Productivity, Electricity, Science: Powering a Green Future

Science and technology offer the opportunity for environmental and social improvement, while providing the higher levels of services and goods that people seek. Notwithstanding efficiency gains, markets for electricity will grow because of the multiplication of population and devices and the deeper penetration of the transport sector.

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The struggle for survival drives enterprises to use resources more productively Managers recognize that this truth, almost too trifling to mention, explains the past and determines the future of the electric power industry. What we have not always appreciated is the contribution productivity growth can make to solving the environmental problem.

In this article I will show the green power of long-run productivity growth. In so doing, I will make evident the most promising strategy for the energy system, consistent with its historical evolution and with social needs and wants. The necessity and opportunities for electricity pervade the strategy.

The context here is the economic quest, driven by competition. As individuals, firms and nations, and therefore as a global collectivity, we are always striving to squeeze more value from a given unit of land, water, material, and energy—and labor. Sometimes the squeeze tightens on one resource, sometimes another. It depends on relative prices and technical possibilities.

Over extended periods, decades and more, technology propels productivity. Thus, my plan is to review some of the accomplishments of technology and its provocative ally science, with respect to the resources just mentioned, and later to reflect on their indispensable role. The hazard and chance for firms and workers is that technological change simultaneously undermines and creates markets, including the market for electricity.

In the last 10 to 15 years, energy analysts have touted the search for "efficiency." In fact, raising productivity of which efficiency is one face, is the oldest game around. Let us turn to the examples.

Land

Land is the resource over which most blood has been spilled. Yields per hectare measure the productivity of land and the efficiency of land use. During the past half century ratios of crops to land for the world's major grains-corn, rice, soybean, and wheat—have climbed, rapidly and globally.

A cluster of innovations, including tractors, seeds, chemicals, and irrigation, joined through timely information flows and better-organized markets, raised yields to feed billions more without clearing new fields. The main joiner is electricity Weather forecasts and futures markets, for example, could scarcely exist without it.

Per hectare, world grain yields rose 2.15 percent annually between 1960-94, more than doubling in the interval. The productivity gains have stabilized global cropland since mid-century, mitigating pressure for deforestation in all nations and allowing forests to spread again in many. The Green Revolution of high-yield crops earned its Nobel Peace Prize; the alternative of extending farming onto hundreds of millions more hectares would surely have evoked deadly strife.

Fortunately the agricultural production frontier remains spacious. On a per-acre basis, the average world farmer grows only about 20 percent of the corn of the top Iowa farmer, who produces about 14 tons/hectare. The average Iowa farmer, 30 years behind the state-of-the-art of the top Iowa producers and about half as productive, even so produces at over twice the world average yield. If technical progress continues as usual, the worlds farmers will grow 8 tons/ha grain around 2060. With yields at that level, 10 billion people could eat an American diet of today while allowing cropland the area of Australia to revert to wilderness.

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Water

Are we similarly squeezing more value from a drop of a water? Since 1975, per capita water use in the United States has fallen at an annual rate of 1.4 percent. Even absolute water withdrawals peaked around 1980.

Industry alert to technology as well as costs, exemplifies the progress, though it consumes but a small fraction of total water. Total U.S. industrial water withdrawals stabilized at around 1970, and have since dropped by one-third. More interestingly industrial withdrawals per unit of GNP have dropped steadily since 1940. Then, 14 gallons of water flowed into each dollar of output. Now the flow is less than three gallons per dollar. The steep decline taps many sectors, including chemicals, paper, petroleum refining, steel, and food processing, and also reflects changes in what forms the economy After adjusting for production levels, not only intakes but discharges per unit of production as well are perhaps one-fifth of what they were 50 years ago.

In manufacturing, technology as well as law and economics have favored frugal water use. Incidentally more efficient use of water and energy usually go together, through better heat-exchangers and recirculation of cooling water.

Despite the gains, the United States is far from most efficient practice. Water withdrawals for even all users in the OECD countries range tenfold, with the U.S. and Canada at the highest level of use. Allowing for national differences in the major uses-irrigation, electrical cooling, industry, and public water supply—large opportunities for reductions remain.

Materials

The picture with respect to the efficiency of the use of materials other than water is complex because of the variety of functions and properties of materials. We use enormous amounts of materials. In 1990 each American mobilized on average about 50 kg/day excluding water and oxygen. Japanese used about the same.

Over time, new materials substitute for old. Successful new materials usually show improved properties per ton, thus leading to a lower intensity of use for a given task. The idea is as old as the epochal succession from stone to bronze to iron.

Modern examples of materials use efficiency abound. Since the early 19th century, the ratio of weight to power in industrial boilers has decreased almost 100 times. In the 1970s, a mundane invention, the radial tire, directly lowered weight and material by one-quarter below the bias-ply tires it replaced. ***An*** unexpected and bigger gain in efficiency came from the doubling of tire life by radials, so halving the use of material. Containers have become lighter and often smaller. Cans of aluminum replaced steel at three times the density, and then themselves thinned by 25 percent, in a struggle for market share and niches with yet lighter polyethylene terephthalate (PET). Five compact discs selling for $100 now contain 90 million home phone numbers of Americans, equivalent to the content of telephone books costing $60,000 and weighing five tons: an impressive example of what analysts have come to call "dematerialization."

Energy

Gains in energy productivity and efficiency astonish. In neolithic times, construction of a house consumed tons of firewood to make the plaster for the walls and floor. **A** thousand years ago, before the invention of efficient chimneys, people in cold climates centered their lives around a fireplace in the middle of a room with a high louvered roof to carry out the smoke—and most of the heat as well.

Consider motors and lamps, first analyzed 25 years ago by EPRI's Chauncey Starr and Richard Rudman **(Figure 1)**. Around 1700 the quest began to build efficient engines, starting with steam. ***300*** years have increased the efficiency of the generators from one to about 50 percent of the apparent limit, the latter achieved by today's best gas turbines. Fuel cells can advance efficiency to about 70 percent.

Lamps have brightened with each decade. **A** new design proposes to bombard sulfur with microwaves. One such bulb the size of a golf ball could purportedly produce the same amount of light as hundreds of high-intensity mercury vapor lamps, with a quality of light comparable to sunlight.

Analyses of the efficiency of the full energy system show that the

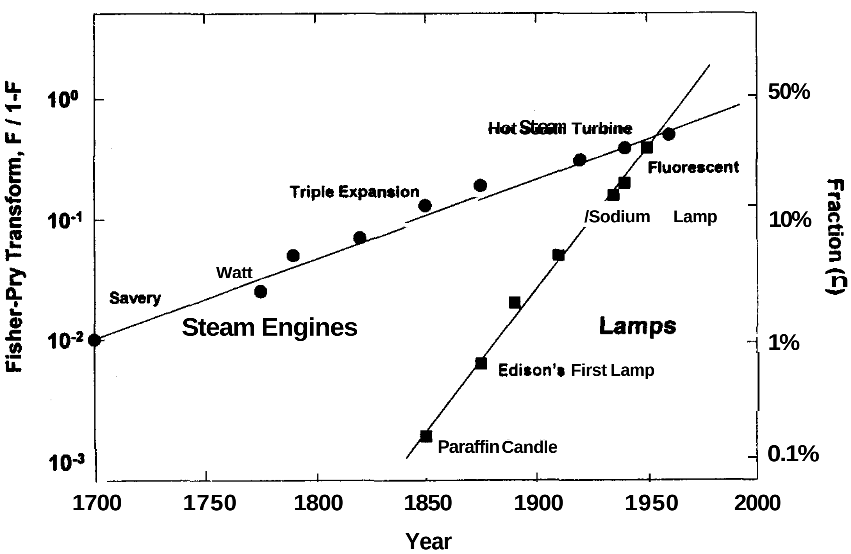
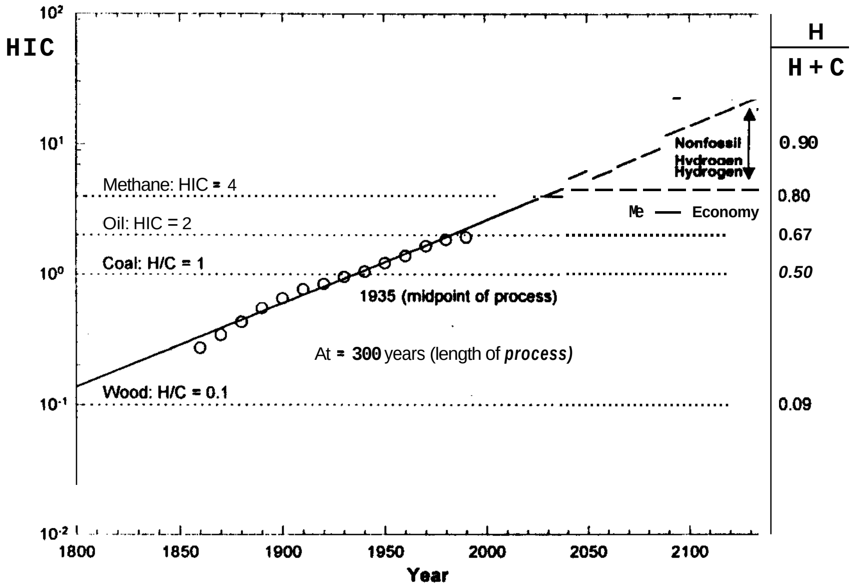


Figure 1: Evolving efficiency of primary generators (right-hand axis) and illumination (left-hand axis), plotted on a logarithmic scale. The data are analyzed as a logistic (sigmoid) growth process with a Fisher-Pry transform that normalizes the data. Source: Ausubel & Marchetti, 1996.

U.S. has averaged about one percent less energy to produce a good or service each year since about 1800. However, our modern economies probably still run at only about five percent efficiency for the full chain from extracting primary energy to delivery of the service to the final user.

The most important single fact to emerge from 20 years of energy analyses is the gradual "decarbonization" of the energy system: the falling number of carbon molecules used to provide a unit of energy or economic product. Carbon darkens the environmental outlook by threatening oily beaches, smoggy air, overheated climate, and black lungs. Between 1860 and 1990, the amount of carbon per unit of primary energy dropped by about one-third, from about 0.76 tons of carbon per kilowatt-year to about 0.52 tons C/kW-yr. **Figure 2** details the shrinking level of carbon used to produce final energy to the consumer in diverse countries in the last few decades. One reason for this change is that people want electricity not coals, in their dwellings, and the generation and distribution of the electricity has become more efficient.

Figure **3:** Decarbonization: evolution of the ratio of hydrogen (H) to carbon (C) in the world fuel mix (logarithmic scale). Wood has an effective hydrogen-to-carbon ratio of 0.1, coal 1, oil 2, and gas **4** (i.e., methane = CH4). Progression of the fuel mix above methane requires production of large amounts of hydrogen fuel without fossil energy. The data are analyzed as a logistic growth process and plotted in the linear transform of the logistic curve. Source: Ausubel, 1996.



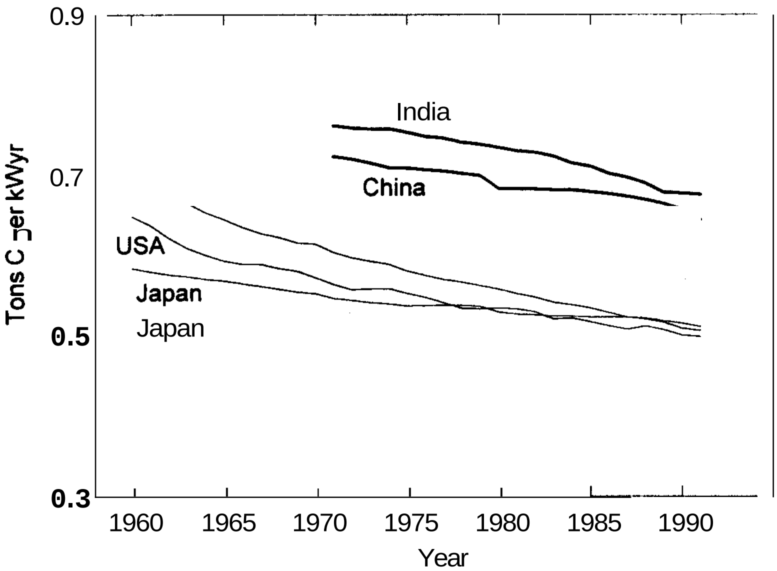


Figure 2: Decarbonization of final energy, five countries. Source: Nakicenovic, 1996.

We can view the process of decarbonization as the replacement of carbon with hydrogen as the source of chemical energy **(Figure 3).** Economizing on carbon, we are on a steady trajectory toward a methane, and eventually hydrogen, economy. The timetable for this change, almost 100 years, tempers our optimism.

Labor

Our modern technologies spare not only physical resources but labor as well. In fact, I suspect the desire to work less while living longer is the real driver of the human social system. The sparing of physical resources may be largely