Where is Energy Going?

FEATURE

by Jesse H. Ausubel

The trend toward "decarbonization" is at the heart of energy evolution

Energy has been a big, innovative business almost forever. In fact, nature made revolutionary energy devices long before humans entered the scene. A billion years ago, chloroplasts and mitochondria could make cells work day and night. The human economy had to wait for Thomas Edison and his light bulbs.

For humans, the first giant step was, of course, capturing fire. Fire solved problems of the cold and the dark, and vastly extended human range and the food supply. The next giant step came only about 10,000 years ago with the invention of farming. We shepherded, and we grew and gathered food, not only for ourselves but also for our animals, which in turn did our work and transported and fed us.

To harness energy, we also started building machines, like sailing vessels and later mills, which run on wind and water. The Domesday Book of 1086 listed 5,624 mills in England. In 1700, 100,000 mills interrupted the flow of every stream in France.

Inefficiency always costs much. Around the year 1000, before the invention of good chimneys, people in cold climates centered their lives around an open fire in the middle of a room with a roof louvered high to carry out the smoke, and most of the heat. Open fireplaces demanded constant replenishing and thus a large woodpile behind every house. A smart stove did not emerge until 1744. Benjamin Franklin's invention greatly reduced the amount of fuel required and, thus, the size of the woodpile was reduced for those who could afford the stove.

While efficiency increased with the panoply of energy devices that emerged (Figure 1), one constant remained until about 1800. The energy system relied on carbon, as it had since the wood fire in the Escale cave near Marseilles more than 750,000 years ago.

Wood effectively burns about 10 carbons for each hydrogen atom. Because the carbon becomes soot or the greenhouse gas CO_2, and hydrogen becomes water (H_2O), carbon is basically a dirty element as fuel and hydrogen a clean one.

The most important, surprising, and happy fact to emerge from energy studies is that for the last 200 years, the world has progressively favored hydrogen atoms over carbon (Figure 2). Coal approaches parity with one or two C's per H, while oil is better with two H's per C, and a molecule of natural gas (methane) is a carbon-trim CH_4. The trend toward "decarbonization" is the heart of understanding the evolution of the energy system (Figure 3).

City size and density essentially determine social complexity and technological evolution. The size of a city, defined as a large group of people connected in daily routines, depends on both population and speed. Higher speed, vertical as well as horizontal, increases potential population. The size and density enable specialization and bring together people to combine ideas. They provide filters and competition for selection and set the market niche for new ideas and products. The technological paradigms for the world emerge from the high-level metropolises. The growth of cities and their interactions with one another and the hinterland pose the most difficult technical problems of communication, transport, and other needs and focus the resources to solve them.

By 1800 or so, in England and other early loci of industry, high population density and the slow but steady increase in energy use per capita increased the density of energy consumption. The British experience demonstrates that, when energy consumption per unit of area rises, the energy sources with higher economies of scale gain an advantage.

Wood and hay, the prevalent energy sources at the start of the 19th century, are bulky and awkward to transport and store. Consider the outcome if every high-rise resident needed to keep both a cord of wood on her floor for heat and a pile of hay in the garage for the Fiat. Think of retailing these goods in the costly real estate of New York. Sales of wood in cities now are, of course, limited to a few decorative logs providing emotional warmth. Biomass gradually lost the competition with coal to fuel London and other multiplying and concentrating populations, despite the fact that wood was abundant.

Coal had a long run at the top of the energy heap. It ruled notwithstanding its devastating effects on miners' lungs and lives, the urban air, and the land from which it came; but about 1900, the advantages of an energy system of fluids rather than solids began to become evident. On the privacy of its rails, a locomotive could pull a coal car of equal size to fuel it. Coal-powered automobiles, however, never had much appeal. The weight and volume of the fuel were hard

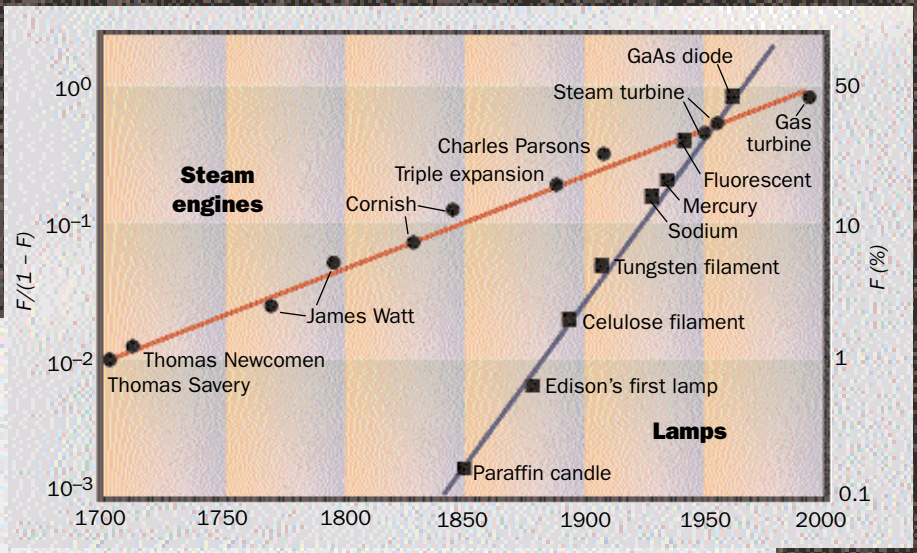

Figure 1. Efficiency of two energy devices (motors and lamps) over the years is plotted logarithmically in terms of the fraction *F* of the limit of efficiency they might obtain. The efficiency of generators has increased from 1% to 50% in 300 years; fuel cells can advance this to about 70%.

problems, especially for a highly distributed transport system. Oil had a higher energy density than coal—and the advantage of flowing through pipelines and into tanks. Systems of tubes and cans can deliver carefully regulated quantities of fuel from the scale of the engine of a motor car to that of the Alaska pipeline. It is easy to understand why oil defeated coal by 1950 as the world's leading energy source.

Yet, despite many improvements from wellhead to gasoline pump, distribution of oil is still clumsy. Fundamentally, oil is stored in a system of metal cans of all sizes. The most famous can is the Exxon Valdez. Transfer between cans is imperfect, which brings out a fundamental point. The strongly preferred configuration for very dense spatial consumption of energy is a grid that can be fed and bled continuously at variable rates. There are two successful grids, gas and electricity.

Natural gas is distributed through an inconspicuous, pervasive, and efficient system of pipes. Its capillaries reach right to the kitchen. It provides an excellent hierarchy of storage, remaining safe in geological formations until shortly before use. Moreover, natural gas can be easily and highly purified, thus permitting complete combustion.

Electricity, which must be made from primary energy sources such as coal and gas, is both a substitute for these (as in space heating) and a unique way to power devices that exist only because electricity became widely available. Electricity is an even cleaner energy carrier than gas and can be switched on and off with little effort and great effect. Electricity, however, continues to have a disadvantage: it cannot be stored efficiently, as today's meager batteries show. Electrical losses also occur in transmission; with the present infrastructure, a distance of 100 km is normal for transmission, and about 1,000 km is the economic limit.

Lacking reserves, the electric power system is largely shaped by maximum rather than mean demand. Because mean demand is typically one-half of peak, an adequate electrical system is large. It also looks inefficient to an engineer or banker, who want expensive capital stock to be working 24 hours a day rather than merely poised for action that may rarely come. Moreover, because of its limited storage, electricity is not good for dispersed uses, such as cars.

Nevertheless, the share of primary energy used to make electricity has grown steadily in all countries over the past 75 years and now approaches 40%. The Internet economy demands further electrification with perfect reliability. Thus, the core energy game for the next 30 to 50 years is to expand and flawlessly operate the gas-electric system.

Globally, perhaps 50 to 100 billion more tons of coal may be used (about 20 to 40 years at the current rate of consumption) before the market makes coal all but disappear. If it is dusk for coal, it is midafternoon for oil, which already is losing ground in energy markets other than transport. For gas, it is midmorning, and the next decades will bring enormous growth, matching rising estimates of the gas resource base, which have more than doubled over the past 20 years.

We will adopt gas in transport as well as for electric power through the use of fuel cells. Fuel cells, essentially continuous batteries, can be fed by hydrogen extracted from methane. In replacing the internal combustion engine, they will multiply automotive efficiencies and slash pollutants. Wood and coal fogged and blackened London for much of the past millennium; methane can complete the clearing of its skies and those of Phoenix, Mexico City, and Bangkok.

Governments will need to make it easier to build and access gas pipelines. Attention must also be given to the safety and environmental aspects of gas use because pipelines and tanks can explode tragically. Natural gas is also a source of greenhouse gas emissions, although each unit of energy produced by oil yields, on average, about one-third more CO_2 than gas, and coal about two-thirds more. By operating gas power plants at very high temperatures and pressures, we can bleed off the CO_2 as a liquid and sequester it underground in porous formations like those that harbor oil.

Still, energy's history will not end with natural gas. The completion of decarbonization ultimately depends on the production and use of pure hydrogen (H_2), already popular as a rocket fuel and in other high-per-

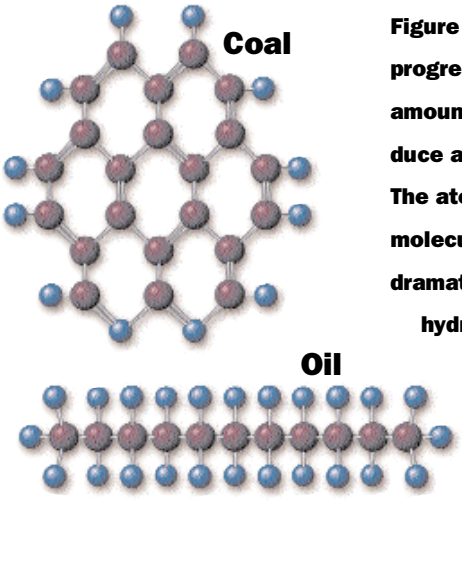

Figure 2. Decarbonization is the progressive reduction in the amount of carbon used to produce a given amount of energy. The atomic structures of typical molecules of coal, oil, and gas dramatize the increasing ratio of hydrogen to carbon seen in more recent sources of energy.

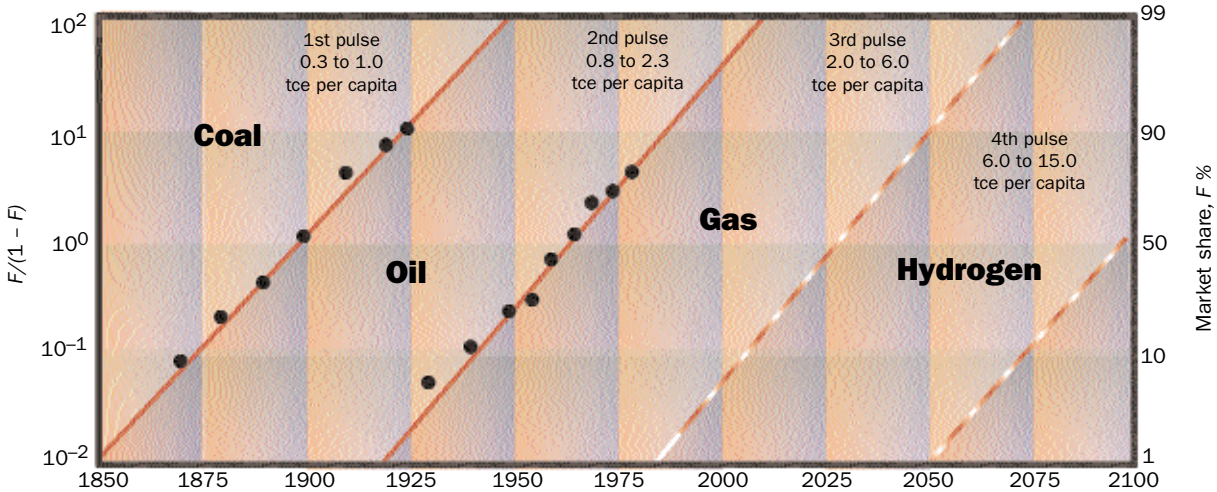

Figure 3. When total world per capita energy consumption (tons of coal equivalent) is dissected into a succession of logistic curves and normalized on a scale that renders each S-shaped pulse into a straight line, energy history is a succession of growth pulses evolving around the lead energy commodity of the era (*F* is market share). In each era, consumption triples.

formance market niches. Environmentally, hydrogen is the immaterial material; its combustion yields only water vapor and energy. Hydrogen, of course, must come from splitting water—not from cooking a hydrocarbon source. The energy required to make the hydrogen must also be carbon-free.

Among the alternatives, including solar and photovoltaic routes, nuclear energy fits the context best. I am old enough to have been impressed by schoolbooks of the 1960s that asserted that the splitting and fusing of atoms was a giant step, akin to harnessing fire and starting to farm. We should persist in peacefully applying Albert Einstein's revolutionary equations. It seems reasonable that understanding how to use nuclear power, and its acceptance, will take a century and more. Still, fission is a contrived and extravagant way to boil water if steam is required only about half of each day at peak hours to make electricity.

Nuclear energy's special potential is as an abundant source of electricity for electrolysis and high-temperature heat for water splitting while the cities sleep. Nuclear plants could nightly make H_2 on the scale needed to meet the demand of billions of consumers. Windmills and other solar technologies cannot power modern people by the billions. Reactors that produce hydrogen could be situated far from population concentrations and pipe their main product to consumers.

This fresco of our energy evolution leaves open at least two important panels: What about efficiency and developing countries? On efficiency, I maintain the engineer's view that improvements are embedded in the lines of development of any machine or process. In spite of market failures and other obstacles, increases in efficiency are documented for everything from aircraft and autos to air conditioners and ammonia production. We will be busy squeezing out inefficiency for at least another millennium. The overall thermodynamic efficiency of our energy system, measured from the woodchopper to the hot soup on the dinner table, advanced from only perhaps 1% in 1000 to 5% in 2000 (Figure 1).

The harder question may be lifestyles and behavior. We live in more numerous and smaller families. We want more square meters per capita in our residences. We want personal vehicles. We travel faster to travel further.

And, in the next 50 years, an additional 3 billion people will need to be hooked to commercial energy, especially electricity, for the first time. A widely voiced concern is that China, India, and other developing countries may rapidly recapitulate the energy history of the already rich countries on a large, destructive scale. Many fear that China will massively expand its coal use.

Connected by common technology, capital, and information, all nations are coupled to one dynamic energy

system. Naturally, some nations adopt technologies early, and others are late in hopping onto the bandwagon. The 19th century industrial paradigm of railroads, coal, and iron is forever gone. Do not look for hay-fed buses or coal-fired jumbo jets on a future visit to Beijing. The structure of end-use demand, taking into account the density of population in China's coastal plain, favors natural gas and electricity. In fact, the coal output of China fell 16% in 1998 from that in 1997 and will sink further as the government removes subsidies from the coal industry.

The leading influence on the national and world energy diet will be the daily routines of the great population concentrations. A great renunciation of economic life and material goods does not seem near or in the interest of many. Worldwide, our 6 billion are now 55% urban. By the time the population reaches 10 billion, the urban share may be 70% or 80%. We will live in a world of many vast urban agglomerations. Even with gains in efficiency, energy use will grow and the consumption per square meter in the skyscraper cities will soar. The cities must be fueled in a safe, healthy, and beautiful way for their own sake and to preserve the rest of Earth.

So, we must decarbonize, favoring natural gas strongly everywhere and preparing the way for hydrogen, which in turn demands a restart of nuclear construction. Hydrogen and electricity can cleanly power a hundred megacities. The global energy system has been evolving in this direction but perhaps not fast enough, especially for those most anxious about climatic change. With business as usual, the decarbonization of the energy system will require a century or so.

The year 2000 will be remembered as the time of the sanctification of gas. But Saint Methane is only an apostle for hydrogen, the forever fuel. Already glimpsed, hydrogen will gradually gain its worldwide following, beginning soon, in the dawning of the nuclear millennium.

BIOGRAPHY

Jesse H. Ausubel (ausubel@rockvax.rocke feller.edu) is director of the Program for the Human Environment at The Rockefeller University in New York. This article has been adapted from one that was originally published in Italian in the millennial issue of Il Sole/24Ore, Italy, November 1999, and delivered as a talk at the AIP Industrial Physics Forum, in Clinton, New Jersey, on Oct. 26, 1999 (see *The Industrial Physicist*, December 1999, p. 30).