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

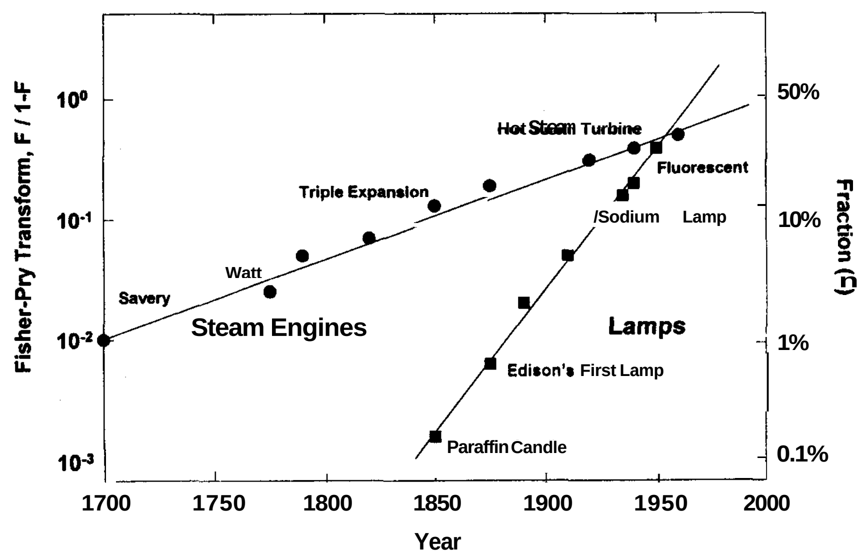
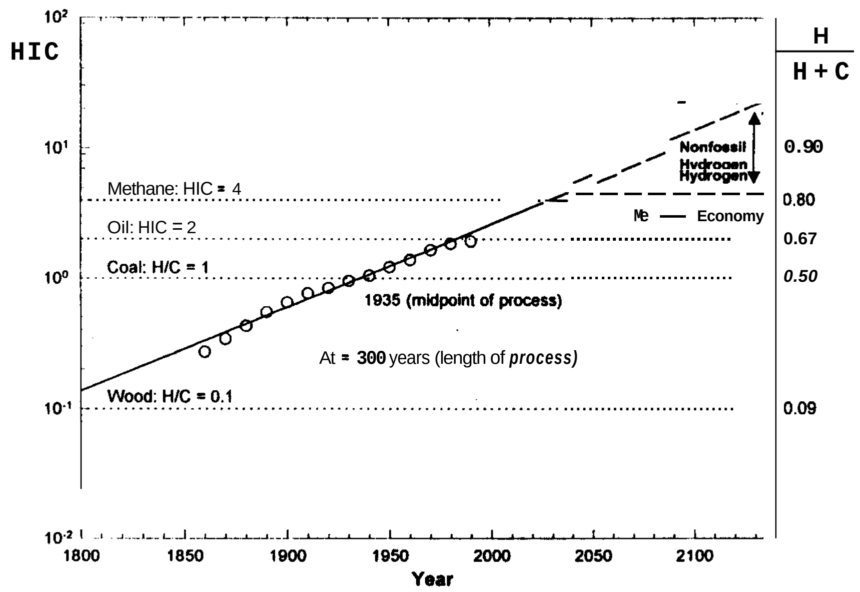


Figure 1: Evolving efficiency of primary generators (right-hand axis) and illumination (left-hand axis), plotted on a logarithmic scale. The data are analyzed as a logistic (sigmoid) growth process with a Fisher-Pry transform that normalizes the data. Source: Ausubel & Marchetti, 1996.

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.



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

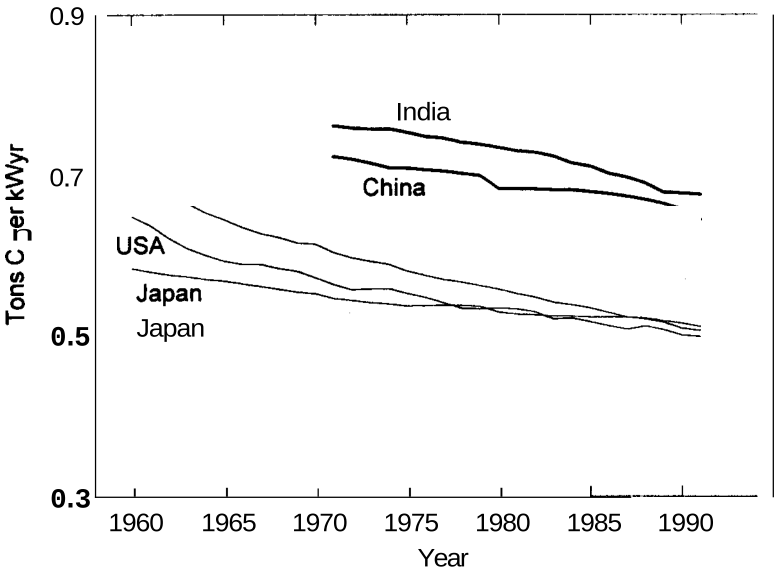


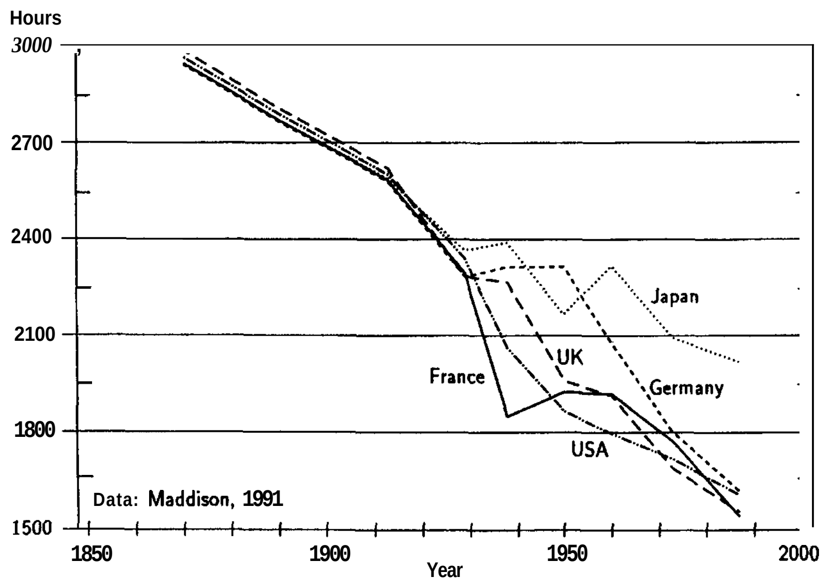
Figure 2: Decarbonization of final energy, five countries. Source: Nakicenovic, 1996.

a byproduct of our quest to live a dream of magical ease.

"Open sesame," the famous old command from the Arabian Nights, expresses the dream of an advanced society. Electricity has a vast and protected franchise in such a world, because it is uniquely capable of action at a distance—to animate the inanimate, to make it work, to lighten our toil.

Our studies indicate that since the middle of the 19th century, *lifetime* hours at paid work have declined consistently: for men in the U.K. from 150 to 88 thousand hours, and for women from **63** to 40 thousand **(Figure 4).** The well-documented long-run reduction in annual per capita work time in many countries suggests the universality of the trend **(Figure 5).** Extrapolated, the U.K. lifetime hours in the year 2050 translate to a 27-hour average workweek for men and women, taken together.

Figure 5: Average annual hours worked in selected countries, 1870-1987. Source: Ausubel & Gruebler, 1995.



Working less and living longer implies new balances and structures of production and consumption and new areas of economic growth, as well as hard questions for social tranquility and security. **A** typical life of 80 years may be spent about 40 years consuming and 40 both consuming and producing (if only at **27** hours per week). When consumption dominates production, we are in the service economy Service industries include transport, tourism, communications, entertainment, retail, finance, education, and health-but not agriculture, mining, and manufacturing, the sectors which made Farmer, Smith, and Miller common family names.

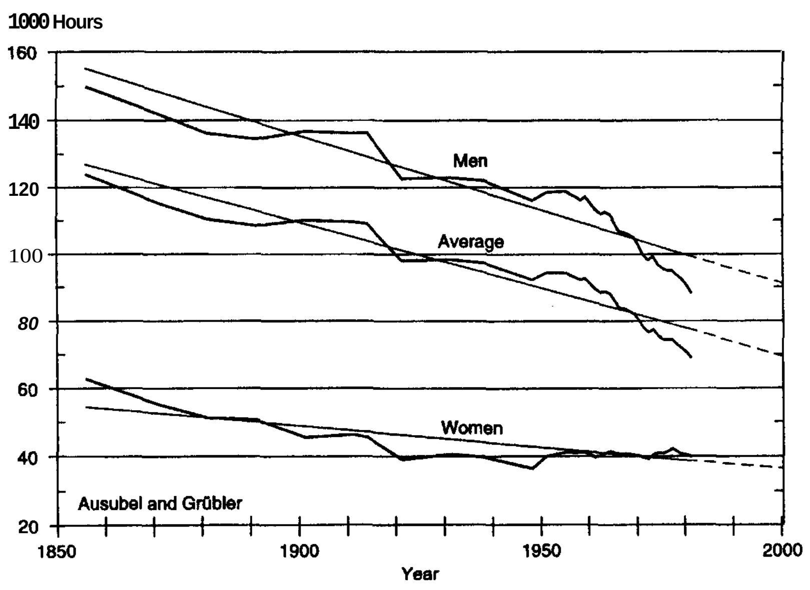


Figure 4: Lifetime hours at work of female, male, and average working population in the U.K., 1856-1981, and best fit linear extrapolation. Source: Ausubel & Gruebler, 1995.

When consumption is the main activity of a day or a life, restaurants, hotels, fitness centers, hospitals, airlines, and the multitude of information handlers-banks, media, schools—hire most labor. Leisure in the so-called leisure society makes the work.

Demand

So far I have described the triumphal and surprisingly straight *march* **of** *technology.* Now the catch for *homo faber,* the toolmaker, is that our technology not only spares resources. If so, our footprints on earth would simply become lighter and lighter. Technology also spares time and makes money, allowing us to consume more. It gives us power, a/k/a speed. ***So*** we can expand our range. We use less energy to travel each mile, but we travel many more miles. Americans abandoned 20 million horses for 200 million cars. At least ten PCs will replace each electric typewriter. As I said at the outset, technology both destroys and creates markets.

Fundamentally, technology expands the human niche. For most animal populations, the niches which encase populations are of constant size. When **animals** can invent new technologies—for example, when bacteria produce a new enzyme to dismantle a component of their broth-then the limits are elastic. Humans ***keep*** inventing. Technology further adds to population by increasing longevity.

Absent fixed limits, we cannot know where population will go in the long **run,** unless we find a way to predict the number of children future parents will choose. No one has or seems likely to do so. Nevertheless, most students of global population agree that it will double or triple during the next century. Population provides a multiplier that determines total consumption. The size of the multiplier makes us wonder whether the products and by-products of our consumption will in **turn** constrict our niche.

Suppose per-capita economic activity continues to double about every 30 years, as it has since the start of the industrial revolution, and the capitas grow in accord with mainstream projections. Then, by about 2060 we will need to reduce emissions per unit of economic activity (as a proxy measure of cleaner behavior) globally by about a factor of ten to keep to today's total burden on the environment. We will require a much less wasteful industrial ecosystem, a micro-emissions economy.

Daunting as it may sound, we have seen the outlines of how the gains can be made. We need food decoupled from acreage, materials smartly designed and recycled, and carefully channeled water. We need a smoke-free system of generating electricity and hydrogen that is highly efficient from generator to consumer. In short, the economy must be lean, dry, and light.

Challenges for Science and Technology

To illustrate the challenge for science and technology, consider the demand for mobility, which shows no satiation, uses about one-third of all energy, and already emits too much because travel burns oil. To appreciate the potential market growth, consider, for instance, that an American on average flies only 70 seconds per day, and a European a fleeting 20 seconds. Most of the world has barely entered the race to be swift.

To meet future demand for intercity transport, in China or the U.S., we can imagine fleets of super jumbo jets taking off like flocks of geese. It does not sound safe, reliable, quiet, or clean. A much better idea, which we are developing, is an addressable metro system at the continental scale with magnetically levitated

trains in low pressure tubes switching packets of passengers and goods, the way the International Standard Data Network (ISDN) already handles message traffic-drawing GWs of electricity, I should add.

This example of green mobility, which is not as far-fetched as it may first sound, brings me to comment on one more resource: ingenuity. If we work less and make more, then the productivity of human resources has increased. Physical prowess today matters only in sports and a few other occupations. Knowledge is what now grows productivity; and science and engineering are the most powerful forms of knowledge. They demonstrate their effectiveness every moment.

The aggressive search for knowledge and its application is perhaps the most significant contribution of western civilization. The game began centuries ago, but has reached completely new levels in the past 50 years, above all in the U.S. Many industries have systematized their search for better practice and have the gains to show, as we have seen. The hard search is costly and requires skillful organization at the level of the nation and the firm, and especially the collection of firms in the sector, which must cooperate in research as well as compete.

I believe the greatest threat to future well-being is the rejection of science and technology. Having come this far, the 5.8 billion cannot **take** the road back. The Islamic world held the cutting edge of science until past 1100 AD. Then it rejected the windmill and, later, the printing press. Loss of economic and political leadership followed. The consequences of rejection of science and technology in the future would be far more painful than marginalization in world affairs.

Of course each community must carefully tailor technology to fit the social body And we must act wisely, a short phrase cloaking a tall order.

To conclude, I have sought to show that science and technology offer the opportunity to spare added environmental degradation, while providing the higher levels of services and goods that people seek. Compounding progress at a few percent per year transforms society in time. For the energy system the message is electricity, plus hydrogen, with a transition through natural gas, and ever more efficient devices from producer to final consumer.

Notwithstanding efficiency gains, markets for electricity will grow because of the multiplication of population and devices and the penetration of the transport sector. The strategy is clear and we should prepare the technologies, but we must also be patient and persistent. Diffusion takes time. Of course, were innovation easy, society would be far more volatile, and even harder for business. ■

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