8

The Pace of Energy Transitions

Not all news concerning America's energy challenge was gloomy during the summer of 2008, though oil prices rose to nearly $150/barrel, raising the country's July crude oil import payments to nearly $42 billion—compared to $22 billion in July 2007—and creating even more anxiety about the country's dependence on foreign oil.

Craig Venter, a pioneer in the sequencing of the human genome, announced that the scientists at his institute had created the first synthetic bacterial genome,[1] another key step toward the completely synthetic bacterium-like organism that Venter's Synthetic Genomics aspires to design for the production of ethanol or hydrogen.[2] And T. Boone Pickens, one of America's most famous billionaires, began to promote his energy transition plan.[3]

Released in July 2008, the Pickens plan got a great deal of attention because of its promoter's background: An octogenarian oilman who had made a fortune in the Texas oilfields was advocating a retreat from oil and spending his own money to do it. Pickens advertised widely, appeared on many TV shows, testified before Congress, and then returned with follow-up TV advertisements seeking public support for his proposal. The greatest appeal of the Pickens plan to reduce America's dependence on foreign oil was its cascading simplicity.

First, Pickens wanted to dot the Great Plains ("the Saudi Arabia of wind power") with enough wind turbines to replace all the electricity currently produced by burning natural gas. Second, he wanted to use the freed-up natural gas to run efficient and clean natural gas vehicles. Third, he believed that this substitution would create a massive new domestic aerospace-like industry that would offer well-paying jobs producing giant turbines and auxiliary equipment and bring economic revival to the depopulating Great Plains. Fourth, he further believed that this substitution would reduce the huge outflow of wealth to oil-producing nations, as under his plan the United States would cut its imports of oil by more than one-third. And, Pickens claimed, he was committed to spending his own money to get the process going, by building the country's largest (4 GW) wind farm in West Texas.

Also released in July 2008, just as oil prices peaked at $147/barrel, was Al Gore's call for a rapid, radical replacement of America's entire thermal electricity generation industry by green alternatives.[4] Gore expressed no doubts either about the plan's incredibly short time frame or about its economic feasibility: "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 trans-formative. . . . To those who say 10 years is not enough time, I respectfully ask them to reconsider what the world's scientists are telling us about the risks we face if we don't act in 10 years." Gore saw only two options for "those who, for whatever reason, refuse to do their part": They "must either be persuaded to join the effort or asked to step aside."[5]

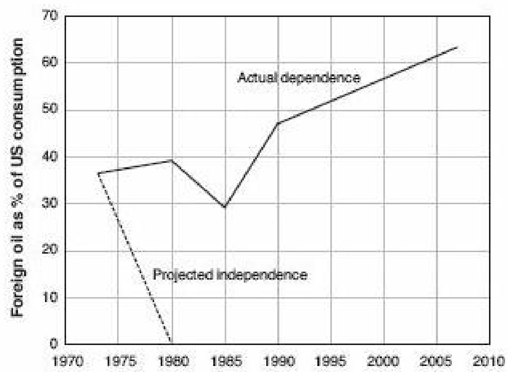
As I will show, the proposals by Gore and Pickens have much in common with similar recent promises, forecasts, and visions of the imminent and profound difference to be made by new energy conversions. All ignore one of the most important realities ruling the behavior of complex energy systems: the inherently slow pace of energy transitions.

Present Realities

I have already deconstructed or alluded to a number of promises similar to those of Gore and Pickens. By the year 2000, coal-based generation of electricity was to be a relic of the past, with all demand supplied by nuclear fission and with the superefficient breeder reactors already taking over; by the year 2000, between 30 and 50 percent of America's energy use was to come from renewable flows; by the year 2000, the world was to derive half its energy from natural gas. And a decade ago, the promoters of fuel cell cars were telling us that by now such vehicles would be on the road in large numbers, well on their way to displacing ancient and inefficient internal combustion engines.

These are the realities: Coal-fired power plants produce almost 50 percent of U.S. electricity and nuclear stations about 20 percent. All the nuclear stations are first-generation, water-cooled fission reactors; not a single commercial breeder reactor is operating anywhere in the world. In 2008 the United States derived less than 2.5 percent of its energy from new renewables—that is, from corn-based ethanol, wind, or photovoltaic solar or geothermal power.[6] Natural gas provided 24 percent of the world's commercial energy, not the 50 percent share predicted in the early 1980s, which means that it is still less important than coal, which in 2008 supplied 29 percent of the world's commercial primary energy.[7] And there are no fuel cell cars to be bought anywhere.

FIGURE 8-1
PREDICTED AND ACTUAL TRENDS IN U.S. DEPENDENCE ON FOREIGN CRUDE OIL



SOURCE: Data points calculated from consumption and import statistics in British Petroleum (BP, 2008).

A revealing illustration of the blunders committed by ignoring the gradual nature of energy transitions is offered by another famous energy plan for America, announced by President Richard M. Nixon in November 1973 and reiterated in his State of the Union address in January 1974: "Let this be our national goal: At the end of this decade, in the year 1980, the United States will not be dependent on any other country for the energy we need to provide our jobs, to heat our homes, and to keep our transportation moving."[8] In 1973, the country was importing just over a third of its crude oil; in 2008 it bought nearly 70 percent (figure 8-1). Gore's repowering plan follows in the unrealistic tradition of Nixon and later of President Jimmy Carter, who, famously fond of wearing an energy-conserving cardigan, said in July 1979: "Beginning this moment, this nation will never use more foreign oil than we did in 1977," as he reset the energy independence date to 1990.[9]

Past Transitions

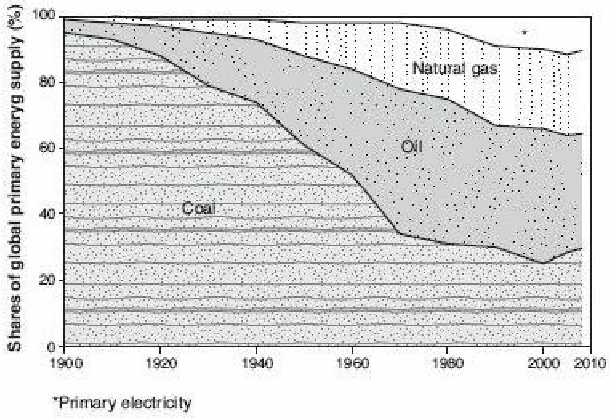
The point has been clearly made: All the forecasts, plans, and anticipations cited above have failed so miserably because their authors and promoters thought the transitions they hoped to implement would proceed unlike all previous energy transitions, and that their progress could be accelerated in an unprecedented manner. Today's advocates and promoters obviously think the same. Could they be right?

To answer this question, we need a simple definition first: An energy transition encompasses the time that elapses between the introduction of a new primary energy source (coal, oil, nuclear electricity, wind captured by large turbines) and its rise to claiming a substantial share of the overall market. This "substantial share" is necessarily arbitrary, though I would argue for at least 15 percent, or roughly every seventh unit of total supply, because the equivalents of shares lower than 10 percent can usually be achieved by demand adjustments and do not require new technical solutions; 20 percent or 25 percent would obviously be a more decisive contribution. Obviously, for a new entrant to become the single largest contributor, it must have a share higher than 33 percent among three supply components, or higher than 25 percent among four. For it to be an absolute leader, it must contribute more than 50 percent of the energy supply. While there are no such fuels or electricity sources on the global scale, many examples exist on national scales.

Some fairly good historical data make it possible to identify the tipping points of the first great energy transition, from the millennia-long reliance on biomass fuels like wood, charcoal, or crop residues to coal or, later, a mixture of coal and crude oil.

In the United States, it was only in the early 1880s that the energy content of coal (and some oil) consumption surpassed the energy content of fuel wood. The best available historical reconstruction points to the late 1890s, when half the world's energy came for the first time from the combustion of fossil fuels and all but a small fraction of that from coal. In Russia, that point came no earlier than the late 1920s, and in China sometime during the 1960s; and in a number of African countries, traditional biomass fuels still continue to dominate the overall energy supply.[10]

FIGURE 8-2
GLOBAL SHARES OF COMMERCIAL PRIMARY ENERGIES, 1900–2008



SOURCE: Based on Smil (2008b) and British Petroleum (BP, 2008).

For fossil fuels on the global scale, coal receded from about 95 percent of the total energy supply in 1900 to about 60 percent by 1950; it was surpassed by oil only in 1965, and it had declined to less than 24 percent by 2000. But even then its importance continued to rise in absolute terms, and in 2001 it began to regain some of its relative importance. Today, coal, which provided nearly 29 percent of primary energy in 2008, is more important in relative terms than it was at the time of the first energy "crisis" in 1973, when it provided about 27 percent; and in absolute terms it now supplies twice as much energy as it did in 1973. The world (thanks largely to China and India, as well as to massive Australian and Indonesian exports) has been returning to coal rather than leaving it behind (see figure 8-2).[11]

Crude oil had become the largest contributor to the world's primary energy supply by 1965, and although its share reached as much as 48 percent by 1973, its relative importance then began to decline, and in 2008 it contributed less than 37 percent. Moreover, during the twentieth century coal contributed more energy than any other fuel, edging oil by about 5 percent. The common perception of a nineteenth century dominated by coal and a twentieth century by oil is wrong. In global terms, 1800–1900 was still a part of the millennia-long wooden era, and 1900–2000 was (albeit by a small margin) the coal century. And while many African and Asian countries use no coal, the fuel remains indispensable worldwide in many ways: It generates 40 percent of the world's electricity and 50 percent of the U.S. total, and it supplies nearly 80 percent of all energy in South Africa, the continent's most industrialized nation, 70 percent in China, and almost 60 percent in India.[12]

The pace of the global transition from coal to oil can be judged from the following spans: It took oil about fifty years from the beginning of its commercial production during the 1860s to capture 10 percent of the global primary energy market and then almost exactly thirty years to go from 10 percent to about 25 percent of the total. And it took natural gas no less than seventy years (1900–1970) to rise from 1 percent to 20 percent of the total. Since that time, natural gas has been the fuel with the highest increases in annual production, but by 2008 its share was, as already noted, only about half what had been expected in the 1970s, and at 24 percent it was below that of coal.[13]

As far as electricity is concerned, hydrogeneration began in the same year as Edison's coal-fired generation (1882). Just before World War I, water power produced about half the world's electricity; its subsequent fast and sustained expansion in absolute terms could not prevent a large decline in its relative contribution, which by 2008 was about 17 percent. Nuclear fission also ascended rapidly, reaching a 10 percent share of global electricity generation just twenty-seven years after the commissioning of the first nuclear power plant in 1956. Its further growth, however, largely stopped during the 1980s, and its share is now roughly the same as that of hydro power.[14]

Energy transitions involve not only new fuel sources but also the gradual diffusion of new prime movers—that is, devices that replace animal and human muscles by converting primary energies into mechanical power, which can then be used to rotate massive turbogenerators producing electricity, or to propel fleets of cars, ships, and airplanes. Transition times from established prime movers to new converters have been often remarkably long. Steam engines, whose large-scale commercial diffusion began in the 1770s with James Watt's improved design, remained important into the middle of the twentieth century. There is no more convincing example of their endurance than the case of the 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 ocean-going ship with diesel engines was launched in 1911. By 1939, a quarter of the world's merchant fleet was propelled by those engines, and virtually every new freighter had them—but 2,751 Liberty ships were still powered by large, triple-expansion oil-fired steam engines.[15] And steam locomotives disappeared from American railroads only in the late 1950s, while in China and India they were indispensable even during the 1980s.

The adoption of automotive diesel engines is another excellent proof of the slow pace of energy transitions. 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 mid1880s, and it reached a remarkable maturity in a single generation after its introduction (Ford's Model T in 1908). But massive car ownership came to the United States only during the 1920s, and in Europe and Japan only during the 1960s, meaning that thirty to forty years in the U.S. case and seventy to eighty years in the European case elapsed between the engine's initial introduction and its 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.[16]

Similarly, it took more than half a century for any internal combustion engine, either gasoline or diesel fueled, to displace agricultural draft animals in industrialized countries. The U.S. Department of Agriculture stopped counting draft animals only in 1963, and the substitution of engines for animals has 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 simply made it larger and more efficient, and these machines now generate more than 70 percent of the world's electricity in fossil-fueled and nuclear stations, with the rest coming from gas and water turbines and diesels.[17]

Why Energy Transitions Are Gradual

No common underlying process explains the gradual nature of energy transitions. In the case of primary energy supply, the time span needed for significant market penetration is mostly a function of financing, developing, and perfecting necessarily massive and expensive infrastructures. For example, the world oil industry handles about 30 billion barrels annually, or 4 billion tons, of liquids and gases. It extracts the fuel in more than a hundred 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.[18] 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—and it is quite obvious that its energy output could not be replicated by any alternative in a decade or two.

In the case of prime movers, there is often inertial reliance on a machine that may be less efficient (steam engine, gasoline-fueled engine) than a newer machine but whose marketing and servicing are well established and whose performance quirks and weaknesses are well known; the concern is that rapid adoption of a superior converter may bring unexpected problems and setbacks. Predictability may, for a long time, outweigh a potentially superior performance, and the diffusion of new converters may be slowed down by complications associated with new machines. One such complication pertains to the high particulate emissions of early diesels; another arises from new supply-chain requirements—for example, sufficient refinery capacity to produce low-sulfur diesel fuel, or the availability of filling stations dispensing alternative liquids.

All energy transitions have one thing 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. Although the second part of this statement seems to be a truism, it is ignored as often as the first part; otherwise, we would not have all those unrealized predicted milestones for electric or fuel cell cars or for clean coal or renewable conversions. These realities should be kept in mind when appraising potential rates of market penetration by nonconventional fossil fuels, by new biomass fuels, or by renewable modes of electricity generation.

The Repowering Challenge

None of the alternatives named has yet reached even 5 percent of its global market. Nonconventional oil, mainly from

Alberta's oil sands, now supplies only about 3 percent of the world's crude oil and only about 1 percent of all primary energy.[19] 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 electricity generation—now provide about 0.5 percent of the world's primary commercial energy.[20] The relevant U.S. production rates were virtually nothing for nonconventional crude oil and about 4 percent for crop-derived ethanol as a share of gasoline demand; less than 1.5 percent of all electricity comes from wind-powered generation and about 0.02 percent from solar conversions.[21]

But is not today's situation fundamentally different? Do we not possess incomparably more powerful technical means to effect faster energy transitions than we did a century or a half century ago? We do—but we also face an incomparably greater scale-up challenge. While the shares of new energies in the global or the U.S. market remain negligible, the absolute quantities needed to capture a significant portion of the total supply 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 a bit of oil) surpassed the burning of wood, charcoal, and straw, each of the two resource categories supplied annually an equivalent of about half a billion tons of oil. If during the coming decades we sought to replace worldwide only 50 percent of all fossil fuels with renewable energies, we would have to displace fossil energies equivalent to about 4.5 billion tons of oil, a task equal to creating *de novo* an industry whose energy output would surpass that of the entire world oil industry that took more than a century to build.

If we are guided by Gore's specific goals, it is rather easy to quantify America's repowering challenge. In 2008, the country generated about 3.75 PWh in fossil-fueled and nuclear stations, the two nonrenewable forms of generation that Gore wants to have entirely replaced by renewable conversions. Installed capacity in these stations was about 870 GW, which means that their load factor was almost exactly 50 percent, and it took the country fifty-seven years to add this capacity.[22] In 2008, the wind and solar electricity generating industries contributed 1.2 percent of the total, and with installed capacity of about 25 GW, their load factor averaged just 24 percent.[23] Accordingly, even if all requisite new HV transmission interconnections were in place, slightly more than two units of generating capacity in wind and solar would be needed to replace a unit in coal, gas, oil, and nuclear—and the country would have to build about 1,740 GW of new wind and solar capacity *in a decade*, 1.75 times as much as it built during *the past fifty or more years*.

But that is not all. If achievable, such a feat would mean writing off in a decade the entire fossil-fueled and nuclear-generation industry, an enterprise whose power plants alone have replacement value of at least $1.5 trillion; and (assuming an average cost of about $1,500/kW) it would also mean spending at least $2.5 trillion to build the new capacity. Conceivably, the first feat can be achieved by some accounting sleight of hand; but where will deeply indebted and financially precarious America get $2.5 trillion to invest in this new generating infrastructure within a single decade? And because those new plants would have to be in areas not currently linked with HV transmission lines to major consumption centers (wind from the Great Plains to the east and west coasts, PV solar from the Southwest to the rest of the country), that "affordable" proposal would also require, as Gore himself admits, a massive rewiring of the United States.

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 2 percent of all electricity. The United States now has about 212,000 miles of HV lines, and inadequacy of the country's poorly inter-connected grids is a major bottleneck for a rapid development of wind and solar generation capacities, while the American Society of Civil Engineers estimates that an investment of $1.5 trillion would be needed by the year 2030 to improve the grid's reliability and connectivity.[24]

But the eventual cost is bound to escalate, given that the regulatory approval process alone is likely to take many years before new line construction can begin. In sum, it is nothing but a grand delusion to think that in ten years the United States can achieve wind and solar generation whose equivalent in thermal power plants took nearly sixty years, while incurring write-off and building costs on the order of $4 trillion, concurrently expanding its electricity grid by at least 25 percent and modernizing the rest—while also reducing regulatory approval of megaprojects from many years to mere months.

False Analogy

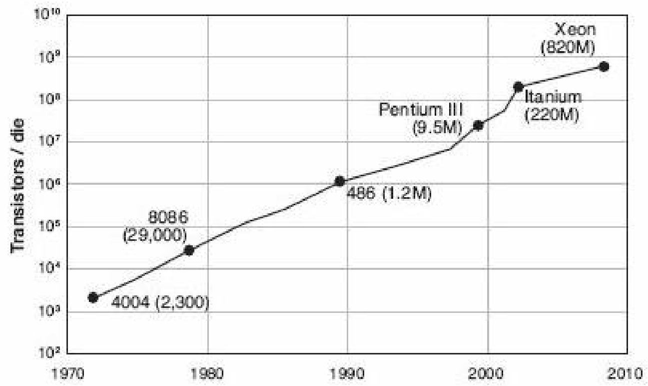
But Gore would argue that the plan is doable and affordable because "as the demand for renewable energy grows, the costs will continue to fall." He then goes on to give the key specific example:

> The price of the specialized silicon used to make solar cells was recently as high as $300 per kilogram. But the newest contracts have prices as low as $50 a kilogram. You know, the same thing happened with computer chips—also made out of silicon. The price paid for the same performance came down 50 percent every 18 months—year after year, and that's what's happened for 40 years in a row.[25]

Gore implies that, analogically, the costs of photovoltaic electricity generation could be halved every eighteen months for decades to come.

But the comparison is wrong, and the implication is impossible. To begin with, if the cost of photovoltaic cells were to decline by 50 percent every eighteen months for just ten years, their cost at the end of that period would be just about 1 percent of the starting value, and the modules, now retailing for nearly $5/W, would be selling before the year 2020 for just $.05/W; we would then be close to producing electricity too cheap to meter. And the comparison is functionally wrong, as well. Moore's law, the doubling of microprocessor performance every two years with ensuing price declines,[26] has worked primarily because of an ever-denser packing of transistors onto silicon wafers—from 2,250 transistors for Intel's first microchip in 1971 to 820 million transistors per die for its latest dual-core processors in 2007 (see figure 8-3)[27]—not because of cheaper crystalline silicon. After all, a blank silicon wafer is worth only about 2 percent of the total value of a finished microprocessor.

FIGURE 8-3
GRAPHIC PRESENTATION OF MOORE'S LAW

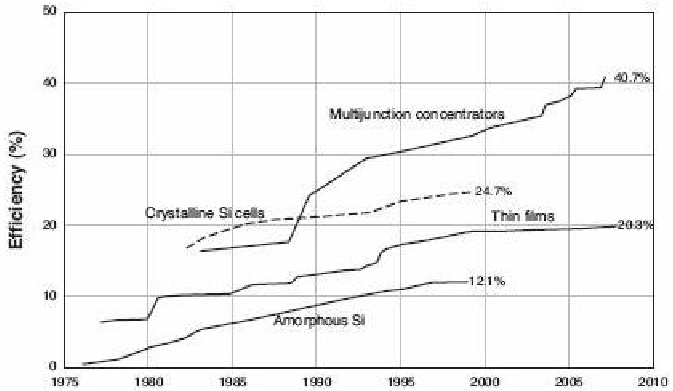


SOURCE: Based on data in Intel (2007, 2010).

Undoubtedly, PV cells have been getting cheaper. Modules cost more than $20 per peak watt in 1980, about $10 by 1985, and around $5 a decade later; but the price was still close to $4.50 at the end of 2009.[28] Moreover, their performance, even from the perspective of the best rates in research settings, has not been improving by orders of magnitude. In 1980, the best thin-film cells were about 8 percent efficient, and by 1995 the efficiency had doubled to about 16 percent; but by 2010 was only about 20 percent, while the performance of the more expensive multjunction concentrating monocrystalline cells rose from about 30 percent in 1995 to about 40 percent by 2010 (see figure 8-4).[29]

Consequently, even the best conversion rates achieved in research settings have doubling periods of fifteen to twenty years, not fifteen to twenty months, and inherent physical limits will make it extremely difficult, if not impossible, to ever achieve yet another doubling for multjunction and monocrystalline cells. Moreover, the PV industry now aims at reducing the price of solar modules from about $4.5/W by the end of 2009 to $1.5–$2/W within a decade, a rate of price improvement far more sluggish than that conforming to Moore's law. And the cells themselves are only part of the overall cost, which also includes their mounting in modules, batteries, inverters, and regulators (adding up to about 80 percent of the final cost) and installation (accounting for the rest). According to surveys by Solarbuzz, a company that researches and consults on solar energy, the price of PV electricity generated by a small (2 kW) residential system declined only 10 percent between the end of the year 2000 and the end of 2009, from nearly 40 c/kWh to just over 35 c/kWh. Similarly, even the electricity produced by the largest (500 kW) industrial systems was only 7 percent cheaper in late 2009 than in late 2000.[30]

FIGURE 8-4
INCREASING CONVERSION EFFICIENCIES OF PHOTOVOLTAIC CELLS



SOURCE: National Renewable Energy Laboratory. 2010. Best research-cell efficiencies. www.nrel.gov/pv/thin_film/docs/kaz_best_research_cells.ppt.

The doubling of microprocessor performance every two years is an atypically rapid case of technical innovation that does not represent the norm of technical advances as far as new energy sources and prime movers are concerned. Inherent physical limits restrict efficiency gains to a doubling or, at most, a tripling of the current values for today's low-performance (thin-film and amorphous) PV cells during the next ten to twenty-five years, and, similarly, unit costs may be halved or quartered during similar periods of time.

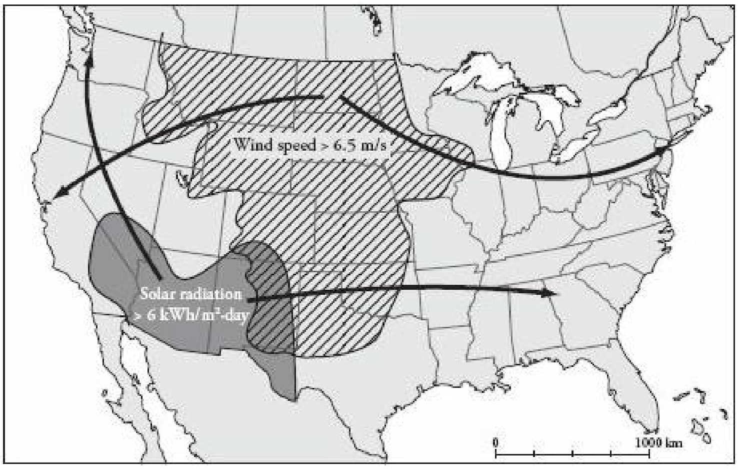
Moreover, Gore's single-decade leap greatly underestimates the task of building new transmission links to carry electricity from the country's windiest states (North Dakota is at the top) and sunniest states (Arizona) to large cities on both coasts (see figure 8-5). He concludes that "the cost of this modern grid—$400 billion over 10 years—pales in comparison with the annual loss to American business of $120 billion due to the cascading failures that are endemic to our current balkanized and antiquated electricity lines."[31]

Characterizing the U.S. transmission grid as balkanized and antiquated is quite correct, and it is also true that the new HV underground cables insulated with cross-linked polyethylene (XLPE), which are increasingly being chosen for new HV transmission links, have become considerably cheaper.[32] But the scaling-up challenge would still be enormous. In 2008, the total worldwide length of these connections (both alternating and direct current and undersea cables) was only about 6,000 miles, and the longest link was just 110 miles (220 kV, 220 MW), between New South Wales and South Australia.[33] This record-long tie (built to trade electricity between the two adjacent states) required a two-year permitting process, even though it goes mostly through the bush, and twenty-one months of construction.

Contrast all these accomplishments with the requirements for America's new supergrid. The country would need at least 50,000 miles of new lines, with multiple underground links from the Great Plains to the coasts each more than 1,000 or even 1,500 miles long, and capacities for each of these lines would have to be in the multiples of gigawatts, not a few hundred megawatts. The whole project would require considerable and rapid scaling up of the existing system. To think that these megaprojects could be designed, the designs approved, and the necessary rights of way obtained in a few years is to have an entirely unrealistic understanding of America's engineering capabilities, its multiple regulatory bureaucracies, and its extraordinary NIMBYism and litigiousness.

FIGURE 8-5

AMERICA'S FUTURE HIGH-VOLTAGE TRANSMISSION CHALLENGE



SOURCE: Author's illustration.

There is no point in fully deconstructing the Pickens plan, which would also have required a massive construction of long-distance HV lines, besides converting most of America's filling stations to dispense natural gas as well as gasoline. In October 2008, Pickens began to warn that the unfolding credit crunch would imperil the project's initial centerpiece, the 4 GW wind farm in West Texas to be built by his Mesa Power Company. In November 2008 he announced that the project would be scaled back, and by July 2009 the plan was suspended.[34] Clearly, America will not see any grand Pickensian wind-for-natural-gas swap within ten years.

And yet in comparison with the latest proposal for a rapid energy transition, both the Gore plan, and even more so the Pickens plan, are models of restraint and relative modesty. The first deals "only" with America's electricity, the other "only" with the country's electricity and cars. In contrast, Jacobson and Delucchi[35] propose to convert all of the world's energy supply to sustainable energy in just two decades by following the WWS (wind, water, and sunlight) path. Given the fact that most of the contemplated capacity in large hydrostations is already in place, their grandiose plan rests on installing 3.8 million large (each with 5 MW capacity) wind turbines and 89,000 photovoltaic and concentrated solar power plants (averaging 300 MW). They estimate the cost of all of this (excluding the requisite new transmission lines) on the order of $100 trillion.

Accomplishment of this lightning-fast extravaganza would require abandoning (except for hydro dams and HV lines) all of the world's existing energy infrastructure and erecting a brand new one by 2030. Average annual cost of this enterprise—taking into account its authors' estimate and adding the cost of extensive new transmission grids, lost capital value of the suddenly abandoned fossil-energy industries, and forgone revenue from their terminated operations—would be easily equal to the total value of the U.S. gross domestic product (GDP), or close to a quarter of the global economic product.

My verdict concerning this project's feasibility has been shared by many other life-long students of energy and could not be expressed better than by quoting just two of many scathing comments submitted to the editors of *Scient fic American*, in which the Jacobson and Delucchi proposal appeared. Michael Briggs wrote: "As a physicist focused on energy research, I find this paper so absurdly poorly done that it is borderline irresponsible. There are so many mistakes, it would take hours of typing to point out all of the problems. The fact that *Scient fic American* publishes something so poorly done does not speak well of the journal."[36] And Seth Dayal added: "This paper is an irresponsible piece of nonsense that would generally be found for order in the back pages of some pulp fiction magazine. The sad part is the editors for some reason chose to not only publish the claptrap but to endorse it."[37]

It is one thing when a former politician endorses an unrealistic project to boost his media presence or when an astute businessman pushes a scheme that would eventually benefit his investments—but it is an entirely different matter when one of the world's oldest science magazines lends its pages to fairy tales that any seasoned engineer and any responsible student of energy systems find grotesquely immature.

The historical verdict is unassailable. Because of the requisite technical and infrastructural imperatives and because of numerous and often entirely unforeseen socioeconomic adjustments, energy transitions in large economies and on a global scale are inherently protracted affairs. That is why, barring some extraordinary—better yet, truly heroic and entirely unprecedented—commitments and actions, none of the promises for greatly accelerated energy transitions will be realized. Moreover, during the next decade, none of the new energy sources and prime movers will make a major difference by capturing 20–25 percent of its market, either worldwide or in the United States. 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 be expensive and will require considerable patience. Coming energy transitions will unfold, as the past ones have done, across decades, not years.