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Complexity, Energy Transformation and Post-Normal Science

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1. Postnormal science

The symposium discussion which is the genesis of this paper is concerned with post-normal science. Early in Allen's career, a colleague offered some generous advice, suggesting that he had just given a brilliant lecture that solved a problem that the students did not have; the lecture had been a failure. So that this symposium should not suffer the same fate, this paper has been written to give the audience a problem for which post-normal science offers a solution. Other discussants will address aspects of post-normal science, but this paper gives an example of a human/energy situation that cannot be solved without liberal use of post-normal science.

In postnormal science [Funtowicz and Ravetz, 1993] the stakes are high, the data are insufficient, and time is short. The meticulous conduct of normal, modern science [Kuhn, 1962] in such situations is moot, but even so science must still offer the best advice it can. Collecting data on energy options, and devising explicit means of using hydrogen as a carrier is important, and can be profitably considered by normal, modern science. However, there is a larger context that makes the issue of energy in the coming century one that is postnormal in character, which will not yield to the careful calibration of normal science. The present paper will discuss how the problems of energy for civilization at large involve high stakes, turn on insufficient data, and represent a pressing issue on a short time fuse. At least some part of the scientific community must adopt a postnormal posture if a happy outcome is to be achieved.

2. Societal collapse

Looking down the long time line of complex societies, Tainter (1988) observes that, for the most part, the narratives told for the collapse of complex societies are at best documentation of some aspects of the events of the decline, offering little explanation for why the collapse occurred. At worst, the explanations appear illogical. Tainter (1988) offers an alternative that is more general and explanatory for many collapses. His arguments turn on the diminishing returns that appear to be the rule in problem-solving in complex societies (Figure 1).

Tainter characterizes societies as problem-solving entities that elaborate structure in order to achieve solutions to problems, such as resource capture and use. Early in the cycle of problem-solving there are many easy solutions to the problems that present themselves. Furthermore, these easy, low cost solutions give much benefit. However, the easy solutions are quickly deployed, leaving only more expensive and less cost effective answers to emerging issues. In the case of empires, for instance, a shift from production exclusively at home to conquest abroad leads initially to great influxes of wealth. Yet, as an empire expands it encounters longer communication lines and must absorb and defend the province. Returns diminish and the burden of the effort is placed on the populace. Sometimes the burden is one of heavy taxation, as late in the Roman Empire. There is not full cost accounting in the deployment of difficult and elaborate remedies to resource problems. As the diminishing returns worsen, eventually it becomes clear that the enterprise is no longer worth the effort. Problems keep arising, as they always do, and eventually the society loses the ability or will overcome them. At the time of the collapse or retrenchment, rather than rallying and overcoming the last problem, those who are asked to carry the burden of the system under stress may choose instead to withdraw, as did Roman peasants who joined barbarians or even invited them in [Tainter, 1994].

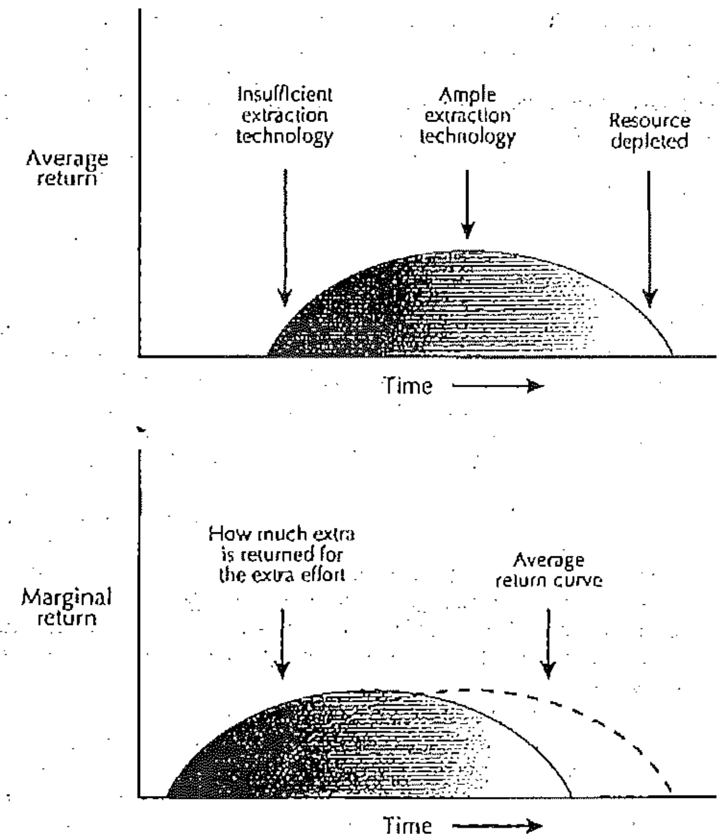

Figure 1. While economists generally do not use time on the abscissa for average and marginal returns, time in this diagram corresponds to a relationship between extraction technology and diminishing reserves. The average return has a first derivative, the marginal return, which is the extra resource that comes from the extra effort. When that curve is flat at the top, extra effort becomes a losing proposition.

For the present purposes, rather than enter into a discussion of the definition of a societal collapse, let us simply note that there are times of decline and retrenchment, some of which will meet the reader's definition of a collapse. The system we will propose operates at several levels of organization and analysis, and so collapse at one scale might appear incidental at a higher level of analysis. Nevertheless, a gradual retrenchment might appear at a lower level of analysis as a bona fide collapse when seen over a longer time span [Ahl and Allen, 1996]. We do not need to distinguish here between collapse and retrenchment.

2.1 Complexity and complicatedness

Allen et al. (1999) have extended Tainter's arguments, and distinguish between systems that complexify, as opposed to those that merely complicate. There is elaboration in both complexification and complication, but the new parts and connections that appear under complexification pertain to an increase in organization. By contrast, in a complication there is merely an increase in variety of parts and connections, with no change in organization. Organization amounts to some parts of the system exerting constraint over others. The hallmark of complexity is asymmetric relationships embodied in constraints. Therefore, in complexification the new parts and connections exhibit asymmetry. Low level parts have degrees of freedom stripped away by higher level parts. This reduction of options gives rise to the whole system coherence that characterizes complex systems. The new parts and connections in a mere complication amount to more of the same. The parts in a complication are simply additive, and so they only extend symmetric relationships. The parts in a complexification are not additive, since some control others (Figure 2)

There is room for confusion in social systems, in that there are structures actually named the organization, perhaps in business or espionage as examples. There is nothing wrong with those entities being associated with our more general notion of system organization, but an elaboration of them may not in fact increase system organization as we view it. It is possible for the administrative organization to become merely more complicated, as when middle level managers proliferate as bureaucracies expand. There elaboration of social organization and asymmetries have arisen, but they occur at the same level of analysis, within the framework of the existing organization. An increase in organization, in the way that we mean it, would require new constraints outside the existing organizational framework, either from above as new overall constraints on the entire system, or as new controls that go to a deeper level below the lowest level theretofore. New constraints from above might pertain to a new energy source, such as coal. New constraints at a level below make fine distinctions and might be control that works on distinctions between materials such as isotopes at a level below chemistry. Elaboration in between is defined here to be just an administrative complication.

When societies solve problems with diminishing returns, the elaboration can be considered a complication rather than a complexification. This is because the diminishing return is by definition inside an existing framework, such as improving irrigation or developing new ways of drilling for oil. The return is still irrigated crops or oil. Solutions that complicate a situation become progressively harder to achieve and maintain, such as drilling under the ocean. The price for complications is paid by burdening the existing system structure, taking out slack, and demanding more of the system components. This cost is hidden by lack of full-cost accounting, allowing decision makers to escape responsibility for the cost of the complications with which they encumber society. Too much societal complication, with its burdens and diminishing returns, has contributed to collapse or serious retrenchment seen in many historical societies.

But societies heavily burdened with complications do not always collapse. Some societies, pressed at the edge of a serious retrenchment, find a new way of operating that resets the diminishing returns. New rules governing the whole system come into play, and this new way of operating obviates the old complications. We set adoption of a new way of operating in contrast to complication, and label it a complexification. Adoption of a new way of operating introduces new asymmetries in the form of new constraints. Let us give some examples.

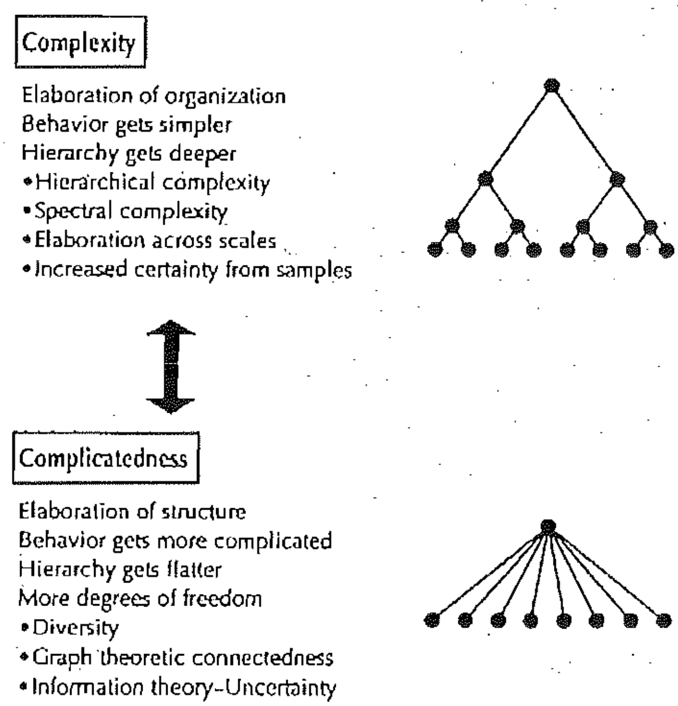

Figure 2. In a complication additional parts widen the span by adding parts that are equivalent to parts already existing at that level. In a complexification, new parts occur at new levels, exerting control over extant parts. Complication is merely structural elaboration, whereas complexification elaborates organization.

When societies become involved in larger changes, such as a move to imperialism, or into the Industrial Revolution, the change is better described as a complexification brought about by a set of positive feedbacks. The benefit of complexification is escape from the high cost and low benefit at the end of the previous cycle of complication. For instance, the move to a dependency on agriculture obviated the problems of moving large distances to the next hunted or gathered resource. The switch to conquest made production of resources a less pressing issue, as resources were simply taken from conquered people in loot or taxes.

In the case of complication, the cost is met by burdening the extant structure. In the concept of complexification that we use in the present discussion, the burden on extant infrastructure is only temporary. For instance, there was a significant burden on the populace when Britain switched from wood, that could be cut in the environs, to coal, that had to be bought. But note that as coal came on line, it brought with it benefits such as industrial production and transportation. The complexifications that illustrate the case we wish to make move in time to the easy capture of new resources that pay for the change. In the case of coal and the Industrial Revolution, there were positive feedbacks wherein coal facilitated the move to coal. Access to coal allowed pumping of mines with steam engines. Pumping capacity made more coal available in a positive feedback. With increased availability of coal, smelting of iron required either the coal or the iron ore to be moved into the proximity of the other. The pump engines were modified and put on wheels to make steam railways that ran on coal and moved on iron rails, so placing a demand on fuel and metal. The availability of iron led to better machines for extracting coal, thus closing a second positive feedback.[1]

The cost of complexification that pertains to our particular issue has two phases. First there is the cost of setting up the positive feedbacks for increased resource exploitation. This can be politically forced forward, much as a complication, and the cost may be born by straining the extant structure. In industrialization, this is the early phase, when there is suffering and burden on the populace as it is forced to shift from cutting wood gratis to buying coal. However, once the feedbacks are in place, they pay for themselves by sequestering ever more of the new resource, be it coal in industrialization or loot in imperialism. The cost of further movement toward the new way of doing things is then paid by dissipation of the new energy or resource gradient. That resource was not pertinent to the old version of the system, the complicated society about to be replaced in the complexification. Complexification is often associated with obvious positive feedbacks where lowering the gradient of the new resource leads to further exploitation of that new resource. We begin to suspect that there is typically positive feedback somewhere underpinning this sort of complexification. By tapping into the new resource, the complexification pays for itself.

The costs and benefits of complication and complexification are largely, but not entirely, separate. A new resource gradient, such as coal, will complexify a society, or the society may elaborate under duress, based on existing resources, to solve a problem. If in the case of duress there is a positive feedback that elaborates society and exploitation of the resource, that would be a complexification in our terms. However, if there is no positive feedback and little extra resource is extracted, the situation is merely a complication. Beyond the disruption of old, comfortable ways of doing things, the cost of complexification is that a gradient is to a degree dissipated. At the time, dissipation of the gradient is of no importance, because resources are abundant. The cost of maintaining complexity is the diminishing returns that attend the complications that occur in the new cycle of activity. The long term cost of complexity is entrapment in the cost/benefit relationship of a new complicating process (Figure 3).

The elaboration of structure in order to solve local problems of resource capture brings up marginal returns. Marginal return is how much extra does society get for extra effort (Figure 1). Because of vicious diminishing returns, resources are often abandoned when well under half has been consumed. The resource becomes not worth the effort a long time before it is materially depleted.

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[1] There is disagreement among the authors about whether complexification in human societies results only from positive feedback. Tainter views complexification arising also from adaptive problem solving, such as when the later Roman Empire proliferated its governmental apparatus and increased its control over individual lives to counter external threats [Tainter 1988, 1994]. There was no intake of new resources, merely harder squeezing of the existing ones. This precipitated negative feedbacks that ultimately contributed to collapse. Allen reserves complexification to mean positive feedback and easing of a system's burdens. New terminology is probably required, although in this paper we use complexification in the sense of the main text.

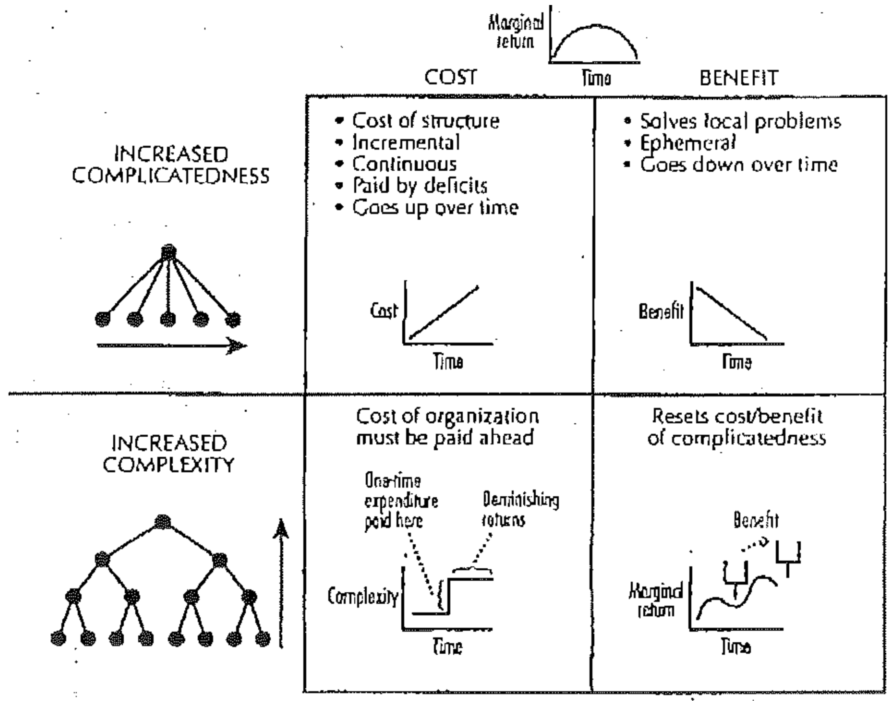

Figure 3. The costs and benefits of complication and complexification are largely separate, but become linked in maintaining new complexity, the cost of which is diminishing return in a new cycle of complication.

3. Quality of resources

A biological example of resource use is most illuminating for the present crisis in energy resources of the first world. There is a genus of ants, *Atta*, that farm fungi on various organic resources. The primitive species use insect droppings to grow their food. The problem with insect droppings is that they are a highly processed resource, several steps away from the source of energy: the sun, leaves, fruit, insect, insect droppings. High quality as insect droppings may be for growing fungi, they are in short supply. This limits the size and degree of organization of the colonies of that species of ant. The more advanced species use leaves instead of insect droppings. Leaf cutting ant societies are far more organized than their insect dropping counterparts. Stripping a tree of leaves involves long trails with under and overpasses through the jungle. The limits on those systems appear to involve efficient organization of waiting time in lines, as described by queuing [Burd 1996]. The increased organization comes from the enormous quantity of leaves as a resource as opposed to insect droppings.

It is no accident that the first entry into farming fungi by ants is through the high quality resource embodied in guano. It is far too unlikely that any sequence of events would lead to using leaves de novo. Guano, on the other hand, is high quality. In a reasonable, but not essential scenario, guano could be brought into the nest attached to collections of "wild fungi". Insect droppings accumulated by happenstance on the floor of the nest could become the basis of "domesticating" fungi inside the colony. It is clearly easiest to start a process of exploitation with high quality material, such as insect droppings

In the fungus farming ants, there appear to be at least two complexifications. First is the emergence of fungus farming. Second is shift from guano to leaves. The first complexification depends on the exceptionally high quality of the resource. That quality imposes order on the primitive ants. The second complexification depends on the leaves as a resource, but is less driven by the resource. Leaves are a low quality resource, not far removed from the sun. Accordingly, it is not the quality of the resource that imposes organization. Rather, leaf cutter organization is driven by the ants becoming more organized in order to deal with the massive amount of resource that must be processed.

3.1 Quality of resource and human society

When we look at human society over millennia, we see a pattern similar to that in the fungus farming ants. In the ants it took a high quality resource to let the ants into a fundamentally new mode of operation, farming. Subsequently, larger and more elaborate systems emerged for the ants based on a low quality resource that needed a lot more processing by the ant users (Figure 4).

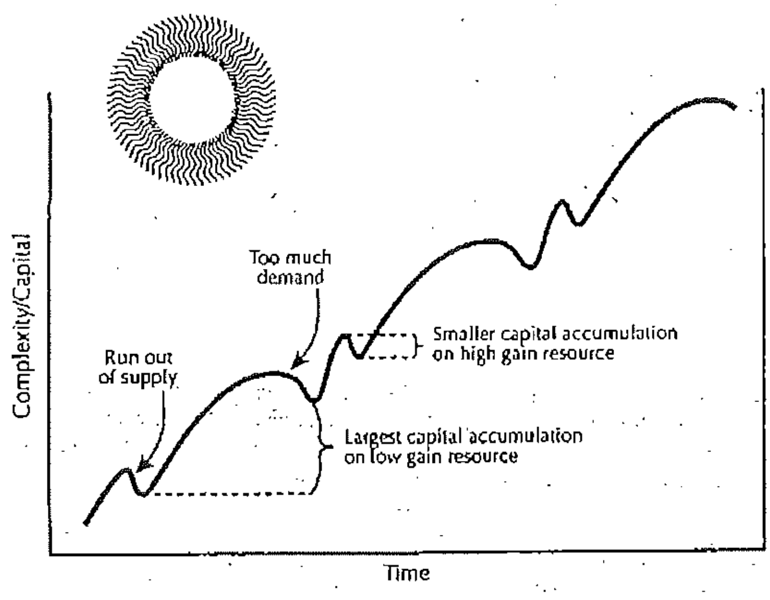

Figure 4. Marginal return curves for ants and human resource capture appear to have two phases. A high quality resource imposes organization on the system, and ends when the resource is depleted. There may follow a cycle of use of a low quality resource that can only be exploited by the system bootstrapping itself into elaborate organization. Low quality cycles end in too much demand being placed on a huge resource by what has become a very large and complicated system.

We identify a similar pattern in human use of resources. Hunter-gatherers often concentrate on abundant, high quality foods, moving to where they may be found. Hunters and gatherers set the scene for agriculture, much as fungus farming ants using guano set the scene for leaf cutter ants. Agriculturalists move closer to the sun by raising tracts of homogeneous food, which they are able to do because their hunter-gatherer forebears found and manipulated plants that were potentially productive and amenable to cultivation.

Agricultural societies are limited ultimately by solar energy, and when they encounter problems one solution is to capture more territory where solar energy falls. Conquest speeds up energy capture, by appropriating other peoples' accumulated surpluses. Yet once these surpluses have been looted, a conqueror must thereafter garrison, administer and defend a province. These responsibilities are paid from yearly agricultural production [Tainter 1988, 1994]. As with bird droppings, loot is valuable but in short supply. By definition, loot is a transitory resource. There is always a need to shift to a new phase of low quality resources, taxes. Taxes are hard to collect and demand a large infrastructure, but in an agrarian landscape there are lots of people to tax. Taxes are a low quality resource for one can only extract relatively small quantities from each person. The preceding looting takes a high quality resource, namely accumulated riches. While the end of a cycle of high quality resource comes when the scarce resource runs out, low quality resource cycles end when there is too much demand put on the large resource base. Imperial taxation produces a large, highly organized system, but the cost of increased taxation becomes unbearable. Long frontiers and an increasingly disgruntled populace erode political stability. Local people reassert autonomy. Imperial cycles always end with too much burden placed on a taxation system.

When Britain found itself without wood for everyday needs, living standards declined and the next best alternative was sought. The move to coal was neither easy nor popular. One can cut wood in the environs, but one must buy coal [Wilkinson 1973]. In retrospect, the move to coal was a very good idea, but at the time it was resisted. The move to coal meant in time that increased productivity did not depend on human muscle, powered by food. Fewer people could achieve more. There have been shifts to other fossil fuels and carbon fuel technologies, and these are reflected in the Schumpeter (1950) curves, well understood in economics. We could analyze those shifts in the same terms as above, but at the grand level of analysis we have considered heretofore, the high quality cycle of fossil fuel appears to be a unified cycle in itself. The industrial world is coming to the end of the high quality cycle that depends on carbon (Figure 5).

3.2 The new shift in quality

The change to a hydrogen and information-based system appears to be a shift to a low quality resource. Pure hydrogen itself is a high quality energy source akin to fossil fuels. Speakers at this workshop have discussed how hydrogen for use in fuel cells can be generated by consuming fossil fuels. However, in a full flowering of the hydrogen economy, the resources that will load the hydrogen carrier are going to be low quality energy such a wind, wave and solar. Unlike the Industrial Age, which solved problems with larger tools using more energy, the Information Age depends on miniaturization. Much as when the Industrial Age began, and the previous agrarian system was left in place, there will be an industrial base that will be taken for granted. In industry material things are moved through a distribution system, and people move to and from places of work. The Information Age minimizes moving material things, or at least makes the process very efficient by moving information instead of people. The flux of information allows the human system to be distributed, a characteristic of low quality resource capture. It is no accident that, while industry with its high quality energy is concentrated, agriculture is distributed. The energy captured in agriculture is low quality, and needs to be massively distributed to supply six billion

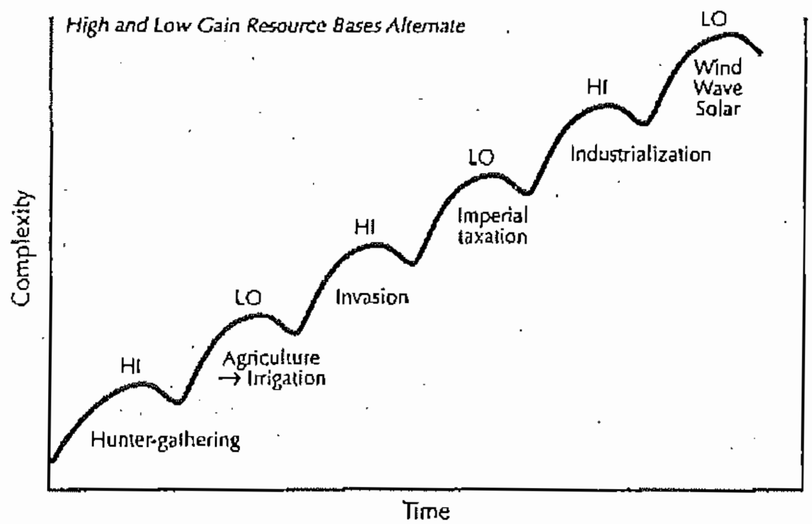

Figure 5. Various changes in human society may be seen as an alternation of use of high and low quality resources. Several levels depicted here, such as third world agriculture and hunting and gathering, persist to this day as fully functioning systems, without much need to modify. The chart does not suggest a sequence or trend of cultural evolution. Even so, noting the alternation of high and low quality is instructive as to the dilemmas of modern and future energy use.

people. The critical features of renewable resources are that they are low quality, but abundant in quantity, albeit distributed.

Whereas the politics of renewable energy gains support from the environmentally sensitive, there is a certain irony in this support. So too is there irony in the intransigence with regard to renewable resources in the political sectors of industry, business and energy suppliers. Whereas green politics decries industry and fossil fuel, the environmental damage done to the world is minimally from industrial sources. That is because the energy used by modern industry is principally high quality, and so does work in a focused fashion with relatively small side effects. There is measurable environmental degradation coming from industry, but it is not the main villain. The principal cause of loss of species and environmental degradation is agriculture. The distributed nature of agriculture means that habitat is removed and landscapes are grossly altered. Increased flooding, soil loss, and non-point centered sources of pollution are principally caused by agriculture. Furthermore, we do not particularly pillory agribusiness with its agrochemicals. Third World peasants are equally destructive. Notice that the environmental impact of ants that use guano is minimal compared to those that strip entire trees of leaves. Environmental degradation is greater when the resource is of low quality, and distributed. The switch to renewable energy sources will be environmentally much worse than anything done by industry using fossil fuel. In the reverse irony aimed at conservatives and the business sector, the profits to be made from building the energy capturing infrastructure are likely to be enormous. Politicians will be less in the pockets of road builders and more influenced by businesses that recreate whole coastlines for wave capture, and cover huge tracts of land with solar collectors. There are two principal paths to the low quality resource economy. Neither looks inviting, but the alternative appears to be the Four Horsemen of the Apocalypse. In the first scenario, the massive infrastructure is bought by burning our way down the mountains of sulphurous coal that dwarf the coal consumed heretofore. Much as leaf cutter ants could not have evolved without the preliminary step of the species that use high quality guano, the hydrogen economy could never have emerged without a high quality carbon energy source as a precursor. The environmental pollution coming from dirty coal over the coming centuries will likely be much worse than that coming from the clean burning oil and gas we use at the moment. Under this scenario the present energy distribution system remains intact, and the huge, decentralized energy capture system dwarfs infrastructure seen heretofore.

The other scenario abandons the present infrastructure, as humans in the first world become decentralized. Urban decay would seem to be part of this scenario. The diffuse information system will keep human activity integrated and will resonate with the decentralization of society. Energy will be captured directly by small individual units scattered across the landscape. We can expect a significant decline in standard of living, as the system decentralizes. The massive infrastructure will take a long time coming, since it will have to be built in a gradual process of accumulation of capital. A useful parallel might be the millennia of capital accumulation following the first agricultural systems, before precious metals and looting took over as system drivers. Hydrogen may be generated as part of the distributed local energy capture system, so that at least some high quality energy is available for special situations that need it. Once enough capital has been accumulated, and expanding local energy production coalesces, the massive infrastructure of highly organized concentration of low quality energy will emerge. Hydrogen would probably play a large role in the fully developed system. The end point will be the same as the scenario that burns sulphurous coal, but the cost will be disruption of human systems more than environmental pollution. Some sort of compromise scenario that uses coal and involves decentralization is also a possibility.

4. We face a post-normal problem

The engineers at the workshop were impressive in the ingenuity they have shown regarding hydrogen as an energy carrier. It appears that there are many alternatives within fossil fuel technology that can stretch the supply of high quality energy to give a surprisingly long glide-down of the carbon-based energy system. Statements have been made at this workshop that the problem with fossil fuel is atmospheric pollution, not running out of fossil energy sources. In the short term that may be true, but it would be imprudent to ignore the inevitable decline of the carbon-based economy. It is noteworthy that while the price of modern information technology goes down, the price of a car or rotor tiller moves up with inflation. We should not be lulled into overconfidence by successes in information systems, because the limits of technology involving moving parts appear real and pressing. While energy for electronics is trivial, the essential problem is energy for electric motors. The industrial underpinning of the information society appears to be the essential weakness of the modern human situation.

It is not going to be possible to finesse our way past the coming obstacles, the engineering brilliance of normal science notwithstanding. Surviving the coming energy crisis will of necessity require radical social reorganization. We are about to pass through a complexification, as renewable resources become the primary source of energy. These transition points are critical, and many societies have failed to make it across them. Further politics of less than full-cost accounting can only last so long before proving disastrous. Continuing with carbon-based energy can only be supported by burdening the system structure. At the end of a cycle of increasing complicatedness, the whole system is supported by a sort of shell game. Continuing with a carbon-based energy system is already generating high cost of energy capture. That cost will go up in terms of more complicated industrial machinery to drill oil under deep water, and in pollution of waters and the air. By moving to hydrogen and low quality, renewable energy, we can escape from under the pressing constraint of diminishing supplies of high quality carbon resources. It is becoming urgent that we cease complicating on carbon. Moving to hydrogen gets us away from the complications of drilling in the Antarctic and over the edges of the continental shelves. The change to a complexification on hydrogen will have its immediate downside, but hydrogen technology will be simpler than the difficulties of the coming carbon energy crisis. The renewable nature of low quality energy will allow a positive feedback of expanded sequestration of those resources.

The coming complexification of organizing ourselves to produce dispersed, low-gain energy must happen, or our civilization will lose its basis. Loss of the carbon system without a move to hydrogen will likely be terminal. We have already used the fossil carbon energy of which non-industrial people could avail themselves. It appears that we only have one shot at a hydrogen economy, and this is it. Our version of guano-using ant colonies is about to go extinct, and we need to transition to something equivalent to leaf cutting. Much as the prospect of the Industrial Age was not inviting, neither is the prospect of a hydrogen economy. It will take all the skill we have in post normal science to make the transition, for it can only happen through the support of the mass of people on whose backs it will be lifted. There are many people who are going to have to change their way of life as fundamentally as did the displaced yeoman of Britain when coal mining became the best work available. With its focus on stakeholders and cognizance of alternative points of view, postnormal science will have a crucial role to play in facilitating the transition. The most cost-effective path to the hydrogen economy, and the one that is most likely allow us passage, is to dismantle the carbon-based system as humanely as possible. There will be enough brutality in the transition of necessity, without adding to the misery by socially careless engineering.

It is encouraging that once complexifications get going they may pay for themselves. We only need to begin to tap the sources of renewable energy at a sufficient scale for the system to move by itself. Renewable energy at a workable cost will encourage movement further in that direction. The engineers will be essential, and the expertise displayed at this workshop is encouraging, but the essential problem is one of bringing the mass of stakeholders along with us. Great transitions do not turn on bright ideas. The origins of agriculture cannot be explained by genius theories. The important transition in the Neolithic Revolution was accepting agriculture as worthwhile or inevitable, just as the shift from wood to coal was inevitable if initially undesirable. The hard part of the transition to renewable resources turns on willingness, values and faith in the system. This willingness to make the move probably cannot be achieved without a self-reflexive science and engineering that post-normal science offers.

In retrospect, those living in the hydrogen economy will be puzzled at the hand wringing in this paper, and of energy experts at the end of the 20th Century. But for us the problem is real since the populace at large is not aware of the problem, how short is the time, how large are the stakes, and how large are the uncertainties. Without post-normal science we could well fall down the gap into oblivion. We have a problem, and the only solution appears to involve embracing values, not putting them aside from the engineering exigencies. The self-reflexivity of post-normal science is the way to bring the stakeholders along, and we cannot solve the energy crisis without them and their good will.

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