Long term global vision of nuclear-produced hydrogen

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Preface

One day in the middle 60's I was sitting in my office at the Euratom center in Ispra meditating on the long term future of nuclear energy. At that time the faith on the future of nuclear was untarnished but I felt a strategic weakness in the current view. Everybody was thinking in term of electricity production even if the most optimistic projection would give about half of the primary energy electrified. Because in the last couple of hundred years energy consumption did double every 30 years or so, even if all electricity were nuclear after 30 years we would be back to square one in terms of fossil fuels consumption. Some words were said about an all electric economy which sounds a little eerie as the generating system should be geared to the instant consumption of energy, on top of the fact that many kinds of vehicles are not easily amenable to the use of electricity.

So I decided that nuclear should be used to produce some sort of fuel and the choice fell on hydrogen. It is transportable, flexible, non polluting, starts from water and ends in water. I started a bibliographic search on the use of hydrogen and discovered to my surprise that all sort of final uses were studied at the time. Even fluorescent lamps where the phosphors are directly excited by the oxidation of hydrogen over them. On top of that hydrogen had a long and successful career as a final energy carrier. City gas is in prevalence hydrogen and was the energy backbone of European and American cities till WW2. The first internal combustion engine built in Lucca by Meucci and Barsanti did run on hydrogen and experiments had been done in the fifties on hydrogen airplanes. The most fascinating application for me was the production of food for the astronauts using microorganisms capable of processing hydrogen. There is there the promise of liberating man from the burden of agriculture. Incidentally chlorophyll splits water into hydrogen and oxygen. Back to square one.

One of the problems insufficiently excavated is why man in the last couple of centuries did pass from wood to coal, and then to oil and gas. One trivial explanation is that forests where overexploited which may be locally true. However world forests now shed in form of biomass something like 100 TW when humanity consumes about 10 TW. No exhaustion in sight. One can say that forests are spread around the world. But so are oil fields. The real problem in my opinion is that exploitations of forests has no or little economies of scale. To cut one tree per hour one needs one lumberjack and to cut two trees per hour, two lumberjacks. Nor the argument of facility of use has sufficient weight. It is true that it would be cumbersome to run a car stuffing it with wood, but in the last century cities like Paris were consuming huge amounts of methyl alcohol produced by wood distillation, an excellent fuel for cars. After all no car runs on crude oil and sophisticated refineries are needed to produce the right brand of fuel.

After carefully examining all the transitions I came to the conclusion that the winning parameter that leads to the transition are the economies of scale. The driving force is the scale of the market, ie the level of consumption and in second approximation the spatial density of consumption. The next competitor wins on the basis of its economies of scale in the range dictated by consumption. The process is better seen inside a global enveloping technology, eg the electric system. Here the capacity of a generator is dictated by the spatial density of electricity consumption and its transportability. So the power station “sees” a certain market via its distribution lines and the generator is sized to it. If the spatial density increases the market seen by the power station increases even faster because the electricity transport system can use higher voltage ie higher capacity lines that carry electricity over larger distances. Examining the American electricity system one sees in fact a doubling of consumption every 7 years and a doubling of the capacity of generators every 6 years. In only 100 years they went from the 10 kw of the Jumbo Dynamo of Edison to the 1GW of today. An incredible jump by a factor of 100 000.

Without such theatrical effects, the productivity (pass km/hr) in commercial airplanes did increase by a factor of 100 in 50 years in tight response to demand, the same for oil tankers, where at any time the largest ship carries a constant fraction of the total world traffic.

The gist of all this reasoning is that if we want to ride a technology destined to success we must create the conditions for the economies of scale to be part of its evolution. In the case of hydrogen as a vector of nuclear energy this will be implicit for the simple reason that hydrogen has high transportability in pipelines and very high as LH2 in cryotankers. We did in Ispra some calculations, with the help of SNAM, the Italian natural gas company, and found that the cost of transportation in large pipelines over long distances compares with that of natural gas. This means a generating station “sees” a market as large as a continent and can grow accordingly. Certainly our nuclear reactors optimized for the fractioned electric markets appear puny in size. Technology will strive to fit the demand as the rewards of size can be huge. In the sixties, when nuclear costs were still fairly transparent, I collected data for stations of similar characteristics and different sizes and found they follow the square root rules as often chemical plants do. This means a plant four times as large costs the double, halving the specific cost, eg per kw. Small is beautiful but big is cheap. Technology tends to trot behind the demand pull. For decades I was in contact with the engineers designing large electric generators and I teased them asking how large can be at the limit a generator. The answer was time invariant: double the present. And they did explain it with lot of convincing details. They were not wrong, but their time horizon was just six years.

Nuclear seems to be here to stay as shown in a report I did prepare for the UE commission in 1990 whose analysis is still fully valid today. It is true that nuclear plant construction did come to a halt, but this is due to the economic Kondratiev cycle. In fact the cumulative power connected to grid follows precisely the Kondratiev prescription of saturating in the 90's, as did steel and cars production capacity by the way. On the other side, I repeat because it is central,in order to escape fossil fuels, one cannot just limit nuclear to the electricity production that may finally require about 50% of the primary input, because a doubling of energy consumption would bring the fossils back to square one. World energy consumption has doubled every 30 years during the last 200 years, and with 2/3 of the emerging countries still running uphill it will keep doubling for a while.

In order to go 100% nuclear or so, a chemical energy carrier is necessary and in the sixties, when I did start meditating about the long term strategies for nuclear, Hydrogen did appear the inevitable choice. Distributing it to the final consumer is no problem as shown by the "city gas", and the few thousand km of high pressure pipelines, transporting it for industrial purposes, pave the way for continental coverage. LNG ships can be the blue print for a global system where LH2 is carried oversea. As I have shown for electricity, spatial consumption and transportability define the size of the generators, which for hydrogen could be extremely large due to the fact transportability is an order of magnitude higher than for electricity. So it is strategically appropriate to think big, and my "Energy Island" with an hydrogen production equivalent to the Middle East, energy wise, may be the reference long term paradigm for that.

How to make hydrogen from nuclear. The strategic choices.

Once identified the carrier, in my Ispra Labs, we started thinking about ways to produce it, from water, using nuclear heat. The trivial solution is to make electrolysis but we discarded it on various grounds. First it represents two processes in series with a too low total efficiency. Second it appears expensive in term of machinery. Third and perhaps most important it is not scalable. The energy system is immense in size be it 10 TW or a 100 TW, and the experience with the historical size evolution of chemical plants show that they shall have production units commensurable with the market. The drive for that is given by the economies of scale which can be as high as the square root. Meaning a reactor ten times as large costs three times as much with the specific cost reduced by a factor of three or so. Obviously the technology must be mature for scaling, but one can trust engineers. In a bare hundred years electric generators did double in size every six years from the 10 Kw of the Edison’s Jumbo Dynamo to the modern million plus Kw alternators, a factor of 100 000. In actual life spatial intensity in consumption and transportability of the medium, be it electricity or hydrogen, define the optimal economic size of the generator and technology runs to provide it.

On the basis of these considerations, elementary but quintessential, we chose the chemical route to go from nuclear reactor heat to water splitting. I must say we discarded all the family of renewable on the basis of parallel arguments, they do not scale. It must be clear I’m speaking of the backbone of primary energy procurement. As the success eg of electric batteries shows, very uneconomic ways of producing electrical energy can have a commercially fat market share, if puny in terms of energy produced. On top of that in my “Energy Island“ scheme I made Uranium “renewable” by extracting it from the seawater used to cool the reactors a line the Japanese did successfully develop during the last 30 years. Renewable means 10000 years which is a sizable time resource to develop the next step, also described in the “Energy Island” paper that would bring us to ten billion years of energy resources, that should quiet also the physiological pessimists.

The chemical processes can be seen as black boxes, we named them Mark-X, where the input is water and high temperature heat and the output low temperature heat plus H2 and O2. All the reactions inside run on closed cycles so that in principle there is no consumption of chemicals. Inventing a good Mark is very tricky because it has to fit so many boundary conditions, the chemicals must be cheap, no corrosive, easily separable etch etch. We could see thousand of them thermodynamically constructed with a computer program. Curiously the dominant reason to discard was that nobody had never studied most of the trivial reactions going into them. Classical chemistry is still fully open to exploration. The best ones, a dozen, finally emerged from the heads and experience of our chemists

Thinking and experimentation reduced the number of processes as the few M$ available did not permit a broad front research. Anyway the team produced an impressive amount of data that made possible an appreciation of the problem technically and economically. The first question was the kind of efficiency that could be expected. As history shows, all chemical processes tend to improve their thermal efficiency during their development in application following logistic equations, the real problem is to have a decent start. The estimates for the sulfur cycle we had studied most in dept with bits and pieces of a demonstration plant gave a comforting 50%. After all the Watts engine had started the industrial revolution with an efficiency of 1% and in a couple of centuries has developed logistically to about 60%.

The basic idea of a thermo-chemical cycle is that because water cannot be cracked in a single go, the necessary temperature is too high for a nuclear reactor,(although fusion people had a go on the idea) then we must split it in two steps, or more. Intuitively one can reason that the first step liberates the hydrogen and binds the oxygen so that the free energy for the process is the difference between the two. The second step liberates the oxygen from a weaker bond than in water.
This procedure requires two reactions forward and two backward to restore the initial state. So most processes that have been proposed have four reactions. Because in principle what the chemical must transfer to the water is free energy, it is possible to conceive a one reaction process where one molecule by heating and cooling accumulates sufficient free energy to finally crack water. The thermal cracking of $H2SO4$ almost does it and in fact at Ispra we did court that reaction adding this and that to close the cycle.

However apart from some loose example I will not enter here into the details of the water splitting processes as the pages allotted in this review would not be enough to describe even one, the details are well covered into the papers and the references found on my website http://www.cesaremarchetti.org/ . and elsewhere in this book. Here I will basically stick to delineating the strategies and the constraints for applying these processes as I think they are not sufficiently treated in the current literature.

The first problem is that of a transition to very large nuclear reactors. In the sixties, with the help of my colleagues in General Electric and in the Prof. Schulten team for the High Temperature Reactor team in Germany, I sketched a toroidal pressure vessel reactor that permits large volumes with limited diameters and filled it with graphite fuel balls, the German way, to produce 200 TW thermal. Mounted on a barge of appropriate size, together with the thermochemical plant, should have been the basic generating module in the Energy Island. It basically shows that many problems can be solved, but an industrial design must grow in steps, as the case of electric generators clearly shows. So one has to find a possible nursery.

Prof Schulten had thought of chemistry to transport nuclear energy and chosen methane steam reforming followed be methane synthesis to place heat at a distance. The system doesn’t stand to strategic analysis, but he had developed both processes in connection to a nuclear reactor and the technology could be used in a different strategic context.

Russia exports to Europe per year about 200 billion cubic meters of natural gas, and this through a limited number of very large pipelines converging in an area in front of Poland and Slovakia. This area is interesting for various reasons, it has water, industries and very old and abandoned oil fields. As I was invited to give a speech in a congress in Moscow dealing with energy, environment and conservation, I tried to make everybody happy by presenting a proposal where some of this methane is steam reformed using nuclear heat, the hydrogen is mixed with the flowing methane and the CO2 is used for tertiary recovery of oil in the fields.

This catches a number of birds with a single stone. The formal reason for the proposal was to start taking care of CO2 emissions, where so many people talk about and nobody takes measures. In this case CO2 disposal would have a precise economic purpose but finally it would disappear in the bowels of the earth by reacting with this and that. The strategic reasons were three. The first one is to provide a nursery for the growth of nuclear reactors. Such a large flux of methane can absorb any power, let say blocks of 50 GWTh, ten times larger than the largest reactor built. Supposedly they would be HTR’s. The second reason is that H2 would be mixed with methane and consequently spread all over Europe. The usual chicken and egg argument that technologies using hydrogen, eg Hydrogen Cars, cannot penetrate for lack of an hydrogen distribution infrastructure would loose weight. The amounts of hydrogen that can be mixed in a way compatible with existing infrastructures can be as high as 20%, making separation with membranes or metallic hydrides presumably simple. And finally nuclear energy would enter the production of fuels on a large scale using well developed technologies.

The proposal was well accepted by the scientific community and the press but had no practical consequences. However from my studies of penetration of new important ideas and technologies I know that the process takes about a Kondratiev, ie about 50 years, so it is not the case to worry. It is important to keep the issue on the table however so that the system keeps absorbing it. In the case of cars or aviation a bunch of crazy guys kept the lights on, providing important practical improvements to the technologies in the process, but basically holding them in the collective imagination.
Strategies can be seen as distant attractors dreams and I tried to provide one with the concept of the Energy Island. I did propose it for the first time in a paper I published in Japan in 1973, “On Hydrogen and Energy”. It had the basic effect of attracting the interest of the Japanese as they saw that the miracle of energy independence, much felt at the time, was not at hand but at least technically possible.

For system reasons the Energy Island should have a size adequate to the market in parallel with what happens for chemical plants. If we export LH2 in cryotankers, the island “sees” the world with its present 10 TW of energy consumption. Adopting a concept often used in the electric systems I adopted for this energy generator the criterion of 10% of the perceived market, ie one TW. It is a large unit, more or less of the order of the Middle East. In spite of the size I did not see insurmountable problems. I should say I can be considered an optimist as in reaction to the screams of my friends of the club of Rome I wrote a paper, ten to 12, where I did find a luxurious installation for a trillion people, on planet earth. With zero exaustion and pollution. Also for the Island I sketched the solutions for a zero ecological impact. The location on a pacific atoll helps a lot.

First the thermal plume. There is in the pacific a strong thermal gradient. If one can pump cooling water say at 500m depth, were the temperature can be 5°, and reject it at sea surface temperature, say at 25°, there will be no visible thermal plume. Using HT graphite ball reactors,fuel manufacturing and reprocessing can be automatized , and possibly done on board, but the amount of fission products to dispose will be large. So at the ISPRA center we devised a self sinking system where capsules loaded with fission products are just earthed, where the heat melts the ground and they just sink. We made extensive experiments to check the equations sinking real capsules. They can go down to eg 15 Km in the volcanic rock of the atoll. Uranium is extracted from the cooling water, so there is no pollution from uranium mining and transportation. The big barges carrying all the conquibus would be armed in appropriate wharfs so that the operation on the islands would be that of bare operation with limited crews.

In this context the cost of the energy produced is basically a capital cost and capital is basically linked to scale. Efficiency so important when the energy source is external and possibly polluting, is here one of the variables and low efficiencies are acceptable if they bring other benefits.

Globalization of energy production has also political consequences, as I stressed in my dinner speech at the first H2 conference in Miami in 1976 (From the primeval soup to world government). Basically the maximum size of an empire is dictated by the speed of the transport system and the multinationals were fast to get the idea, but the political systems are sluggish and did not. One of the possible byproduct of this globalization could be the formation of a real world authority to administrate the energy business and the rest.

In the course of this analysis I did quote the fact that the world forests could well support our energy needs if it were not for an inappropriate interface, that of chopping trees to get their energy content. So I mused if a solution could be found. It can and is described in my paper “The Hydrogen tree”. The inspiration came from the leguminous plants where (nitrogen) bacteria create nodules in their roots where they produce hydrogen by decomposing the photosynthate of the plant (sugars) into CO2 and H2, in a sense reversing photosynthesis. Hydrogen is used to produce ammonia, sent back to the plant to pay for the rent. So I reasoned, if one could construct large galls doing the same and collect the hydrogen via a drop irrigation system operated in reverse, then the forest could be “milked” producing a perfect fuel for the counterpart. Apart from developing the gall which requires the best in genetic engineering, the system requires no particular skill in installation and operation and could be ideal for isolated villages here and there. I did present the idea in three congresses and was much appreciated. I report it here to hold it in the stream of attention.