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Building a Low-Carbon Economy

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Over the past half-million years, the world's climate has seen four ice ages and four warm periods separating them, with extensive glaciers engulfing large swaths of North America, Europe, and Asia and then retreating, thousands of species displaced, and the shape of coastlines rearranged as sea levels rose and fell. Yet throughout these hundreds of thousands of years, the atmospheric concentration of carbon dioxide (CO_2), which plays a key role in regulating the climate, has never risen above 300 parts per million.[1]

In 2007, the atmospheric concentration of CO_2 passed 382 parts per million—and it is already at the equivalent of 430 parts per million if the effect of other greenhouse gases is included. (See Figure 6–1.) Humanity is at risk of creating a climate unlike any seen before—unfolding at an unnatural, accelerated pace—more dramatic than any changes in the climate since Earth was last struck by a large asteroid nearly a million years ago. Unless greenhouse gas emissions begin to decline within the next decade, we risk triggering a runaway disruption of the world's climate, one that could last centuries and that our descendants would be powerless to stop.[2]

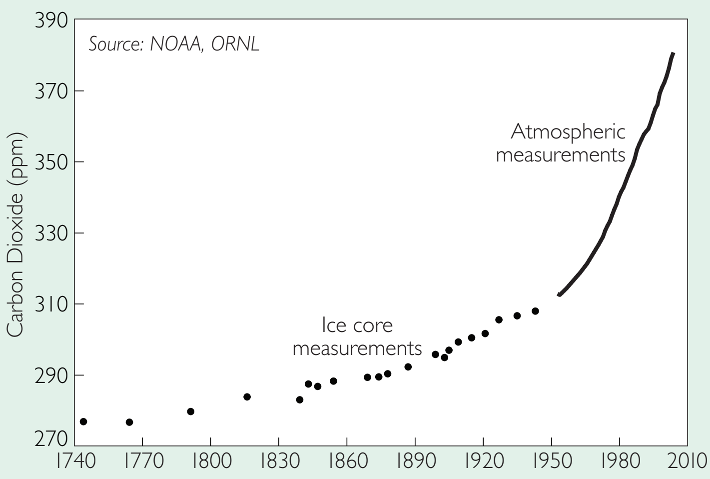
The world is entering uncharted territory. Fossil fuels made the modern economy and all of its material accomplishments possible. But building a low-carbon economy is now the central challenge of our age. Meeting that challenge will require restructuring the global energy industry through technological, economic, and policy innovations that are as unprecedented as the climate change it must address.

Avoiding Catastrophe

Only recently have scientists understood that changes in the concentration of carbon dioxide, methane, and other less common gases could trigger an ecological catastrophe of staggering proportions. The climate, it turns out, is not the vast, implacable system it appears to be.

Past climate changes have been caused by tiny alterations in Earth's orbit and orientation to the sun—providing, for example, just

Figure 6–1. Atmospheric Concentration of Carbon Dioxide, 1744–2004



enough added energy to warm the planet over thousands of years, increasing the concentration of carbon dioxide in the atmosphere, and in turn triggering even larger changes in the temperature, which scientists call a positive feedback. Today's massive release of CO_2 and other greenhouse gases is leading to far greater changes to the atmosphere in a period of decades.[3]

Scientists now project that within the decades immediately ahead, the capacity of the earth and ocean to absorb carbon emissions will decline, while vast changes in the Arctic may further accelerate warming. Melting tundra will release millions of tons of methane, a greenhouse gas more powerful than CO_2. And as the Arctic ice pack disappears in summer—nearly half is already gone—it will be like removing a large air conditioner from Earth's northern hemisphere. This will further warm the climate and could mean the end of the million-year-old Greenland ice sheet—which by itself contains enough water to raise worldwide sea levels by more than seven meters.[4]

When the world will reach such a tipping point—or whether it already has—is not known. But it is already clear that ecological change of this magnitude would lead to unprecedented disruptions to the world's economies. A groundbreaking 2006 study led by former World Bank chief economist Nicholas Stern concluded that climate change could cut global economic output by between 5 and 20 percent. In his 2007 book, *The Age of Turbulence*, Alan Greenspan, the leading free-market economist of the day, included climate change as one of five forces that could derail the U.S. economy in the twenty-first century. The uneven and disruptive nature of these changes could set off an even more serious crisis as conflict within and between societies undermines their stability.[5]

In 2006 the combustion of fossil fuels released 8 billion tons of carbon to the atmosphere—nearly a million tons every hour—with coal and oil contributing roughly 40 percent each and natural gas accounting for the rest. (The manufacture of cement released nearly another 350 million tons, while deforestation and agriculture contributed roughly 1.6 billion tons.) Global fossil fuel carbon emissions have increased fivefold since 1950 and are up 30 percent just since 1990. Today, fossil fuels provide four fifths of the energy that powers the global economy.[6]

Burning fossil fuels on this scale is a vast and risky experiment with Earth's biosphere; scientists are still not sure when the world will cross an invisible but catastrophic threshold of no return. But growing evidence suggests that it may be close. James Hansen, Director of the NASA Goddard Institute of Space Studies, is among a growing group of climate scientists who believe that the world should make every effort to avoid pushing the atmospheric concentration of CO_2 beyond 450 parts per million and the effective concentration (including methane and trace gases) beyond 500 parts per million. This would limit the increase in the average global temperature to 2.4–2.8 degrees Celsius above pre-industrial levels. The increase so far is just under 0.8 degrees Celsius.[7]

Table 6–1. Global Energy Use and Carbon Emissions in 2006 and in 2050 Under Two Scenarios

		2050	
Indicator	2006	Business as Usual	Stabilization Scenario
CO_2 concentration (parts per million)	382	~550	< 450
Energy (billion tons oil equivalent)	12	22	16
Energy-related carbon emissions (billion tons)	8	16	4

Source: See endnote 9.

To keep the world's climate within the range it has occupied for at least a million years, current emission trends will need to be quickly reversed, according to the complex models used by scientists and included in the report of the Intergovernmental Panel on Climate Change (IPCC) released in early 2007. The IPCC scenario that most closely matches likely ecological limits suggests that global carbon emissions will need to peak before 2020 and be reduced by 40–70 percent from the current emissions rate by 2050, eventually falling to zero.[8]

The magnitude of the challenge is clear when the emissions path needed to stay below an atmospheric CO_2 concentration of 450 parts per million is compared with the current path. (See Table 6–1.) The U.S. Department of Energy forecasts that both world energy use and carbon emissions will grow nearly 60 percent by 2030—an average rate of 1.8 percent per year. This would take emissions to nearly 12 billion tons in 2030 and, assuming continued growth at that rate, to almost 16 billion tons in 2050—nearly four times the annual emissions of 4 billion tons that would be needed to keep the CO_2 concentration below 450 parts per million.[9]

Complicating the challenge is the fact that the energy needs of poor countries such as India and China have accelerated in recent years as they entered the most energy-intensive stages of their development—building industries and infrastructure at an astonishing pace. In 2006, industrial countries, with less than 20 percent of the world's population, contributed roughly 40 percent of global carbon emissions, and they are responsible for more than 60 percent of the total carbon dioxide that fossil fuel combustion has added to the atmosphere since the Industrial Revolution began. But this picture is now changing rapidly, particularly in China, where emissions are now rising at 10 percent a year—10 times the average rate in industrial nations. By 2006, China's fossil fuel emissions were only 12 percent below the United States—and gaining rapidly. (See Table 6–2.) Emissions are also growing quickly in the Middle East, where rapid population growth, rising oil wealth, and low, subsidized energy prices have led to skyrocketing energy demand.[10]

At the G-8 Economic Summit in Ger-

Table 6–2. Energy-Related Carbon Emissions, Selected Countries, 2006

Country or Region	Carbon Emissions*	Carbon Emissions, Per Capita	Carbon Emissions, Per $ GDP
	(million tons)	(tons)	(kilograms per $1,000 GDP (PPP))
United States	1,600	5.3	120
China	1,400	1.1	140
Western Europe	930	2.2	71
India	400	0.4	97
Japan	330	2.6	78
Africa	300	0.3	130
World	8,000	1.2	120

**Does not include emissions resulting from gas flaring, cement making, or land use change.*
Source: See endnote 10.

many in June 2007, Canada, France, Germany, Italy, and Japan called for a 50-percent cut in global emissions by 2050—consistent with the trajectory needed to keep atmospheric concentrations below 450 parts per million. Although Russia and the United States abstained from that portion of the final statement, it is clear that the need for drastic cuts in emissions is increasingly accepted by political leaders as well as scientists. This is an ambitious goal, and achieving it will mean reversing an upward trend in carbon dioxide emissions that has been under way for a century and a half.[11]

Providing energy services for the much larger global economy of 2050 while reducing emissions to 4 billion tons of carbon will require an energy system that is very different from today's. For the world as a whole to cut emissions in half by 2050, today's industrial countries will need to cut theirs by more than 80 percent. Getting there depends on three elements in a climate strategy: capturing and storing the carbon contained in fossil fuels, reducing energy consumption through new technologies and lifestyles, and shifting to carbon-free energy technologies.[12]

A variety of combinations of these three strategies can in theory do the job. Princeton scientists Robert Socolow and Stephen Pacala have broken the task down into 15 1-billion-ton "wedges" of reductions—including such options as improved fuel economy or massive construction of wind farms—that policymakers can choose from. The key question is which combination of strategies will minimize the substantial investment cost but also provide a healthy and secure energy system that will last.[13]

Phasing out oil, the most important fossil fuel today, may turn out to be the easiest part of the problem. Production of conventional crude oil is expected to peak and begin declining within the next decade or two. By 2050, output could be a third or more below the current level. Reliance on natural gas, which has not been as heavily exploited as oil and which releases half as much carbon per unit of energy as coal, is meanwhile likely to grow.[14]

But the slowdown in the rate of discovery of oil and gas is pushing world energy markets toward dirtier, more carbon-intensive fossil fuels. The greatest problem for the world's climate is coal, which is both more abundant and more carbon-intensive than oil, and the "unconventional" energy sources such as tar sands and oil shale, which at current oil prices have become economically accessible.

The central role of coal in the world's climate dilemma has led policymakers and industrialists to focus on so-called carbon capture and storage (CCS). Although it is only likely to be feasible for large, centralized uses of fossil fuels, many energy planners are counting on it. They hope to build a new generation of power plants equipped with devices that capture carbon either before or after the combustion of fossil fuels and then pipe the CO_2 into underground geological reservoirs or into the deep ocean, where it could in principle remain for millions of years.

Coal can either be gasified (as it already is in some advanced power plants), with the CO_2 then separated from the other gases, or it can be directly burned in a super-critical pulverized plant that also allows the capture of carbon dioxide. Three significant CCS projects are in operation in Algeria, Canada, and Norway. The facilities in Algeria and Norway simply capture CO_2 that is extracted together with natural gas, which is much easier than capturing CO_2 from coal combustion. A better demonstration of technical feasibility is offered by the sequestration project in Weyburn, Canada, which captures CO_2 from a coal gasification plant. However, even these advanced facilities lack the modeling, monitoring, and verification that are needed to resolve the many outstanding technical issues.[15]

The United States, the European Union, Japan, and China have all launched government-funded CCS programs in the last few years, but the pace of the programs is surprisingly lethargic, given the urgency of the climate problem and the fact that much of the power industry expects CCS to allow continued reliance on the hundreds of coal-fired power plants that today provide over 40 percent of the world's electricity. A 2007 study by the Massachusetts Institute of Technology (MIT) concluded that the U.S. Department of Energy's main program to demonstrate large-scale CCS is not on track to achieve rapid commercialization of key technologies. Locating, testing, and licensing large-scale reservoirs where carbon dioxide can be stored is a particularly urgent task.[16]

In light of the lead times required for technology development and demonstration, it will be 2020 at the earliest before significant numbers of carbon-neutral coal plants come online. Nor is it guaranteed that CCS plants will be competitive with other carbon-free generators that are likely to be in the market by that date. But the bigger question is whether that would not be too late, considering the hundreds of new coal-fired power plants that are currently being considered in China, the United States, and other nations. To have any hope of halving carbon emissions by 2050, it is hard to avoid the conclusion that the uncontrolled burning of coal will need to be eliminated—and soon. In the meantime, a growing number of climate experts are calling for a moratorium on building new coal-fired power plants unless or until CCS becomes available.

The Convenient Truth

Many energy industry executives argue that reducing carbon emissions as rapidly as scientists now urge would risk an economic collapse. According to conventional wisdom, the available alternatives are just too small, unreliable, or expensive to do the job. In 2001, for example, Vice President Dick Cheney described saving energy as a moral virtue but not important enough to play a major role in the national energy policy proposals he was developing at the time. The World Energy Council, which represents the large energy companies that dominate today's energy economy, declared in 2007 that renewable energy has "enormous practical challenges.It is unlikely to deliver a significant decarbonisation of electricity quickly enough to meet the climate challenge."[17]

A thorough review of studies that assess the potential contribution of new energy options, as well as the rapid pace of technological and policy innovation now under way, points to the opposite conclusion. Improved energy productivity and renewable energy are both available in abundance—and new policies and technologies are rapidly making them more economically competitive with fossil fuels. In combination, these energy options represent the most robust alternative to the current energy system, capable of providing the diverse array of energy services that a modern economy requires. Given the urgency of the climate problem, that is indeed convenient.

The first step in establishing the viability of a climate-safe energy strategy is assessing the available resources and the potential role they might play. Surveys show that the resource base is indeed ample; the main factors limiting the pace of change are the economic challenge of accelerating investment in new energy options and the political challenge of overcoming the institutional barriers to change.

Energy productivity measures an economy's ability to extract useful services from the energy that is harnessed. From the earliest stages of the Industrial Revolution, energy productivity has steadily advanced; in the United States, the economy has grown 160 percent since 1973, while energy use has increased 31 percent, allowing the nation's energy productivity to double during the period. Germany and Japan, starting with higher productivity levels, have achieved comparable increases. But even today, well over half of the energy harnessed is converted to waste heat rather than being used to meet energy needs.[18]

This suggests enormous potential to improve energy productivity in the decades ahead. Light bulbs, electric motors, air conditioners, automobiles, power plants, computers, aircraft, and buildings are among the hundreds of systems and technologies that can be made far more efficient, in many cases just by using already available technologies more widely—such as compact fluorescent light bulbs and hybrid electric vehicles. Further gains can be made by altering the design of cities—increasing the role of public transport, walking, and cycling, while reducing dependence on automobiles.

A global assessment by the McKinsey Global Institute of the potential to improve energy productivity concluded that the rate of annual improvement between now and 2020 could be increased from 1 percent to 2 percent, which would slow the rate of global energy demand growth to just 1 percent a year. If these gains are extended to 2050, the growth in world energy use could be held to roughly 50 percent, rather than the doubling that is projected under most business-as-usual scenarios. This large difference represents the combined current energy consumption of Europe, Japan, and North America.[19]

The greatest potential turns out to lie in the most basic element of the energy economy—buildings—which could be improved with better insulation, more-efficient lighting, and better appliances, at costs that would be more than paid for by lower energy bills. With technologies available today, such as ground-source heat pumps that reduce the energy needed for heating and cooling by 70 percent, zero-net-energy buildings are possible that do not require fossil fuels at all. All countries have untapped potential like this to increase energy productivity, but the largest opportunities are found in the developing nations, where current energy productivity tends to be lower. Future increases in energy productivity will not only reduce consumption of fossil fuels, they will make it easier and more affordable to rapidly increase the use of carbon-free energy sources.[20]

On the supply side, one of the post-carbon energy sources receiving much attention these days is nuclear power, which already plays a major role in some countries but faces considerable obstacles to its expansion in the decades ahead. (See Box 6–1.) Renewable energy, in contrast, relies on two primary energy sources—sunlight and the heat stored below the earth's surface—that are available in vast abundance. The sunlight alone that strikes Earth's land surface in two hours is equivalent to total human energy use in a year. While much of that sunlight becomes heat, solar energy is also responsible for the energy embodied in wind, hydro, wave, and biomass, each with the potential to be harnessed for human use. Only a small portion of that enormous daily, renewable flux of energy will ever be needed by humanity.[21]

Several studies have assessed the scale of the major renewable resources and what their

Box 6–1. What About Nuclear Power?

Nuclear power is a largely carbon-free energy source that could in theory help phase out fossil fuels. More than 300 nuclear plants currently provide 15 percent of the world's electricity. But this energy source has been plagued by a range of problems, most fundamentally high cost and the lack of public acceptance, that have halted development for more than 20 years in most of Europe and North America. Over the past decade, global nuclear capacity has expanded at a rate of less than 1 percent a year; in 2006, the world added 1 gigawatt of nuclear capacity but 15 gigawatts of wind capacity.

Major efforts are now under way to revive the nuclear industry—driven by a combination of high natural gas prices, concern about climate change, and a large dose of new government subsidies. Technology advances have led several companies to develop modestly revamped plant designs that are intended to make nuclear plants easier to control, less prone to accidents, and cheaper to build. The most important innovations are to standardize designs and streamline regulatory procedures. So far, two nuclear plants are being built in Europe, several are under construction in China, and the United States is expecting as many as 32 plants to be ordered by the end of 2008. Unfortunately for the industry, several different plant designs are being promoted by different companies, limiting the potential for standardization.

It is too early to tell whether these nuclear plants will be economical enough to launch a wave of construction. The first new European reactor has been under construction in Finland and is already two years behind schedule and $1 billion over budget. A study by a Keystone Center panel composed of academics, energy analysts, and industry representatives estimated the cost of new nuclear power at 8–11¢ per kilowatt-hour—more expensive than natural gas- and wind-powered generators. And because of large capital requirements and long lead times, nuclear plants face a risk premium that other generators do not.

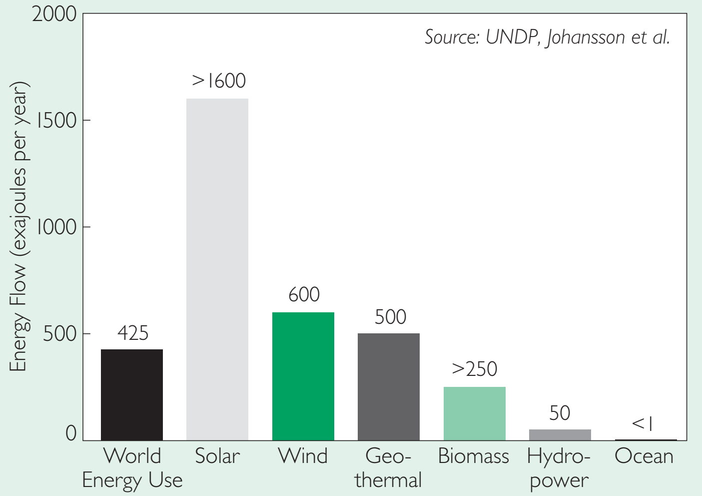
Energy planners will also have to reckon with the scale and pace of construction that would be needed to make a serious dent in the world's climate problem. MIT researchers estimate that 1,000–1,500 new reactors would be needed by 2050 for nuclear to play a meaningful role in reducing global emissions—a construction pace 20 times that of the past decade and five times the peak level in the 1980s.

Many advocates of nuclear power argue that given the urgency of doing something about climate change quickly, it must be pursued. Speed, however, is not one of nuclear power's virtues. Planning, licensing, and constructing even a single nuclear plant typically takes a decade or more, and plants frequently fail to meet completion deadlines. Due to the dearth of orders in recent decades, the world currently has very limited capacity to manufacture many of the critical components of nuclear plants. Rebuilding that capacity will take a decade or more.

Source: See endnote 21.

practical contribution to the energy economy might one day be. One study by the National Renewable Energy Laboratory in the United States, for example, concluded that solar thermal power plants built in seven states in the U.S. Southwest could provide nearly seven times the nation's existing electric capacity from all sources. And mounting solar electric generators on just half of the suitable rooftop area could provide 25 percent of U.S. electricity. In the case of wind power, the Pacific Northwest Laboratory found that the land-based wind resources of Kansas, North Dakota, and Texas could meet all the nation's electricity needs, even with large areas excluded for environmental reasons.

Figure 6–2. Estimates of Available Energy Resources Using Today's Technology



These reports demonstrate that resource availability will not be a limiting factor as the world seeks to replace fossil fuels. With improved technologies, greater efficiency, and lower costs, renewable energy could one day replace virtually all the carbon-based fuels that are so vital to today's economy. (See Figure 6–2 and Table 6–3.)[22]

Designs for a New Energy Economy

The greatest challenge for the widespread adoption of renewable energy sources is fitting them into an energy system that was designed around fossil fuels—fuels that have the advantage of being concentrated and easily stored. To seriously de-carbonize the energy economy, ways must be found to power everything from transportation to the latest electronics on seemingly ephemeral energy sources such as solar energy and wind power.

Electricity is the single most important element of today's energy system, essential for lighting, cooling, electronics, and many industrial processes; its role will only grow as new technologies allow grid electricity to be used for plug-in hybrid cars and to heat and cool homes efficiently through ground-source heat pumps. Electricity also happens to be the output of the largest and most easily replaced contributor to carbon emissions: coal-fired power plants. It is therefore fortuitous that solar, wind, geothermal, ocean, and bioenergy are all able to produce electricity.

From the generator's viewpoint, the main disadvantage of most of these electricity sources is their intermittency—wind and solar, for example, tend to be available only 25–40 percent of the time, depending on the tech-

Table 6–3. Estimates of Potential Contribution of Renewable Energy Resources

Energy Source	Potential Contribution
Solar water heaters	Could provide half the world's hot water
Solar cells	Could supply 10 percent of grid electricity in the United States by 2030
Solar power plants	Seven states in U.S. Southwest could provide more than 7,000 gigawatts of solar generating capacity—nearly seven times U.S. electric capacity from all sources
Wind power	Could provide 20 percent of world's electricity; offshore wind farms could meet all of European Union's electricity needs
Biomass	One billion tons could be available for energy conversion in the United States in 2025, replacing one third of current oil use
Geothermal heat	Could provide 100 gigawatts of generating capacity in the United States alone
Wave and ocean thermal energy	Long-run contribution could be on same order of magnitude as current world energy use

Source: See endnote 22.

nology and site. Intermittency turns out, however, to be not as big a problem for renewable electricity as utility engineers once anticipated. Power companies are already accustomed to dealing with fluctuating demand, and even conventional power plants are sometimes shut down unexpectedly. So intermittency is not a new concept, though dealing with it does take planning and a willingness to make adjustments in grid operation as penetration levels rise.

Power companies in some regions have already gained experience in operating grids that include a sizable number of wind turbines. Several U.S. utilities have found that when wind turbines meet 10 percent of peak power demand, only minimal adjustments to grid operations are needed. And in areas of northern Europe, where wind contributes over 20 percent of peak power, only minor strengthening of grids and adjustments to the operations of other generators are required. Utilities with substantial hydropower capacity have the ability to quickly ramp up power generation when needed, but most use gas turbines to provide "peak power" when demand is particularly high (or when other generators are not working.) Strengthening weather forecasting capabilities and interconnecting multiple, dispersed wind farms also enables utilities to avoid most problems related to high levels of dependence on wind power.[23]

As reliance on coal is reduced in the decades ahead, it is likely that many regions will move well beyond the 20 percent threshold for wind, solar, and other intermittent power sources. To do this, they can pursue some combination of three strategies: add local generating capacity using microturbines and fuel cells, move to digital "smart" grids that are more flexible in their ability to balance demand and supply, and develop the capacity to store energy economically so that it is available when needed.

The digital grid would allow the electricity system to operate much the way the Internet does—an electronically controlled grid that responds in real time to decisions made by users, providing the same kind of efficiency, interconnectivity, and precision as the digital devices that it powers. One advantage of such a system is that the electricity meter can be transformed into a consumer gateway that transmits price signals instantaneously and allows unneeded devices to be turned off when prices are high or renewable resources are not as available. Kurt Yeager, who directs the Galvin Electricity Initiative, believes that the introduction of digital grids will increase the ability to achieve higher levels of reliance on intermittent renewable generators.[24]

The ability to store energy is also developing rapidly. Wind farm operators' desire to qualify for the "capacity credits" earned when power can be generated during peak periods has pushed some to explore storage options, notably in the form of compressed air that can be kept in underground steel pipes or in geological formations. One company plans to mount a compressor under the structure that houses the generating components and send the compressed air down the tower, where it will be stored underground; when electricity is needed, the compressor is reversed, generating electricity. TXU, a large electric power company in Texas, recently canceled eight coal-fired power plants and is planning instead to build a 3,000-megawatt wind farm—larger than any now in operation—that may include compressed air storage.[25]

The development of less expensive, longer-lived batteries will further ease the way to greater reliance on renewable energy. Portable electronic devices and hybrid electric cars are rapidly increasing demand for advanced batteries made of nickel metal hydride and lithium; as they become less expensive and more widely used, these will allow power companies and consumers to complement distributed micro-solar generation with distributed storage. And the planned introduction of plug-in hybrid cars by General Motors and Toyota in the next few years will allow automobiles to run on sunlight and wind power as well as renewable biofuels, while the cars themselves can be plugged into the grid and used as "peaking plants" when demand is high.[26]

Flexible, secure electricity grids will be further aided by a new generation of micropower generators that is being developed. Small-scale gas turbines, sterling engines, and fuel cells can easily generate up to a third of the total electricity supply, with the waste heat available for use in the buildings in which they are located. And unlike the large power plants that dominate today's power system, micro-generators will be able to respond quickly to shifts in demand. In the longer run, the natural gas that currently courses through the world's gas pipelines may be replaced by hydrogen or ammonia that is produced from a broad range of renewable resources.

The ability to integrate new energy sources into the existing energy infrastructure will speed the transition and reduce its cost. Already, wind power is being blended into many electric grids, while ethanol is being added to gasoline. In Brazil, most new cars are designed to run on any mixture of ethanol and gasoline. In Germany, local producers have begun to add biogas (methane) to natural gas pipelines. And in Japan, many homeowners are generating electricity with solar cells—sending power to their local grids as well as drawing from them.[27]

The Economics of Change

When oil was first discovered in western Pennsylvania in the 1860s, it was virtually useless—far more expensive than coal and, prior to the development of the refinery or internal combustion engine, useless for transportation. Even as oil became widely used for lighting in the late nineteenth century, the idea that it would become a dominant energy source—let alone reshape the global economy—was inconceivable.

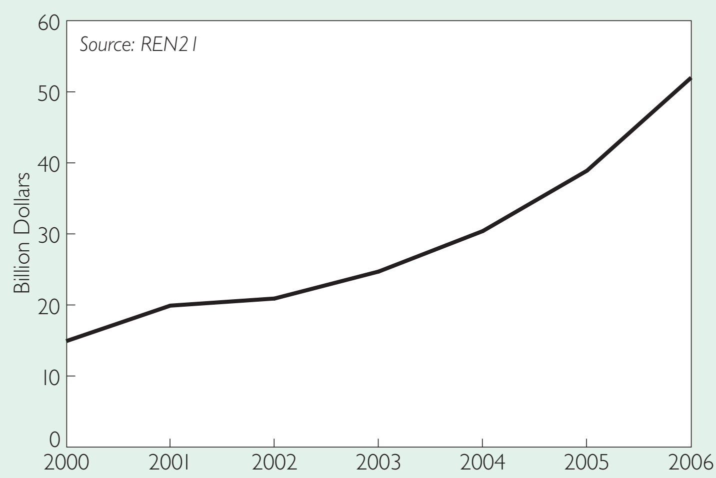
The history of economic transformation follows a familiar path. Dominant technologies and businesses are generally reliable and economical, and over time they develop a network of institutional and political support that effectively resists change. New technologies and businesses generally enter a niche of the broader market, offering a higher cost service that meets specialized needs. But over time the new competitor becomes more economical and widens its share of the market, eventually undercutting the cost of the dominant player and gradually remolding the institutional infrastructure to meet its own needs. The transition from one generation of technology to another is often gradual at first, but then speeds up as the economic advantage flips.

According to conventional wisdom, the energy sector is far from such a transformation. New renewable energy sources represent less than 2 percent of the total energy supply, and in 2007 total U.S. government support of renewable energy R&D came to little more than $600 million—about what the government spent in Iraq in a single day. What these figures fail to capture is the recent infusion of private- sector capital and technology and the fact that today's renewable energy pioneers are not limited to "energy technology" but rather draw on fields as diverse as semiconductor physics, biotechnology, aerodynamics, and computer engineering.[28]

Over the past five years, the manufacture of wind turbines has grown at 17 percent annually, and solar cells at a 46-percent annual rate. This rapid growth has turned these industries into lucrative businesses, with demand outrunning supply and profits soaring. Some $52 billion was invested in renewable energy in 2006, up 33 percent from 2005. (See Figure 6–3.) At that level, investment in renewable energy is already one quarter that of the oil industry—and gaining ground rapidly. Some of the world's leading corporations have made major investments in renewable energy, including Applied Materials (solar photovoltaics (PV)), BP (wind and solar PV), General Electric (wind), DuPont (biofuels), Goldman Sachs (wind, and central solar), Mitsubishi (wind), Royal Dutch Shell (wind, hydrogen, and solar PV), Sharp (solar PV), and Siemens (wind).[29]

Corporate R&D on clean energy technologies reached $9.1 billion in 2006. A single company, Vestas Wind Systems, spent $120 million on R&D in 2006, while the U.S. government spent less than $50 mil-

Figure 6–3. Global Investment in Renewable Energy, 2000–06



lion on wind R&D. Even these numbers understate private R&D, which is often embedded in commercial projects, and exclude R&D investments by privately held companies, many of them funded with venture capital and other forms of equity investment. Venture capital and private equity investment in clean energy totaled $8.6 billion in 2006, 69 percent above the 2005 level and 10 times the 2001 level. (See Chapter 13.) By early 2007, these investments had helped create 146 clean energy start-up companies with names such as Nanosolar, Celunol, SunPower, E3 Biofuels, and Miasole, most of them working to develop and commercialize new energy technologies.[30]

These tiny firms may be the real game changers in the new energy industries, following in the footsteps of companies like Microsoft and Google, which quickly came to dominate their more established competitors—bringing a level of innovation that larger firms are rarely capable of.

In Silicon Valley, clean energy is helping drive a post-dotcom revival. Although it is regrettable that serious investment in renewable energy did not begin earlier, the science and technology available today will allow the industry to achieve performance and cost goals that would not have been possible in the past.

One example is photovoltaics, where producers are pursuing a host of strategies for reducing materials requirements, raising efficiency, and lowering manufacturing costs of the crystalline cells that dominate the market. Other companies are developing new thin-film photovoltaic materials that hold the promise of dramatic cost reductions. With demand outrunning supplies of PV materials in the past two years, price trends have temporarily reversed their usual downward course. But the industry is planning to increase its manufacturing capacity as much as eightfold over the next three years, and dramatic price declines are likely, spurring the industry to develop new applications and markets that would not be feasible today.[31]

Beyond the advance in technology, the economics of renewable energy will further improve as the scale of production rises—the same phenomenon that has successively turned televisions, personal computers, and mobile phones from specialty products for high-income technology pioneers into mass-market consumer devices. An analysis of production costs in several manufacturing industries by the Boston Consulting Group found that each time cumulative production of a manufactured device doubles, production costs fall by 20–30 percent.[32]

The annual production of wind turbines is now doubling every three years—and wind is already competitive with natural gas–fired power in the United States. It would be competitive with coal-fired power plants if they had to pay the current European CO_2 price of $32 per ton. Solar electricity is still twice as expensive as retail grid electricity in most markets, but annual production is doubling every two years—which should cut costs in half in the next four to six years.[33]

Making Energy Markets Work

Advancing technology, rising energy prices, and the growing move to place a price on carbon emissions in many parts of the world have created an extraordinarily favorable market for new energy technologies. Reaching a true economic tipping point will depend on more than these simple variables, however. Energy markets virtually everywhere are regulated, complex, often inefficient, and rarely predictable. What happens to the energy economy, and to the world's climate, in the years ahead will be heavily influenced by hundreds of policy decisions made at international, national, and local levels—and whether these new policies can be sustained.

Many energy economists argue that the reason fossil fuels dominate today is their inherently lower cost compared with the alternatives. This suggests that putting a price on carbon—likely through a carbon dioxide tax or a regulatory cap on emissions such as the one in Europe—would solve the climate problem. Getting the price signals right is an essential step, but its limits are demonstrated by the modest impact that the $50 increase in the cost of a barrel of oil has had on petroleum consumption in the past five years. That is equivalent to a carbon dioxide price of $120 per ton; the current price of a carbon credit in Europe is $32 per ton, while one of the leading climate bills before the U.S. Congress would cap the price of carbon at $12—equivalent to $5 per barrel of oil.[34]

The neoclassical economic view assumes an economically frictionless world in which buyers and sellers have all the information and capital they need, and there are no serious barriers to the introduction of new technologies. At the extreme, neoclassical economists sound like economic fundamentalists, envisioning an idealized, mechanistic economy that is never found in the real world. Economic research beginning in the 1920s has shown that the costs of transactions can greatly limit the effectiveness of markets, while other research suggests that people's behavior often fails to follow neoclassical rules. Nobel laureate economist Douglass North has shown that laws, customs, and social priorities greatly influence the working of the economy. Without them, most markets would work inefficiently if at all.[35]

Because energy markets have been shaped more than most others by government policy, institutional constraints, and the power of large industrial enterprises, simple economic theory provides minimal insight about how to spur change. The electric power industry is particularly far from the neoclassical model, governed as it is by extensive government regulation that is intended to facilitate development of large, reliable electric systems, with one company dominating most local grids and in some cases owning the transmission lines and power plants as well.

Although this economic model has been broadly successful in delivering affordable electricity to billions of people, it has done so mainly by making it easy to add energy supply—but providing much less incentive or opportunity to improve energy efficiency. Regulations have also favored large fuel-intensive generators at the expense of smaller, capital-intensive units. The result is an electricity system that is far from the economic ideal—and that will require major reforms if it is to maximize economic efficiency, let alone account for the massive environmental externalities represented by global climate change.

The profits of most electric utilities are determined by regulators based on the amount of power sold. This naturally makes them proponents of growth—the more electricity consumers buy, the more profitable the utility is. And as long as the regulator approves, there is no risk in building a power plant since there are no competitors, and costs are borne by the consumer. The utility also bears little risk if the plant burns a fuel whose price is volatile—fuel adjustment clauses allow price increases also to be passed to the customer.

Although consumers should in theory be interested in making investments in energy efficiency whenever it is economical, they face many obstacles, including a lack of capital to invest in conservation and a lack of information about which investments make sense. Perceiving the lack of demand, potential manufacturers and installers of energy-efficient equipment have little incentive to scale up production or build businesses that would facilitate efficiency improvements.

One of the easiest ways to overcome these kinds of market barriers is government mandates. Since the 1970s, many governments have required that home appliances, motor vehicles, and buildings meet minimum efficiency standards in order to be sold, and these standards have been gradually ratcheted up over time. Additional tightening is now in order, and many governments are moving quickly in that direction. Average auto efficiency standards, for example, will soon move to 47 miles per gallon in Japan and 49 miles per gallon in Europe, and the U.S. Congress is considering tightening the U.S. standard, which has been stuck at 27.5 miles per gallon for over two decades. Another approach to requiring efficiency can be seen in the law recently passed in Australia to phase out the use of most incandescent light bulbs, which would be replaced by compact fluorescent bulbs that are four times as efficient.[36]

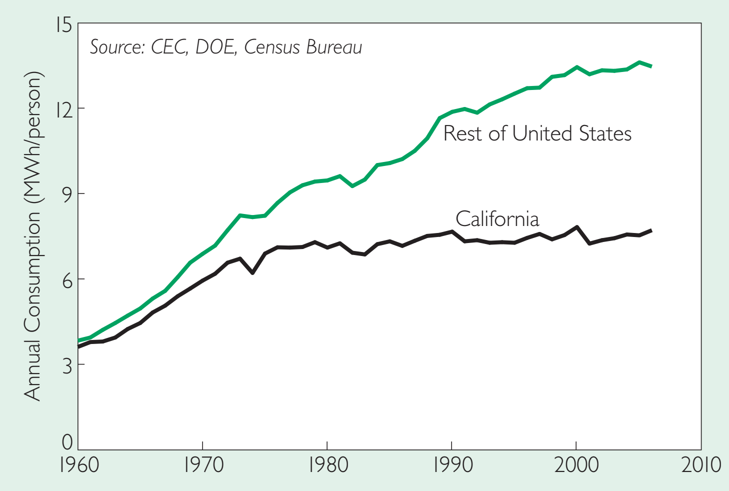
Government mandates are also being used to compel the construction of more energy-efficient buildings and to require the introduction of renewable energy into electricity grids as well as the markets for liquid fuels. Several national governments and 24 states in the United States now have binding "renewable portfolio standards" requiring that specified amounts of renewable electricity be added to their grids. In Spain, a recent update of building codes requires all new buildings to incorporate solar water heaters. As of April 2008, the state government of Baden-Wurttemberg, Germany, will require that 20 percent of new buildings' heating requirements be met with renewable energy. Brazil, the United States, and the European Union are among the jurisdictions that require that a minimum proportion of biofuels be blended with gasoline and diesel fuel, spurring growth in their use.[37]

Such mandates can patch over some of the holes in a market economy, but they are at best blunt instruments that do not harness the full power of the market to effect change. While they are a useful backstop to ensure that minimal rates of change occur and to remove the very worst technologies from the market, it is also essential that markets reward innovation and investment that strives to achieve the best possible performance. One important step in this direction is to de-couple electric utilities' profits from the amount of power they sell by introducing a regulatory formula that instead rewards utilities for providing the best service at the least cost. California regulators have already made this change; as a result of this and other policies, Californians use less than half as much electricity per person as other Americans do. (See Figure 6–4.)[38]

John Hoffman, an energy efficiency expert and former U.S. Environmental Protection Agency official, has proposed an additional strategy for spurring efficiency investments—a "transaction bridge" that allows manufacturers and installers to share in the savings derived from installing more-efficient equipment in buildings. This would motivate them to continually develop better technologies, to work with utilities to accelerate the development of new markets, and to scale up both production and installation in order to lower cost. This mechanism could also be used to spur introduction of micro-power technologies such as photovoltaics, as well as ground source heat pumps. And Hoffman has proposed a similar system for motivating the production and sales of efficient vehicles.[39]

European governments have developed another economic tool to spur investment in renewable energy. Beginning in the early 1980s, Denmark decided to reduce its dependence on oil-fired generation by encouraging its agricultural industry to enter the power

Figure 6–4. Electricity Use Per Capita, California and Rest of United States, 1960–2006



business by selling wind- and biomass-based electricity to the utilities at prices set by government. This stopped the utilities from thwarting potential competitors, and over two decades it reduced Denmark's dependence on fossil fuels and made it a leading generator of renewable power.[40]

Germany and Spain adopted similar market access laws in the 1990s, and they too moved quickly into the leading ranks of renewable energy development. Over time, the prices governments set have been adjusted downward as the cost of renewable technologies has fallen. As a result of this law, Germany now holds the pole position in solar PV and wind-generating capacity—despite the fact that it has modest resources of sun and wind.[41]

The Final Tipping Point

There are good reasons to think that the world may be on the verge of a major transformation of energy markets. The powerful interaction of advancing technology, private investment, and policy reform have led to a pace of change unseen since men like Thomas Edison and Henry Ford created the last great energy revolution a century ago. But is it enough? Will the coming years bring the accelerated change and trillions of dollars of investment that Nicholas Stern estimates is needed to reverse the tide of climate change?[42]

The answer to that question will likely be found not in the messy world of economics but in the even messier world of politics. Can the enormous power of today's industries be set aside in favor of the common good? Time is growing short. In the United States alone, 121 coal-fired power plants have been proposed. If built, they could produce 30 billion tons of carbon dioxide over their 60-year lives. China is building that many plants every year.[43]

There were growing signs in 2007 that the years of political paralysis on climate change may be coming to an end, spurred by the warnings of scientists and the concerns of citizens. One sign of the changing times is that many of the planned coal plants are under attack by local and national environmentalists, and some have already been scrapped. Germany recently announced that its centuries-old hard coal industry will be closed by 2018. Several potentially game-changing political developments in 2007 are worth noting:

- Twenty-seven major U.S. companies—from Alcoa and Dow Chemical to Duke Energy, General Motors, and Xerox—announced support for national regulation of CO_2 emissions.

- The European Union committed to reducing its carbon dioxide emissions 20 percent below 1990 levels by 2020, and member states are ramping up their energy efficiency and renewable energy programs in order to achieve these goals.
- China announced its first national climate policy, pledging to step up its energy efficiency and renewable energy programs and acknowledging that earlier policies were not sufficient.
- Seventeen states in the United States moved toward adopting regulations on CO_2 emissions, increasing pressure on the U.S. Congress, which was considering national legislation.
- Brazil recognized the threat that climate change poses to the country's economically crucial agriculture and forestry industries and signaled a new commitment to strengthening international climate agreements.[44]

As negotiations begin on the international climate agreement that will supplant the Kyoto Protocol after 2012, the world's political will to tackle climate change will be put to an early test. The politics of climate change are advancing more rapidly than could have been imagined a few years ago. But the world has not yet reached the political tipping point that would ensure the kind of economic transformation that is required. And the divide between industrial and developing countries over how to share the burden of action must still be resolved.

As people around the world come to understand that a low-carbon economy could one day be more effective than today's energy mix at meeting human needs, support for the needed transformation is bound to grow. Urgency and vision are the twin pillars on which humanity's hope now hangs.

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