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Genetic Engineering and the Energy System: How to Make Ends Meet

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ABSTRACT

The Energy Systems Program at IIASA devotes itself not only to the analysis of new energy systems work, but also to the synthesis of technical methods to solve the problems the analysis brings into evidence. The question of the very high capital investment in solar systems is dealt with, as is the possible problem of reducing this to a level bearable for developing nations.

Introduction

In this article, an attempt is made to devise a conceptual framework, a "system synthesis," for the possibility of a really *soft solar energy option*, making the best use of the theory of energy systems, plant ecology and physiology, and genetic engineering. Although the results of the synthesis may appear a little chimeric, the components come from actual lines of research in the relevant disciplines, as is shown in the literature quoted. The aim of the article, however, is not to provide a finished product but *to point to possible realizations of the soft technology concept which mean what they say*, even under strict real world constraints.

The Clumsy Solar

Energy systems tend to become more and more capital intensive, and solar energy is well into that trend. Projected costs of $5000 per mean kW(e) for large stations [1], and actual costs of $40,000 per peak kW for 1-kW solar pumping stations installed in the Sahel area [2], make these installations at best showpieces of the very rich, and certainly contradict the argument that solar energy is free.

Just for comparison, an internal combustion engine may cost $10 to $20 per kW and over a period of 20 years consume a weight of fuel (5 tons) that is comparable to the weight of the hardware of the solar pumps in the Sahel, but which costs only $1000. Even for heat at low temperature, the figures, although much lower, are not much more encouraging. The mere bulk of materials necessary to deploy the collection system and to provide some kind of storage makes a cheap solution appear physically impossible [1].

Thus, contrary to what is often claimed in the current literature, solar energy does not seem a good bet for the developing countries—chronically and intrinsically short of

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capital—*at least with current concepts*. For these countries, buying oil and gas, which require relatively little investment at the point of use, appears the only possible solution; but even this will place too heavy a burden on their balance of payments. The only way to avoid the impasse is to have a *really soft technology* available, defined as a means of achieving an end through possibly very sophisticated knowledge but with little hardware and perhaps little know-how at the point of use.

Since creating income is a much harder task than creating jobs, a soft technology should also need little manpower for maintenance and operation. "Jobs" will rapidly find their way to income once it is generated.

The Clumsy Forest

The central problem of solar energy use being that of unwieldy hardware, it is an elegant idea to use a living thing whereby the hardware is automatically produced and maintained by transcoding of genetic messages and where the raw materials are collected mainly from the atmosphere. In fact, the idea of using the world forests as solar energy collectors, even qualitatively, is not an alien one. While the world's energy consumption is about 8 TW, or approximately eight billion tons of coal equivalent per year, world forests have a metabolism in the range of 100 TW, and about half is just discarded in the form of falling branches, leaves, and dead trees [3].

Solar energy enthusiasts often tend to stress that solar energy is free. All natural resources are in fact free, and the decaying wood and other organic matter are no exception. What does cost money is to mobilize the resource and make the products flow to the consumer in the proper form and amount, and that is where the various proposals for using plants as solar collectors, publicized under the trade names of biomass or energy plantation, are bogged down.

Forests actually do a neat job in collecting solar energy and storing it in a fairly stable chemical form. The collected energy, however, is spatially diluted and in a form awkward to handle. Harvesting it requires a lot of manpower and quite sophisticated machinery [4]. But collecting is only the beginning. Wood material and biomass are not suitable for transportation techniques competitive with those developed for oil and gas, nor are they suitable for present technologies of final utilization. Consequently, an intermediate transformation, e.g., to natural gas, is finally introduced. As people in the business of coal gasification know well, this transformation necessitates so much capital investment and causes such large energy losses that as a consequence oil and gas appear unexpectedly cheap. The hope that oil and gas will very rapidly increase in price, due to their exhaustion, appears to have little chance of materializing [5]. Forests, we have seen, shed in chemical form as much as five times the energy we consume. The access to this tantalizing source depends on the invention of a proper interface. Perhaps, in this little studied direction, we may find the shortcut to solar energy utilization. I will open the race.

The Competent Interface

At this point the problem is fairly focused. One should add that, in the world energy system, gas is probably going to be the dominant energy source for the next 50 years [5], and consequently a trunk gas pipeline is the most likely configuration such an interface has to match on the consumer side. The gas can be methane or hydrogen, which, as numerous studies have shown, are largely interchangeable. The suggestion I will make pivots on two observations:

1. Trees are machines with a metabolic power (average) of the order of 1 kW. The average power per house in a housing development area connected to the gas grid is about 1 kW. So I thought that the cost of a net of pipelines collecting gas from each tree could be easily estimated from the cost of a net of pipelines distributing gas to houses. I did talk with a gas company, and the cost comes out to be in the range of $100 to $200 per kW average, distributed (or collected), if the pipes are laid before construction. Drip irrigation systems for orchards, with individual nipples for the trees, are in the same cost range or about $1000/ha, including wells and pumps. With a collected energy density of 1 W/m² this makes in fact $100/kW.
2. As the decoding of a DNA message produced such a magnificent structure as a plant, why not add a few bytes to the message and instruct the plant to produce a little accessory matching the collecting grid?

This may appear to be a tall order, but in nature numerous brilliant, if sometimes extravagant, sets of solutions have already been found to this kind of problem and operate right before our eyes. Many insects are capable of inducing the formation of bodies in plants—the galls—that may be related to tumors but are profoundly different in that they grow according to a precise functional architecture, as does any other organ or a plant. These galls are engineered to provide protection and food for the larvae of the insect, and are perfectly adjusted to their needs and timed to their state of development [6].

Not only insects but also bacteria and fungi have found their way to induce gall formation. They number in tens of thousands of different kinds. Oaks host a few hundred types of galls. Their structural and functional variety is astonishing: they range in size from a pinhead to a rugby ball, and appear as spongy nests or complex structures with precisely machined doors opening at the proper time for the mature insect to come out (Fig. 1).

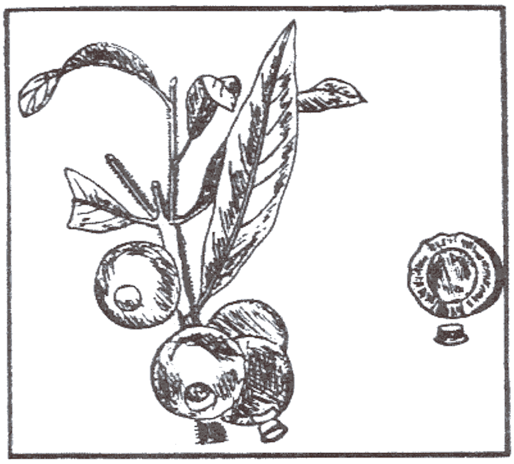

Fig. 1. Cecidosis eremita with "genetically cut" bore. The Cecidosis eremita shows some of the sophistication of a gall induced by an insect. The escape hole is not drilled by the insect, a soft fly, but is produced through genetic control causing a cylindrical layer of cells to dry [6].

How information is transferred between parasite or symbiont and host for the generation of galls and nodules has been the subject of extensive speculation for many years, but the obvious suspicion—that a transfer of DNA is at work—has been proven, at least in some cases, only recently [7]. Without DNA or RNA, however, the extreme structural and functional sophistication of the galls would be unthinkable.

One of the cases clarified is that of the *Agrobacter tumefaciens*, a bacterium capable of inducing tumor-like galls in the crown of most broad-leaved trees (Fig. 4). In this case the information is transferred through a plasmid, a self-consistent and self-controlled DNA ring, the bacterium injects into the plant cell [7]. These plasmids are often swapped between bacteria, carrying relevant news for survival in the gadgetry, e.g., the code for an enzyme to metabolize penicilline. In the last few years geneticists have learned to manipulate the plasmids with great facility; they can not only transfer plasmids, but modify them opening the DNA ring and inserting new strings of DNA (Fig. 2). Just as an exercise, the n.i.f. (nitrogen fixation genes)—i.e., the DNA sequence coding for the machinery to fix nitrogen—has been transferred from *Klebsiella pneumoniae* to *Escherichia coli*, and its activity preserved [8]. The same operation has been done between *K. pneumoniae* and *A. tumefaciens* with the intention of transferring the n.i.f. to a plant, enabling the plant itself to fix nitrogen [9].

Let us assume for a moment that the mechanism to induce and shape the gall, biochemically and architecturally, is under control. What should we try to do?

The answer is condensed in Figures 3 and 4. The tree can be seen as a machine producing sugars (photosynthates) from hydrogen and CO_2. Hydrogen is obtained by decomposing water with solar light; the chlorophyll system does just that. The photosyn-

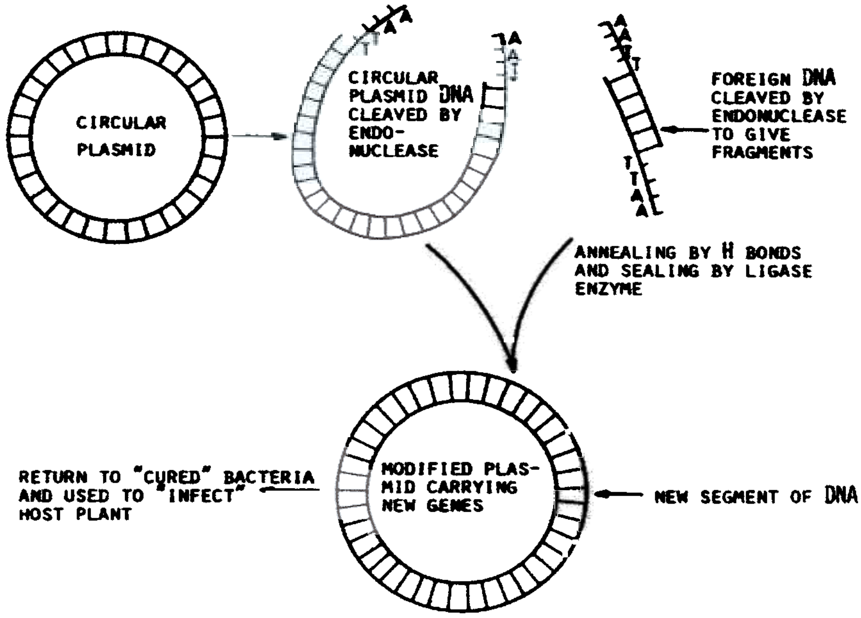

Fig. 2. Genetic grafting in plasmid. As information can be transferred to plant cells through a plasmid, extra genetic material like the n.i.f. gene, coding for hydrogenase and nitrogenase, and morphological genes could be inserted into it using current techniques of genetic grafting.

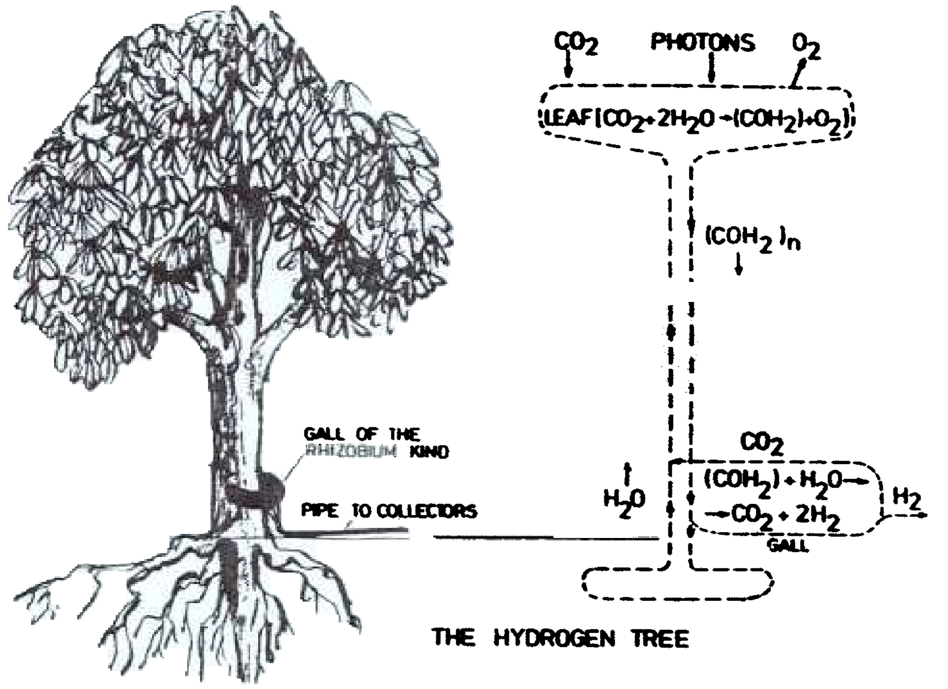

Fig. 3. **The hydrogen tree. Graphical presentation of the proposal with a very schematic chemistry. The gall actuates a reversal of photosynthesis and makes hydrogen (or methane) available in an enclosed cavity that can be tapped by a collector pipe.**

thates flow from the leaves down to the supporting structure; the strongest flow is in the stem. Somewhere in the stem a large gall should be located. It should be large enough to sequester a substantial portion of the sugar flow and have a tough skin and a spongy interior, characteristics not uncommon in galls; and it should produce something that is easily obtained from transformation of the sugars and which is, of course, adapted to the energy system downstream.

The three products deserving most attention in my opinion, are, in increasing order of interest, methanol, methane, and hydrogen. All three can be obtained from sugars with relatively simple enzymatic machinery that can be found ready-made in the appropriate bacteria. Hydrogen production actually occurs also in the blue green algae, where the precise reaction which mirrors the photosynthesis shown in Figure 3 is used to generate hydrogen for subsequent fixation of atmospheric nitrogen.

From Here to There

All this would look like pie in the sky were it not for the fact that the system already exists and operates, on the grand scale common in nature. *Rhizobium* root nodules in leguminous plants, which fix nitrogen from the atmosphere, are not far from our specification except with respect to size. These nodules are complex structures in which atmospheric nitrogen can flow through the walls of the nodule and combine with the hydrogen generated by the splitting of sugars through a set of enzymes. Oxygen is trapped by a form of hemoglobin, leg-hemoglobin, which then releases it to the bacterium, which is an

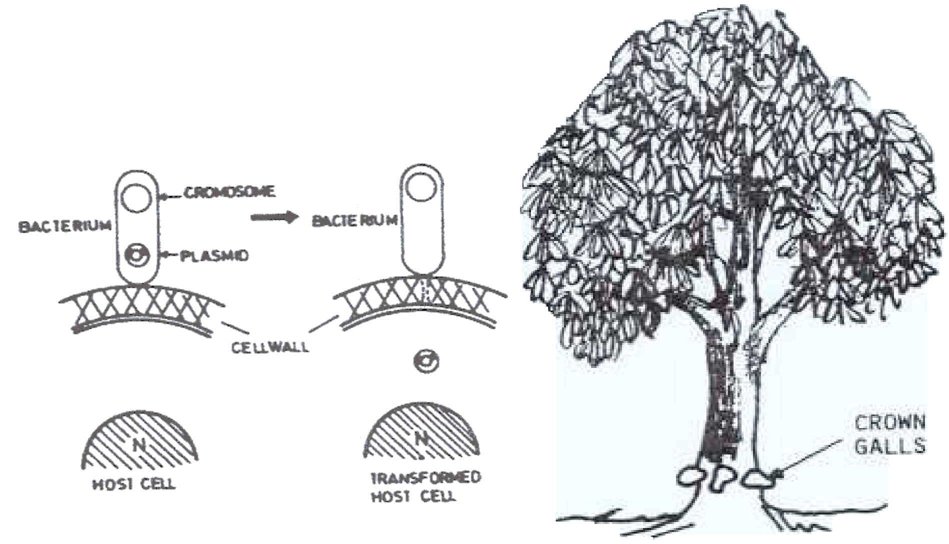

Fig. 4. Crown galls from Agrobacter tumefaciens. A possible line of attack could be to transmit the information for building a gall with the desired properties through a broad-spectrum infectious agent like the Agrobacillus tumefaciens. A. tumefaciens is capable of attacking most broad-leaved plants, producing an unorganized gall: the Crown Gall [7].

obligate aerobi. The reason for this side-loop is that the central enzymes for nitrogen fixation, hydrogenase and nitrogenase, are very sensitive to oxygen poisoning.

Rhizobia sequester a sizable amount of the photosynthate produced by their host, perhaps 30%, without, however, overdrawing it presumably via regulatory feedback process [10]. They obviously possess all other feedbacks necessary for a harmonious symbiosis [11]. Presumably because of the open nodule structure needed for nitrogen to diffuse into it, the nodules leak hydrogen into the atmosphere. It has been estimated that the U.S. soybean plantations leak about 30 billion m^3 of hydrogen every year [10].

As they are, Rhizobium root nodules could not be used for our purpose for various reasons, including the following:

Rhizobium bacteria are extremely selective in the sense that each leguminous species has a specialized symbiont. *A. tumefaciens*, on the other hand, is very aspecific as it can infect most broad-leaved plants. Aspecificity may be transferable once its mechanisms are understood.

The nodules are very small. But here again, *A. tumefaciens* is a good example of the possibility of generating large galls.

Their structure is better adopted to seeping rather than to holding. Instead, the complex architecture of many insect galls would provide better flexibility in engineering the connections with the collection pipes.

I think that the above considerations reduce the pipe dream to a very complex but manageable problem. As the parallel dream of transferring the nitrogen fixing capacity to graminaceous plants has stimulated intensive research, I should say that the problem lies within the mainstream of R&D.

The hierarchical structure of the system can now be visualized:

Antenna chlorophyll molecules, the primary *photoreceptors* that, in arrays up to about 100, convey the energy collected to reaction centers or "traps" all contained in the chloroplast membrane.

Chloroplasts are organized inside a *cell* providing the proper management of operation and repair, and exporting the products.

Cells are organized in a leaf and the leaves in a *tree*, with its stem centralizing the product flow.

The gall provides the chemical and physical interface to the next level in the hierarchy, and a small pipe drawing *hydrogen* for a hierarchy of collectors leads upward to a *trunk pipeline*.

A recurrent question in solar-based systems is storage, and a gaseous fuel provides a neat answer. Methane (or hydrogen) can be economically stored in porous underground structures like aquifers or exhausted gas fields [5] in amounts sufficient to provide a seasonal buffer. The tree itself may provide gas generation at night.

How much energy may we draw from such a system? As an easy to remember round figure for rule of thumb calculations, I would suggest one watt per square meter. It is not a small figure. On the basis of actually forested areas, all large world regions could be energy independent, including Europe!

Is it possible to improve on that figure? Well, once one has started fiddling with plant physiology one can go very far indeed as experience shows [12]. A first line of attack could consist in inhibiting plant photorespiration with substances produced by the gall [13]. Trees may waste in photorespiration half of the energy they collect and chemical inhibition appears possible.

Conclusions

We have proposed a new way of looking at solar energy in the context of various energy systems, some of which seem to have energy to throw away and some of which seem to be in need of it. By focusing on the system's central problem a solution is suggested which appears to fit the low capital availability of developing countries, and their preference for unsophisticated technologies. *This is done by creating a proper interface between a vast solar collection system, the forests, and an efficient energy transportation and distribution system, the natural gas pipeline net*. Development of the biological fix, however, will be a tough challenge even for the advanced nations, and probably at the limit of their scientific and technical competence.

To give an example, the extraordinarily complex regulatory systems at the genetic, cellular, and organismic level, are only dimly understood [12], and we propose to manipulate them in order to synthesize a vital parasite. The fact, however, that tens of thousands of different kinds of galls have been evolved by a broad variety of organisms, lends a high probability of success to the enterprise, in the long run.

This article was in fact written with another purpose in mind, to show the advantages of thinking in terms of systems when substructures are strongly coupled.

Summary

World forests produce an amount of carbohydrates of the order of 100 TW. Man uses about 8 TW, mostly in the form of fossil fuels. Many proposals have been made to link the two systems in order to alleviate the world's dependence on fossil fuels.

An analysis of the structure of the two systems suggests the characteristics that an interface between them should have. An analysis of the mechanisms of plant parasitism and symbiosis, particularly of *Rhizobia*, shows that the interface could be created by genetic engineering. In the configuration proposed the cost of high-quality fuels from solar energy would be less by one order of magnitude than that of current schemes. The great sophistication required to develop the biological components of the system and the great simplicity in applying it in order to collect solar energy, are a perfect example of *technological transfer* suited for the recipient, that is, developing nations.

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