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Moore’s Curse and the Great Energy Delusion

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Our transition away from fossil fuels will take decades—if it happens at all.

During the early 1970s we were told by the promoters of nuclear energy that by the year 2000 America’s coal-based electricity generation plants would be relics of the past and that all electricity would come from nuclear fission. What’s more, we were told that the first generation fission reactors would by then be on their way out, replaced by super-efficient breeder reactors that would produce more fuel than they were initially charged with.

During the early 1980s some aficionados of small-scale, distributed, “soft” (today’s “green”) energies saw America of the first decade of the 21st century drawing 30 percent to 50 percent of its energy use from renewables (solar,wind, biofuels). For the past three decades we have been told how natural gas will become the most important source of modern energy: widely cited forecasts of the early 1980s had the world deriving half of its energy from natural gas by 2000. And a decade ago the promoters of fuel cell cars were telling us that such vehicles would by now be on the road in large numbers, well on their way to displacing ancient and inefficient internal combustion engines.

These are the realities of 2008: coal-fired power plants produce half of all U.S. electricity, nuclear stations 20 percent, and there is not a single commercial breeder reactor operating anywhere in the world; in 2007 the United States derives about 1.7 percent of its energy from new renewable conversions (corn-based ethanol, wind, photovoltaic solar, geothermal); natural gas supplies about 24 percent of the world’s commercial energy—less than half the share predicted in the early 1980s and still less than coal with nearly 29 percent; and there are no fuel-cell cars.

This list of contrasts could be greatly extended, but the point is made: all of these forecasts and anticipations failed miserably because their authors and promoters ignored one of the most important realities ruling the behavior of complex energy systems—the inherently slow pace of energy transitions.

> It is delusional to think that the United States can install in 10 years wind and solar generating capacity equivalent to that of thermal power plants that took nearly 60 years to construct.

"Energy transitions" encompass the time that elapses between an introduction of a new primary energy source oil, nuclear electricity, wind captured by large turbines) and its rise to claiming a substantial share (20 percent to 30 percent) of the overall market, or even to becoming the single largest contributor or an absolute leader (with more than 50 percent) in national or global energy supply. The term also refers to gradual diffusion of new prime movers, devices that replaced animal and human muscles by converting primary energies into mechanical power that is used to rotate massive turbogenerators producing electricity or to propel fleets of vehicles, ships, and airplanes. There is one thing all energy transitions have in common: they are prolonged affairs that take decades to accomplish, and the greater the scale of prevailing uses and conversions the longer the substitutions will take. The second part of this statement seems to be a truism but it is ignored as often as the first part: otherwise we would not have all those unrealized predicted milestones for new energy sources.

Preindustrial societies had rather simple and fairly stationary patterns of primary energy use. They relied overwhelmingly on biomass fuels (wood, charcoal, straw) for heat and they supplemented their dominant prime movers(muscles) with wind to sail ships and in some regions with windmills and small waterwheels. This traditional arrangement prevailed in Europe and the Americas until the beginning of the 19th century, and it dominated most of Asia and Africa until the middle of the 20th century. The year 1882 was likely the tipping point of the transition to fossil fuels, the time when the United States first burned more coal than wood. The best available historical reconstructions indicate that it was only sometime during the late 1890s that the energy content of global fossil fuel consumption, nearly all of it coal, came to equal the energy content of wood, charcoal, and crop residues.

The Western world then rapidly increased its reliance on fossil fuels and hydroelectricity, but in large parts of Africa and Asia the grand energy transition from traditional biomass fuels to fossil fuels has yet to be completed. Looking only at modern primary energies on a global scale, coal receded from about 95 percent of the total energy supply in 1900 to about 60 percent by 1950 and less than 24 percent by 2000. But coal's importance continued to rise in absolute terms, and in 2001 it even began to regain some of its relative importance. As a result, coal is now relatively more important in 2008 (nearly 29 percent of primary energy) than it was at the time of the first energy "crisis" in 1973 (about 27 percent). And in absolute terms it now supplies twice as much energy as it did in 1973: the world has been returning to coal rather than leaving it behind.

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Although oil became the largest contributor to the world's commercial energy supply in 1965 and its share reached 48 percent by 1973, its relative importance then began to decline and in 2008 it will claim less than 37 percent of the total. Moreover, worldwide coal extraction during the 20th century contained more energy than any other fuel, edging out oil by about 5 percent. The common perception that the 19th century was dominated by coal and the 20th century by oil is wrong: in global terms, the 19th century was still a part of the millennia-long wooden era and 20th century was, albeit by a small margin, the coal century. And while many African and Asian countries use no coal, the fuel remains indispensable: it generates 40 percent of the world's electricity, nearly 80 percent of all energy in South Africa (that continent's most industrialized nation), 70 percent of China's, and about 50 percent of India's.

The pace of the global transition from coal to oil can be judged from the following spans: it took oil about 50 years since the beginning of its commercial production during the 1860s to capture 10 percent of the global primary energy market, and then almost exactly 30 years to go from 10 percent to about 25 percent of the total. Analogical spans for natural gas are almost identical: approximately 50 years and 40 years. Regarding electricity, hydrogeneration began in 1882, the same year as Edison's coal-fired generation, and just before World War I water power produced about 50 percent of the world's electricity; subsequent expansion of absolute production could not prevent a large decline in water's relative contribution to about 17 percent in 2008. Nuclear fission reached 10 percent of global electricity generation 27 years after the commissioning of the first nuclear power plant in 1956, and its share is now roughly the same as that of hydropower.

These spans should be kept in mind when appraising potential rates of market penetration by nonconventional fossilfuels or by renewable energies. No less important is the fact that none of these alternatives has yet reached even 5 percent of its respective global market. Nonconventional oil, mainly from Alberta oil sands and from Venezuelan tar deposits, now supplies only about 3 percent of the world's crude oil and only about 1 percent of all primary energy. Renewable conversions—mainly liquid biofuels from Brazil, the United States, and Europe, and wind-powered electricity generation in Europe and North America, with much smaller contributions from geothermal and photovoltaic solar electricity generation—now provide about 0.5 percent of the world's primary commercial energy, and in 2007 wind generated merely 1 percent of all electricity.

The absolute quantities needed to capture a significant share of the market, say 25 percent, are huge because the scale of the coming global energy transition is of an unprecedented magnitude. By the late 1890s, when combustion of coal (and some oil) surpassed the burning of wood, charcoal, and straw, these resources supplied annually an equivalent of about half a billion tons of oil. Today, replacing only half of worldwide annual fossil fuel use with renewable energies would require the equivalent of about 4.5 billion tons of oil. That's a task equal to creating de novo an energy industry with an output surpassing that of the entire world oil industry—an industry that has taken more than a century to build.

The scale of transition needed for electricity generation is perhaps best illustrated by deconstructing Al Gore's July 2008 proposal to "re-power" America: "Today I challenge our nation to commit to producing 100 percent of our electricity from renewable energy and truly clean carbon-free sources within 10 years. This goal is achievable, affordable, and transformative."

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Let's see. In 2007 the country had about 870 gigawatts (GW) of electricity-generating capacity in fossil-fueled and nuclear stations, the two nonrenewable forms of generation that Gore wants to replace in their entirety. On average,these thermal power stations are at work about 50 percent of the time and hence they generated about 3.8 PWh (that is, 3.8 x 1015 watt-hours) of electricity in 2007. In contrast, wind turbines work on average only about 23 percent of the time, which means that even with all the requisite new high-voltage interconnections, slightly more than two units of wind-generating capacity would be needed to replace a unit in coal, gas, oil, and nuclear plants. And even if such an enormous capacity addition—in excess of 1,000 GW—could be accomplished in a single decade (since the year 2000, actual additions in all plants have averaged less than 30 GW/year!), the financial cost would be enormous: it would mean writing off the entire fossil-fuel and nuclear generation industry, an enterprise whose power plants alone have a replacement value of at least $1.5 trillion (assuming at least $1,700/installed kW), and spending at least $2.5 trillion to build the new capacity.

But because those new plants would have to be in areas that are not currently linked with high-voltage (HV)transmission lines to major consumption centers (wind from the Great Plains to the East and West coasts,photovoltaic solar from the Southwest to the rest of the country), that proposal would also require a rewiring of the country. Limited transmission capacity to move electricity eastward and westward from what is to be the new power center in the Southwest, Texas, and the Midwest is already delaying new wind projects even as wind generates less than 1 percent of all electricity. The United States has about 165,000 miles of HV lines, and at least 40,000 additional miles of new high-capacity lines would be needed to rewire the nation, at a cost of close to $100 billion. And the costs are bound to escalate, because the regulatory approval process required before beginning a new line construction can take many years. To think that the United States can install in 10 years wind and solar generating capacity equivalent to that of thermal power plants that took nearly 60 years to construct is delusional.

And energy transitions from established prime movers to new converters also take place across time spans measured in decades, not in a decade. Steam engines, whose large-scale commercial diffusion began with James Watt's improved design introduced during the 1770s, remained important into the middle of the 20th century. There is no more convincing example of their endurance than the case of Liberty ships, the "ships that won the war" as they carried American materiel and troops to Europe and Asia between 1942 and 1945. Rudolf Diesel began to develop his highly efficient internal combustion engine in 1892 and his prototype engine was ready by 1897. The first small ship engines were installed on river-going vessels in 1903, and the first oceangoing ship with Diesel engines was launched in 1911. By 1939 a quarter of the world's merchant fleet was propelled by these engines and virtually every new freighter had them. But nearly 3,000 Liberty ships were still powered by oil-fired steam engines. And steam locomotives disappeared from American railroads only by the late 1950s, while in China and India they were indispensable even during the 1980s.

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Automobilization offers similar examples of gradual diffusion, and the adoption of automotive diesel engines is another excellent proof of slow transition. The gasoline-fueled internal combustion engine—the most important transportation prime mover of the modern world—was first deployed by Benz, Maybach, and Daimler during the mid-1880s, and it reached a remarkable maturity in a single generation after its introduction (Ford's Model T in 1908).

But massive automobilization swept the United States only during the 1920s and Europe and Japan only during the 1960s, a process amounting to spans of at least 30 to 40 years in the U.S. case and 70 to 80 years in the European case between the initial introduction and decisive market conquest (with more than half of all families having a car). The first diesel-powered car (Mercedes-Benz 260D) was made in 1936, but it was only during the 1990s that diesels began to claim more than 15 percent of the new car market in major EU countries, and only during this decade that they began to account for more than a third of all newly sold cars. Once again, roughly half a century had to elapse between the initial introduction and significant market penetration.

And despite the fact that diesels have been always inherently more efficient than gasoline-fueled engines (the difference is up to 35 percent) and that modern diesel-powered cars have very low particulate and sulphur emissions, their share of the U.S. car market remains negligible: in 2007 only 3 percent of newly sold cars were diesels.

And it has taken more than half a century for both gasoline- and diesel-fueled internal combustion engines to displace agricultural draft animals in industrialized countries: the U.S. Department of Agriculture stopped counting draft animals only in 1963, and the process is yet to be completed in many low-income nations.

Finally, when asked to name the world's most important continuously working prime mover, most people would not name the steam turbine. The machine was invented by Charles Parsons in 1884 and it remains fundamentally unchanged 125 years later. Gradual advances in metallurgy made it simply larger and more efficient and these machines now generate more than 70 percent of the world's electricity in fossil-fueled and nuclear stations (the rest comes from gas and water turbines as well as diesels).

There is no common underlying process to explain the gradual nature of energy transitions. In the case of primary energy supply, the time span needed for significant market penetration is mostly the function of financing, developing, and perfecting necessarily massive and expensive infrastructures. For example, the world oil industry annually handles more than 30 billion barrels, or four billion tons, of liquids and gases;

it extracts the fuel in more than 100 countries and its facilities range from self-propelled geophysical exploration rigs to sprawling refineries, and include about 3,000 large tankers and more than 300,000 miles of pipelines. Even if an immediate alternative were available, writing off this colossal infrastructure that took more than a century to build would amount to discarding an investment worth well over $5 trillion—but it is quite obvious that its energy output could not be replicated by any alternative in a decade or two.

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In the case of prime movers, the inertial nature of energy transitions is often due to the reliance on a machine that may be less efficient, such as a steam engine or gasoline-fueled engine, but whose marketing and servicing are well established and whose performance quirks and weaknesses are well known, as opposed to a superior converter that may bring unexpected problems and setbacks. Predictability may, for a long time, outweigh a potentially superior performance, and associated complications (for example, high particulate emissions of early diesels) and new supply-chain requirements (be it sufficient refinery capacity to produce low-sulfur diesel fuel or the availability of filling stations dispensing alternative liquids) may slow down the diffusion of new converters.

All of these are matters of fundamental importance given the energy challenges facing the United States and the world. New promises of rapid shifts in energy sources and new anticipations of early massive gains from the deployment of new conversion techniques create expectations that will not be met and distract us from pursuing real solutions. Unfortunately, there is no shortage of these unrealistic calls, such as the popular claim that America should seek to generate 30 percent of its electricity supply from wind power by 2030.

And now Al Gore is telling us that the United States can completely repower its electricity generation in a single decade! Gore has succumbed to what I call “Moore’s curse.” Moore’s Law describes a long-standing trend in computer processing power, observed by Intel cofounder Gordon Moore, whereby a computer’s power doubles every year and a half. This led Gore to claim that since “the price paid for the same performance came down by 50 percent every 18 months, year after year,” something similar can happen with energy systems.

But the doubling of microprocessor performance every 18 months is an atypically rapid case of technical innovation. It does not represent—as the above examples of prime mover diffusion make clear—the norm of technical advances as far as new energy sources and new prime movers are concerned, and it completely ignores the massive infrastructural needs of new modes of electricity generation.

The historical verdict is unassailable: because of the requisite technical and infrastructural imperatives and because of numerous (and often entirely unforeseen) socio-economic adjustments, energy transitions in large economies and on a global scale are inherently protracted affairs. That is why, barring some extraordinary commitments and actions, none of the promises for greatly accelerated energy transitions will be realized, and during the next decade none of the new energy sources and prime movers will make a major difference by capturing 20 percent to 25 percent of its respective market. A world without fossil fuel combustion is highly desirable and, to be optimistic, our collective determination, commitment, and persistence could accelerate its arrival—but getting there will demand not only high cost but also considerable patience: coming energy transitions will unfold across decades, not years.

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