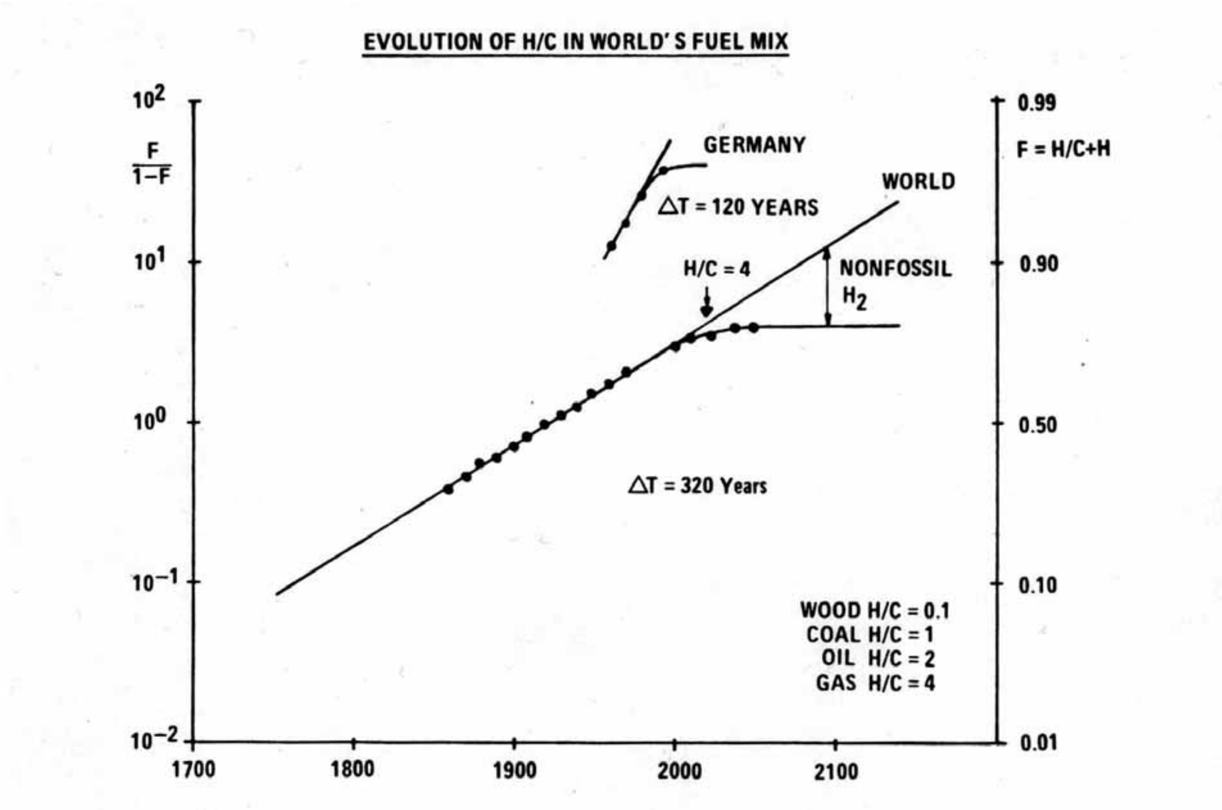

Figure 2.

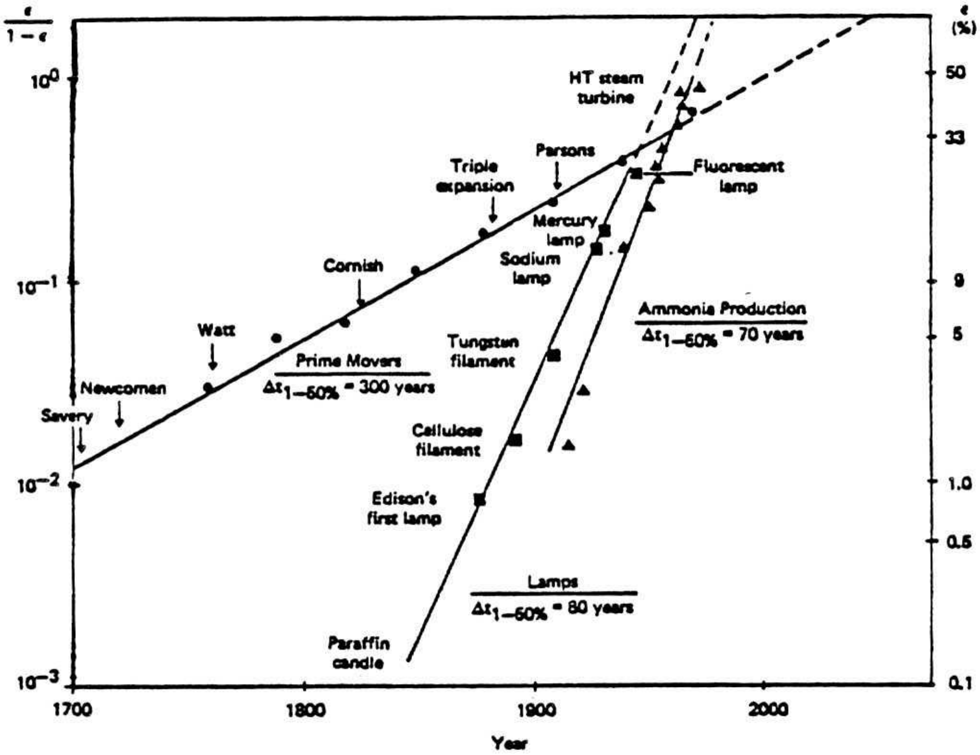

Figure 3.

Nuclear energy, the subsequent primary energy, has zero carbon emissions, but as Figure 1 shows penetration times amount to a century or so, and for the next century we are left in the cold. Second law efficiency amounts now to a miserable 4%, but progress in that direction is slow (see Figure 3), if only for some specific technology. In spite of the high critics of the Greens, cars are not the real culprits (they have an efficiency of perhaps 15%), but house heating with less than 3%.

Following the above observations during the 1970s, I made a series of proposals to technically solve the problem of carbon emissions in case CO_2 appears to be a threat of some sort. Because my previous analysis had shown that technological substitution has a life of his own, I concentrated on the introduction of new technologies that in due time may produce the desired effect.

The first proposal I made at the end of the 1960s was to produce hydrogen by decomposing water and distribute it in the same way as methane. The technology is not new as the city gas of the cities of La Belle Epoque was basically hydrogen. But I took nuclear reactors as primary energy sources and thermochemical processes to split water. At such scale electrolysis cannot work.

By cooling these very large reactors with seawater and extracting the uranium it carries, one creates a sort of perpetuum mobile that fascinated the Japanese when I presented the proposal to them in 1973.They kept working assiduously on the various problems, HT reactors, uranium extraction, and thermochemical watersplitting and are now ready for a demonstration.

The solution is "final" because one can build energy islands on atolls where liquid hydrogen is exported with tankers. With zero emissions at the business end. In my proposal the size was appropriate with an energy export capacity per island equivalent to the Middle East. The Japanese are near step zero, but this is only a seed that can bring fruits in a century. The very large reactors, for instance, are still to be designed.

The logistics used to fit current technological substitutions are usually predictive. If we take Figure 2, we see that around year 2000 even the penetration of methane cannot hold the secular trend of hydrogen substituting carbon so that a source of hydrogen of nonfossil origin is called in. Watersplitting with nuclear or solar could perfectly match.

In between, if necessary, we should do something with fossil fuels and in fact during the 1970s, especially through my consulting work with General Electric, I was stimulated to take the shorter view and find shorter-term solutions. Back to basics, CO_2 thrown into the atmosphere, tends to go into the ocean that constitutes an almost unlimited buffer.

Thermal stratification, however, offers only the first 100 meters or so to exchange with the atmosphere a relatively small volume that communicates with the depths through a few "sinks" activated by thermohaline disequilibria, one at the Weddel Sea near the Antarctic, one in front of Norway, and the third at Gibraltar where the warm but saline waters from the Mediterranean sink a thousand meters or so into the Atlantic.

By separating CO_2 at some place, inevitably where energy is handled in bulk (e.g., at a refinery or at a large power station), one can pipe it to a sink and inject it there to be carried into the middle of the big buffer, the ocean. A paper of mine published in 1977 can be considered the first structured proposal for large scale CO_2 management. The title, 'On Geoengineering and the CO_2 Problem', gives the perspective point of view.

Transporting CO_2 by pipeline is cheaper than transporting oil or gas, but obviously it is important to minimize the shuffling. So I devised other injection methods now intensively studied by the Japanese. A pipeline can go to a certain depth and release the CO_2. If the depth is 3000 meters or so, CO_2 stays liquid and, being denser, rolls to the bottom of the ocean.

The Japanese are studying certain very deep configurations of the ocean bottom in the form of huge geological buckets where liquid CO_2 can station for eons, and experimenting the procedures of injection. Because dissolving CO_2 in water makes water denser, the Norwegians are tinkering with the idea of letting this water roll down the continental shelf.

The earth provides interesting CO_2 sinks, starting with exhausted gas or oil fields which are just made to contain gases and liquids. In the various proposals I made in time, I also included geological configurations of the same type, usually containing water and the water table. If it contains silicate gravel or sand they react with CO_2 producing carbonates sequestering it for ever.

In two conferences in Moscow I presented possible configurations to implement the principles. E.g., by steam reforming the natural gas coming from Russia to Europe, sending the hydrogen to Europe and sinking the CO_2 at the reforming site appropriately situated over old and exhausted oil fields near Poland.

Because the reforming reaction is endothermic, I also proposed to use nuclear power to provide the heat so that finally the energy carried by the hydrogen would be boosted with respect to that carried by the natural gas and we would finally get chemical fuels out of nuclear energy in form of hydrogen as it should.

Because hydrogen can be mixed to methane up to a point the installation could be built in blocks to gain experience in these processing units that should be very large in terms of chemical and nuclear technology. On top of that, hydrogen to burn has different requirements than hydrogen for chemistry and this may streamline the design of the plants.

Also oil refineries could do the same. They disassemble hydrocarbons to reassemble other hydrocarbons and could be conceived to finally produce just hydrogen.To be piped as usual and distributed for instance at the gas pumps for delivery to the final consumer, the car operator. Hydrogen cars, which are now in the pipeline, would then find a new brand of Super to tank. SH.

Looking into the next 50 years with the wisdom collected from the last 200 as sketched in Figure 1, we see that methane is to be the dominant primary energy and as a consequence the dominant source of CO_2 emissions in spite of the fact that it is the cleanest hydrocarbon from that point of view.

Because every anti-CO_2 measure will be slow to implement, the decarbonization of methane should have a strategic priority. E.g., we can specifically desorb methane from coal seams using the CO_2 produced by its combustion at mine mouth, so to speak, to produce electricity or hydrogen for export.

The same trick could be used by decomposing methane hydrates through the injection of CO_2 that replaces methane in the hydrate providing the necessary reaction heat and finally remaining sequestered there.

These processes have the problem of N_2 from the combustion air producing impediments of various sorts, so, still in the 1970s, I made the bold proposal to separate N_2 before burning with oxygen. This requires a redesign of the plants, tendentially making them smaller and more efficient.

Air separation plants would be huge, as everything in the energy system, and this plus the technological evolution, e.g., through the introduction of magnetic cooling, may straighten the economics. Which at the moment is fair but open to unilateral critics.

At this point it is necessary to introduce our smokeless guest, nuclear energy. I am perfectly aware that saying nuclear energy will play a role as energy source in the mean term, the next 50 years, is not politically correct, but I said it before it was discovered that antinuclearism can be a basis for a political career.

Figure 1 is an inexhaustible source of information and shows that a new primary energy is introduced into the market every 55 years or so. After natural gas, nuclear appears to be born at the appropriate time and have grown healthily. More than 400 nuclear plants are spinning out almost 20% of the electricity consumed. In France it is 80%.

It is true that nuclear plant construction has stopped, and the Greens attribute the merit to themselves. But a quantitative modeling of the situation shows a different picture. Figure 1 gives the market fractions covered by primary energies, i.e., it expresses the relative terms. If we look at actual consumption in absolute terms, we go to Figure 3. Energy consumption grows in logistic spurts spaced about 55 years at the center points.

This is a normal behavior linked to the Kondratiev cycles. Cars do the same, or steel production. Consequently, the logistics that describe penetration saturate around 1995 which is the end of the present cycle. It happens that the logistics representing penetration of nuclear energy, e.g., as GW connected to the grid, grow exactly that way.

The case of Germany is reported in Figure 4. Germany is interesting because opposition to nuclear has been particularly active and occasionally violent. But no trace is left on the facts, GW connected grows according to a logistic of mathematical precision. The same for France, where penetration is deeper and opposition nominal.

So according to the internal logic of this analysis, nuclear will soon restart in spite of vociferous minorities. Another primary energy can be expected around 2025 and here the natural candidate is fusion of some sort. Solar has too many handicaps for a large-scale application, although it can provide an interesting array of devices in the area of small, isolated power applications.

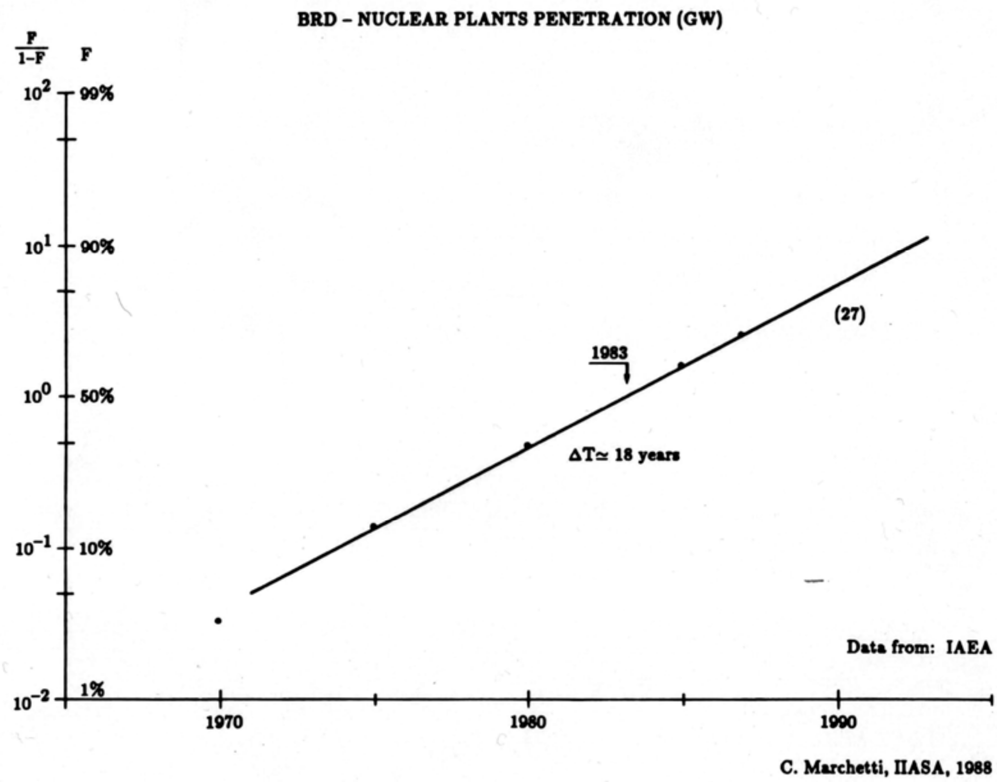

Figure 4.

A way of capturing CO_2 with mechanisms outside the energy system is via chlorophyll. Humanity consumes, round figure, 10 billion tons coal equivalent, and forests shed about 100 billion tons coal equivalent as leaves and branches. We are still in the small league and we may join the big one for help.

Reforestation is in many ways advisable although the effect is ambiguous as what we really want is a favorable radiation balance which is hampered by infrared absorption of CO_2. But woods are usually darker than the ground on which they are planted so that the reduction in CO_2 absorption is compensated by a decrease in albedo increasing energy deposition at the earth surface.

The mass of carbon sequestered by forests grows logistically and saturates for old forests, taking into account also the organics left in the soil. The Amazon has a zero balance in terms of CO_2 and the suggestion that it is the lung of the Earth is a purely poetic image. Like the feeling of being oxygenated when jogging in a wood.

The oceans, however, are an immense extense with albedo less than 10% and biologically a desert. This is because primary producers are short of traces of iron. Oil tankers leaking iron sulfate can create a swath of life where they travel and this could generate new jobs for tankers in their back trips. Seas with algae are also lighter in color.

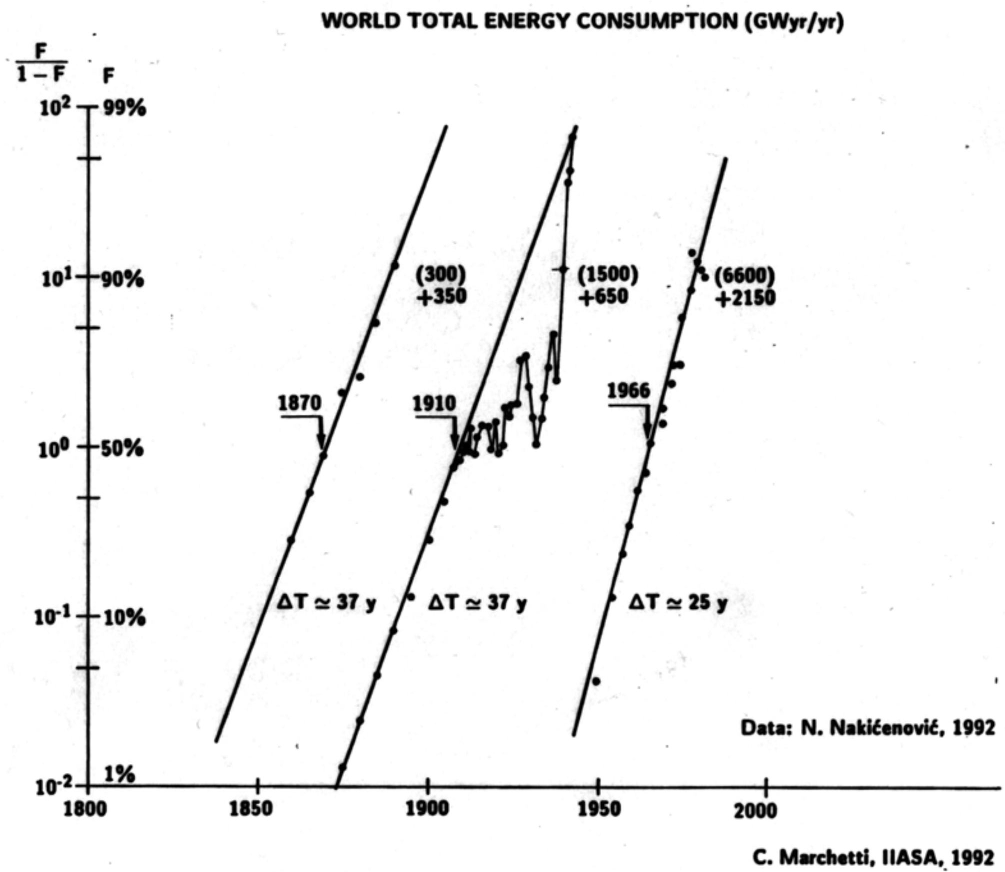

Figure 5.

The idea has been shuffled around for a while, but it suffers from the fact that organic materials produced should sink below the mixing zone, better even to the bottom. But what happens is that the frenetic metabolism of the system tends to burn on the spot everything in sight. For that reason I proposed a scheme where the water is soon anoxic providing the appropriate preservatives.

The case is that of the Black Sea, where due to the peculiarities of its circulation water is anoxic and contains sulfidic acid, say below 200 meters, so that everything falling to the bottom is not eaten by other living things. My scheme would be to grow something macroscopic on the surface like water lilies, whose corpses can fall down rapidly.

The whole Black Sea could absorb most of the CO_2 emitted by humanity. However, in spite of the many amusing schemes I presented in time, most of the activity concerning CO_2 management is dedicated to the production of hot air, hoping perhaps that the problem will disappear the same way it appeared.

Why not, let's hope.