Jesse H. Ausubel

Hydrogen and the Green Wave

Will hydrogen win in the fierce and dirty competition among sources of energy?

Jesse H. Ausubel is a fellow in Science and Public Policy at the Rockefeller University in New York City and the Director of Studies for the Carnegie Commission on Science, Technology, and Government. He was director of the NAE Program Office from 1984 to 1989. This article is based on the keynote address to the National Hydrogen Association, 9 March 1990, in Washington, D.C.

Hydrogen is precious because it can be manufactured from something abundant, namely water; because it can be substituted for most fuels now in use; and, above all, because the product of its combustion, water vapor, is nonpolluting. But, will hydrogen win in the fierce and dirty competition among sources of energy? If so, when?

To help answer these questions, I will offer a glimpse into the deep structure of environmental issues. To do this, it is necessary to take a long-term, quantitative perspective spanning several decades, even a century, both backward and forward in time. I will also introduce three analytical frameworks, or ways of thinking about environmental quality. These frameworks are industrial metabolism; materials usage or "dematerialization;" and technological trajectories, the long-term regularities in the evolution of technology. The frameworks were developed as part of a study on technology and environment carried out in 1988–1989 by the National Academy of Engineering.[1]

The need for better frameworks, for a better vocabulary for thinking about environmental issues, should not be underestimated. The "Green Wave" of environmental concern that is circling our planet makes it clear that analysts and managers have overlooked something.

Traditionally, the United States and other countries have tended to emphasize regulatory approaches to environmental problems. Moreover, most environmental programs have aimed to regulate point sources of pollution, usually those in industry, and the actions have been at the "end of the pipe," after pollution has been created. This has brought significant gains in such areas as the operation of steel, paper, and power plants. However, the regulation of the individual components of the industrial system has had frustratingly little overall effect on pollutant and materials flows. So along come problems like climatic change and hazardous wastes, which do not respond to the current system of regulatory sticks and carrots. And we have hardly stopped to think how factors like the growth of service industries and the suburbs increasingly drive issues of environmental quality.

Given this piecemeal approach to environmental research and management, it is not surprising that our track record in predicting environmental and resource problems has not been very good. It is easy to list problems of the past 30 years that were badly exaggerated, as well as the surprises that both the analysts and the advocates failed to anticipate. There is an urgent need to think about environmental issues in ways that stress comprehensiveness, a total systems approach. The three frameworks mentioned above are important and useful because they capture or recognize three things: (1) the total human economy; that is, both production and consumption; (2) the dynamics of change; and (3) the role of technology. The further development of frameworks like these can go a long way toward providing society with tools that would reveal in profound and reliable ways the sources and solutions of environmental problems.

Before giving a few details about the frameworks, let me preview the conclusion of my analysis. There is a genuine environmental crisis. There is a waste explosion, and we are seeing it in all its manifestations. In New York City, if all types of waste (including both municipal and industrial wastes) are counted, there are some 5 to 10 pounds per day of waste per resident. A society simply cannot generate that level of waste without enormous problems and challenges. To give another illustrative fact, the United States now has about 185 million motor vehicles. To operate a fleet that large—and still growing by a couple of million per year—in a clean manner is a huge challenge.

At the same time, I believe that a large fraction of the public is in a period of global hypochondria. Only partly in jest, I have conjectured that society and individuals obey a "Law of Conservation of Concern." If we reduce our anxiety about one matter, we raise anxiety about another. The front page of the newspaper is always filled. Perhaps as our concern about nuclear war has subsided since Mikhail Gorbachev assumed power in the USSR in 1985, we have compensated partly by filling our anxiety quotient with environmental woes.

In the developed countries, where the Green Wave originated, it is hard to reconcile the ambient anxiety with the actual environmental quality. Although there are certainly great gains still to be sought and achieved in air and water quality and other domains, the present human health consequences of current levels of environmental quality in most economically advanced areas are not commensurate, in my view, with what people are certainly feeling. (The threats to ecosystems are probably a more justified immediate concern.) At the same time that environmental quality has in many ways improved in developed countries in this century, concern and goals have been elevated, not decreased.

There is an important lesson here: Societies need to operate economies that actually enhance environmental quality and prevent pollution, so that there is little reason to fear for the environmental future. This can be achieved by behavioral change, on the one hand, and technical progress, on the other. Is there any path that does not involve increasing and high reliance on hydrogen? Let me now present a few highlights about each framework and establish the context for this conclusion.

Industrial Metabolism

The notion of industrial metabolism proceeds from the premise that societies possess certain organic properties; that is, societies metabolize. They are systems for the transformation of materials. The concept of industrial metabolism, as developed by Robert U. Ayres, has its roots in at least two areas. One is the comprehensive accounting of nuclear materials. The other is the studies of the biogeochemical cycles of carbon, sulfur, nitrogen, and phosphorus that have been so popular among geochemists the past 15 years. What is new is to look carefully at such elements as cadmium, bromine, chromium, arsenic, mercury, and lead. What activities most significantly mobilize and release these elements? As reported in the NAE study, it is extremely difficult to obtain and compile data to perform the needed, detailed materials-balance studies.

Thinking in terms of industrial metabolism generates a number of insights. First, it puts a new perspective on monitoring, which is usually oriented toward levels in a particular medium, like water. Industrial metabolism reminds you to go with the flow. It also suggests an expanded and more vigorous role for industry in monitoring. Perhaps more industries that handle selected environmentally significant materials should be responsible for comprehensive physical accounting of the materials they acquire and either sell or dispose of.

Second, industrial metabolism broadens the scope of concern from production to consumption. In fact, industry is controlling materials flows with ever more care. Municipalities and especially consumers are not. It is important to remember that the entropy in the system is often associated with the environmental problems. It is important to examine the retail, as well as the wholesale, level of the economy for environment. Many small transactions can create large environmental problems.

Third, industrial metabolism gives us insight into how many uses of materials are inherently dissipative, tending to scatter rather than concentrate their elements. It would be valuable to obtain measures of dissipation. Currently, dissipation is not measured or monitored, except perhaps in rare cases such as the tritium from nuclear weapons testing. Dilution has been a solution for some environmental hazards, but its limits are more evident. This is true, for example, of fuels, food, packaging, lubricants, and pesticides. Industrial metabolism also reminds us that complexity in products and materials can create problems. It was easier to recycle an automobile of 1960 vintage than a 1985 model, with the latter's expanded use of composites, plastics, and electronics. In fact, some new materials are a crazy soup of ingredients that may prove troublesome from an environmental perspective.

A fourth outcome of thinking about industrial metabolism is an understanding of the globalization of environmental problems. It is quite straightforward that problems of consumption tend to become global in extent. Although production and manufacturing may be concentrated in a few sites, consumption is almost always widespread. For example, almost everyone uses batteries. The diffusion of most consumer goods, and therefore most materials, is global.

A final insight is how little of industrial metabolism is monetized. There are few economic signals associated with many materials flows.

Dematerialization

Let me now introduce dematerialization. In fact, you have been hearing about it for years. Many commentators say, "Everything is becoming smaller and lighter, and information, not tangible goods, is the heart of the new economy."

Let us define dematerialization simply as the decline over time in weight of materials or of embedded energy in products. There is a logic to dematerialization. Over their life cycle, many goods tend to become more compact. The ability to miniaturize many kinds of goods has grown. Some people also argue that a saturation of material wants comes with affluence. There is a limit to how much food an individual will consume, for example.

Dematerialization would be good news for the environment, other things being equal. But is it occurring? Robert Herman (NAE), Siamak Ardekani, and I developed some ideas for answering that question. First, of course, there are two underlying forces toward materialization—population growth and economic growth. Most people on the planet are not near the hypothesized transition where they begin to want only more information and not more goods. Among several other factors that need to be taken into account in assessing the prospects for dematerialization is the quality of goods; well-made goods that last longer may generate less waste.

The perception of dematerialization is correct in some areas. The average U.S. car became lighter by some 400 pounds between 1978 and 1986, largely because of reduced use of plain carbon steel. Indeed, several examples suggest that it may be possible to generalize to say that industry is dematerializing. However, consumers are not. Consumption, summarized by municipal waste, appears to be undergoing a linear increase with time. Moreover, U.S. life-styles are not heading in the direction of stemming this increase. As more of the population is housed in suburbs and has a vacation home, there are needs for more roads, cars, buildings, pipes, paint, furnishings of all kinds: in short, materials. And who can explain why Americans are now buying about five pairs of shoes per capita each year when four sufficed throughout the 1970s? Perhaps it is because shoes are now difficult or expensive to repair, or because of fashion, which tends to be a force for materialization.

There are, alas for the environment, not many signs of saturation of material wants. When the wealthy unpack from a holiday or a shopping trip, they are usually bearing more than their less well-off cousins.

What about the effect of the information revolution? Contrary to many forecasts, in the information era paper consumption has vastly increased, and the trees of the world are at risk. It is estimated that 4 trillion pages will be printed in the United States in 1990. Electronic memory appears only to have augmented the demand for "hard copy" and large buildings in which to read, discuss, and store it.

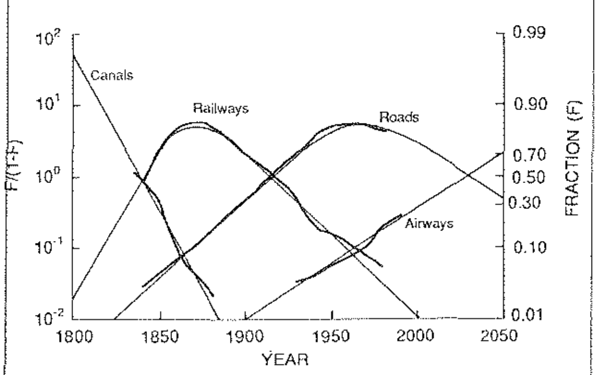
One problem in understanding dematerialization is that the data are poor. There are only very partial data on garbage, and these data are mostly on solid waste taken away by municipal services. International comparisons of materials use and waste generation are weak because of inadequate surveys or different times when the surveys were carried out.

Although the overall trend may not yet exist, there is an imperative to seek reduced materials intensiveness or dematerialization. Dematerialization is one of the master questions of our age. At present, only about 1 percent of the $80 billion dollars spent each year in the United States on environmental protection goes for pollution prevention.

Long-Term Regularities

The first point about long-term regularities in technological development, or technological trajectories, is that they exist. There are patterns, and these can be interpreted from an environmental point of view and offer possibilities for prediction. For example, there has been a remarkably steady evolution of transport infrastructures in the United States (Figure

FIGURE 1



Shares of total operated intercity route mileage of competing transport infrastructure in the United States. Source: Nakicenovic (1988).

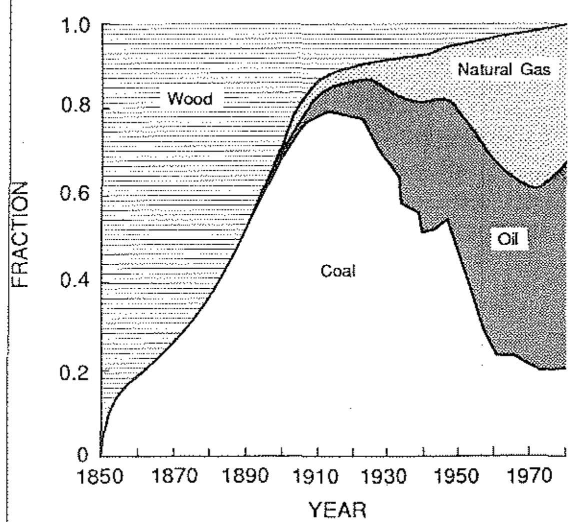
1). Think of the total transport infrastructure of the country as a growing pie, quantified in miles of routes. At any time, it is possible to say how big a slice, or fraction (*F*), of the pie is in canals, railways, paved roads, or airways.

Large infrastructure systems like those for transport usually both solve and introduce environmental problems. A major environmental crisis that came with the railroads, it is usually forgotten, was a wood crisis. In a 1905 speech to the American Forest Congress, Theodore Roosevelt said,

> Unless the vast forests of the United States can be made ready to meet the vast demands which this [economic] growth will inevitably bring, commercial disaster, that means disaster to the whole country, is inevitable. The railroads must have ties. . . .If the present rate of forest destruction is allowed to continue, with nothing to offset it, a timber famine in the future is inevitable.

Chemical technologies, especially the use of creosote to extend the life of railroad ties, and the saturation of the route network of railways essentially ended the problem. Today, the image of railroads is usually environmentally benign. Paved roads, which replaced rails as the dominant transport infrastructure, have brought their own environmental problems; for example, urban air and noise pollution and the salts used to keep the roads ice free. A good question is what the problems of the air transport system, the emerging dominant infrastructure, will prove to

FIGURE 2

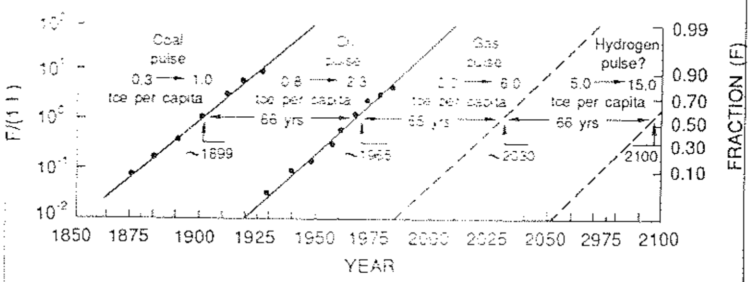


Hydrocarbon fuel consumption in the United States, fraction by fuel type, 1850–1980. Source: National Research Council (1986).

be. Perhaps the problem will be associated with oxides of nitrogen in the troposphere.

Figure 2, showing the relative sizes of the four main primary energy sources for the United States since 1850, illustrates the equally regular long-term behavior of technologies in the energy sector. The environmental story is that first wood dominated, bringing concerns about forests and town smoke; then coal, with its sulfurous fumes; and then oil and its spills and urban smog and brown clouds over Denver and Los Angeles. Now natural gas, temporarily diverted by congressional legislation in the 1970s, is climbing to first place in the United States and worldwide. Ironically, natural gas, by far the cleanest fossil

FIGURE 3



Past and projected growth pulses in world per capita energy consumption (tons of coal equivalent), with midpoints indicated. In each pulse, per capita energy consumption roughly triples. Source: Ausubel et al. (1988).

fuel, may end up contributing more carbon dioxide to the atmosphere than any other fossil fuel, simply because energy demand is growing so much higher than when wood, coal, or oil ruled.

Another regularity is that growth in the energy system has come in pulses. Figure 3, which is the result of ongoing collaboration with two colleagues in Austria, Nebojsa Nakicenovic and Arnulf Gruebler, shows one pulse lasting some 40 years built around coal. By our calculations, the world is now at the end of a second pulse of growth in energy consumption, the oil pulse. It appears that a new pulse of growth in energy demand, which has been rather stagnant for a decade or so, is just being born around natural gas. We conjecture that after gas will come the hydrogen pulse. Note that the succession of fuels is a succession toward environmental compatibility at each step. Many populated regions of the world would already be dangerously unhealthy and environmentally devastated if most of the roughly 10 billion tons coal equivalent of primary energy that humanity will use in 1990 were actually provided by coal.

This brings out the second point about technological regularities. They exhibit some of the very positive roles historically played by technologies. My favorite example is the shift from horses to cars. At the peak of the equine era, there were about 20 million horses in the United States. Just thinking environmentally, the United States never could have accommodated 185 million horses, the current number of motor vehicles. Better technologies have enabled society to accommodate higher densities of population and economic activity by orders of magnitude even within this century.

Third, the long-term regularities in technology show the critical role of substitution processes. As the late Elliot Montroll said, evolution is a sequence of replacements. The key is to make replacements that are environmentally superior, as well as superior in other respects. There are already 500,000 natural gas powered cars in the world. I believe that the substitution of natural gas for gasoline in cars will be one of the most environmentally significant shifts of the next 20–30 years. To neglect the possibility of substitution and extrapolate only on the basis of current technology leads to very poor forecasts. In 1955 AT&T made cables out of copper, steel, and lead. If the company had made the cables in 1984 with the same recipe, AT&T would have used 1 billion pounds of lead that year, an environmentally daunting prospect. But, in 1984 the cables were 40 percent plastic, and lead had become an almost insignificant fraction, only 1 million pounds. Now, glass fibers are in turn replacing today's still-bulky cables.

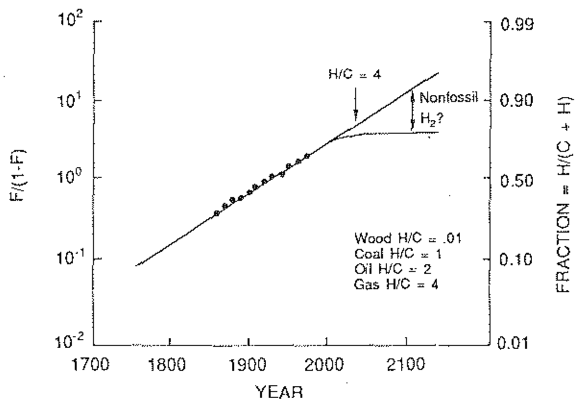
A final point about technological trajectories is that they may be regarded as providing the "envelope" or boundaries within which regulation or incentives may function easily. History shows that it is costly to deviate far from the trajectories.

To summarize, attention to long-term regularities in technology brings a more complete and dynamic history of the economy than that which usually frames environmental debates. Such studies reveal the time scales at which processes operate. They show the scope of progress and the need for long-term, patient application to goals.

Conclusion

We can now put hydrogen in perspective. Suppose all the materials used by society were placed into a big blender. What would be the resulting mixture? Physicist and engineer Alvin Weinberg (NAE) asked this question some 20 years ago. In 1968 he and Herbert Goeller (1976) calculated the make-up of an imaginary element that they named "demandite," the average nonrenewable resource used by human society. In that year, hydrocarbons made up 80 percent of demandite for the United States and 60 percent for the world as a whole. If demandite were synthesized for 1989, its make-up would have changed a

FIGURE 4



Evolution of the ratio of hydrogen (H) to carbon (C) in the world fuel mix. Source: Marchetti (1985).

little. The rest of the world would be relying more, not less, on hydrocarbons, and their hydrocarbon mix would be more like that of the United States, as many nations have increased their consumption of oil and gas relative to coal. The facts are that we are still in the "fossil" era and the end may only barely be in sight. The displacement of hydrocarbons remains by far the largest single environmental challenge facing the planet.

And we will succeed in meeting this challenge. Why am I confident? If the materials placed in the blender are limited to hydrocarbon energy sources, including wood, and the mixture is calculated for the globe for each year since the mid-nineteenth century, then it becomes clear that the technological trajectory is to move toward hydrogen and away from carbon (Figure 4). To me, the evolution of the H/C ratio, an insight for which we are indebted to the Italian materials engineer Cesare Marchetti, is the most important single fact in the entire environment-energy discussion. It should be regarded the way the functioning of DNA is regarded in genetics, as the central dogma.

The problem is that hydrogen is not going to win soon. If history is a guide, large amounts of hydrogen will begin to be produced in about a decade. However, hydrogen will not displace gas as the central fuel for the United States and the world until the middle of the next century. The fun of it is that the next decade or two will see much critical experimentation with technologies for production, transport, and storage of hydrogen. The cutting edge applications, like those in the aerospace sector, will grow rapidly. Out of the turbulence may arise major new hydrogen-based enterprises.

The heartbreak is that there will be lots of failures in the hydrogen contest, and that we will have to live with fossil fuels for another 50 years or more, even though we recognize the likely consequences of oil spills, smog, acidification, and global warming. As the medieval alchemists learned, it is not so simple to transform something common into something precious, though processing water into hydrogen with nuclear or solar heat, clever chemistry, and electricity is clearly a better bet than going from base metals to gold.

In conclusion, in the environmental problem, we are confronted with our own materialization. We draw some 40 or 50 pounds of materials from the environment daily and discard perhaps as much as 10 pounds daily as waste in the United States. Volume is a problem, composition is a problem. Disposal in all media is difficult and will become more so. Many, even most, of our environmental issues can be interpreted as manifestations of materialization. They are not isolated or peculiar. We need a general solution, centered on engineering design and economic incentives for waste reduction and certain kinds of efficiency. At the center of a new industrial metabolism should be our friend hydrogen, the immaterial material. It appears that powerful, lasting winds are blowing us in that direction.

Ride the Green Wave.

NOTE

1. Many of the ideas and data in the paper are reported in the NAE book published in 1989 entitled *Technology and Environment*, J. H. Ausubel and H. E. Sladovich (eds.), National Academy Press, Washington, D.C.

REFERENCES

Ausubel, J. H., A. Gruebler, and N. Nakicenovic. 1988. Carbon dioxide emissions in a methane economy. Climatic Change 12:245-263.

Goeller, H. E., and A. M. Weinberg. 1976. The Age of Substitutability or What Do We Do When the Mercury Runs Out? Report 76-1, Institute for Energy Analysis, Oak Ridge, Tenn.

Marchetti, C. 1985. Nuclear plants and nuclear niches. Nuclear Science and Engineering 90:521–526.

National Research Council. 1986. Acid Deposition: Long-Term Trends. Washington, D.C.: National Academy Press.

Nakicenovic, N. 1988. Dynamics and replacement of U.S. transport infrastructures. Pp. 175–221 in Cities and Their Vital Systems, J. H. Ausubel and R. Herman, eds. Washington, D.C.: National Academy Press.