WORLDWATCH REPORT 178

Low-Carbon Energy:

A Roadmap

CHRISTOPHER FLAVIN

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On the cover: Solar roof in San Francisco, California.
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Chris has participated in several historic international conferences, including the Earth Summit in Rio de Janeiro in 1992 and the Climate Change Conference in Kyoto, Japan, in 1997. He speaks frequently to business, university, and policy audiences. He also testifies before national and state legislatures and meets frequently with government and international leaders. Chris is a native of Monterey, California, and a cum laude graduate of Williams College, where he studied economics, biology, and environmental studies.

Summary

Technologies available today, and those expected to become competitive over the next decade, will permit a rapid decarbonization of the global energy economy. New renewable energy technologies, combined with a broad suite of energy-efficiency advances, will allow global energy needs to be met without fossil fuels and by adding only minimally to the cost of energy services.

The world is now in the early stages of an energy revolution that over the next few decades could be as momentous as the emergence of oil- and electricity-based economies a century ago. Double-digit market growth, annual capital flows of more than $100 billion, sharp declines in technology costs, and rapid progress in the sophistication and effectiveness of government policies all herald a promising new energy era.

Advanced automotive, electronics, and buildings systems will allow a substantial reduction in carbon dioxide (CO_2) emissions, at negative costs once the savings in energy bills is accounted for. The savings from these measures can effectively pay for a significant portion of the additional cost of advanced renewable energy technologies to replace fossil fuels, including wind, solar, geothermal, and bioenergy.

Resource estimates indicate that renewable energy is more abundant than all of the fossil fuels combined, and that well before mid-century it will be possible to run most national electricity systems with minimal fossil fuels and only 10 percent of the carbon emissions they produce today. The development of smart electricity grids, the integration of plug-in electric vehicles, and the addition of limited storage capacity will allow power to be provided without the baseload plants that are the foundation of today's electricity systems.

Recent climate simulations conclude that CO_2 emissions will need to peak within the next decade and decline by at least 50 to 80 percent by 2050. This challenge will be greatly complicated by the fact that China, India, and other developing countries are now rapidly developing modern energy systems.

The only chance of slowing the buildup of CO_2 concentrations soon enough to avoid catastrophic climate change that could take centuries to reverse is to transform the energy economies of industrial and developing countries almost simultaneously. This would have seemed nearly impossible a few years ago, but since then, the energy policies and markets of China and India have begun to change rapidly—more rapidly than those in many industrial countries. Renewable and efficiency technologies will allow developing countries to increase their reliance on indigenous resources and reduce their dependence on expensive and unstable imported fuels.

Around the world, new energy systems could become a huge engine of industrial development and job creation, opening vast new economic opportunities. Developing countries have the potential to "leapfrog" the carbon-intensive development path of the 20th century and go straight to the advanced energy systems that are possible today.

Improved technology and high energy prices have created an extraordinarily favorable market for new energy systems over the past few years. But reaching a true economic tipping point will require innovative public policies and strong political leadership.

The Road to Low-Carbon Energy

Speaking in Washington on June 23, 2008, James Hansen, the top climate scientist at the U.S. National Aeronautics and Space Administration, had a sharp warning for policymakers: "If we don't begin to reduce greenhouse gas emissions in the next several years, and get on a very different course, then we are in trouble.... This is the last chance."[1*]

After two decades of halting and largely ineffectual efforts to address the world's climate crisis, humanity has reached a moment of truth. As scientific alarm about the probability and catastrophic consequences of climate change has grown in recent years, annual fossil fuel emissions of the most important greenhouse gas, carbon dioxide, have soared 35 percent above their 1990 rates.[2] And because we have waited so long and must now cope with skyrocketing emissions in China and other developing countries, the reduction in emissions will need to be steeper, and the challenge to societies and economies that much greater.

Stabilizing the climate will require changes in many sectors of the economy, including agriculture and forestry. But fossil fuels are the largest part of the problem, and reducing their dominance of the global energy system is the key to climate stability. Leading scientists have concluded that carbon dioxide emissions from fossil fuels will have to be cut at least 50 to 80 percent below current levels by 2050—and possibly to zero—in order to prevent potentially catastrophic rates of climate change.[3] And they will have to continue falling beyond that date.

* Endnotes are grouped by section and begin on page 37.

To call these targets ambitious is to understate the challenge. Carbon-based fossil fuels made the modern economy and all of its material accomplishments possible. Powering the global economy without those fuels will require restructuring the energy industry through technological, economic, and policy innovations that are as all-encompassing as the climate change they must address. A large-scale shift to carbon-free sources of energy is the essential centerpiece of such a transformation, together with major advances in energy efficiency.

The question of whether such a transition is possible is one of the most complex and hotly debated issues of our time. Many experts, particularly those employed by today's energy industries, believe that fossil fuels must remain dominant for decades to come, and that the only viable energy strategy relies on even more massive use of coal, coupled with development of a vast system to capture and store the resulting carbon dioxide. But since the 1970s, a small but growing tribe of energy dissidents has argued that there is another option: that the solution to our carbon problem is not at the "end-of-the-pipe" but in an entirely new energy system. Today, such a transition appears more feasible—and more imminent—than ever before.

The technologies that are available today, or are projected to become available over the next two decades, will allow a rapid shift in the mix of energy sources on which the world depends—and equally dramatic changes in the systems for transporting, storing, and using that energy. Solar, wind, geothermal, and biological resources each have the potential to supply vast quantities of energy that can be converted to electricity and liquid and gaseous fuels, as well as used to supply heat directly to buildings and industry. But new technologies will need to be complemented by major changes in the world's energy infrastructure and by far more efficient use of energy than ever before.

At a time when genes can be engineered and spacecraft sent to Mars, shifting to a new energy system is hardly an impossible task. But it will require mobilizing substantial resources, which in turn will depend on major policy changes that overcome the decades of subsidies and structural impediments that prop up the current energy system. Nor will it be inexpensive, likely costing several trillion dollars by the time the transition is complete.[4]* While most of that investment will come from funds that otherwise would have gone to additional development of fossil fuels, upfront costs will be greater and the price of energy may be somewhat higher in the short term. But if a new commitment to renewable sources of energy is accompanied by a matching commitment to improved efficiency, energy needs will be smaller and the bills paid by individuals and businesses could well be lower than they would be if we remained addicted to fossil fuels.

To many people, such a transformation remains unimaginable. For nearly a century—since the times of Thomas Edison and Henry Ford—energy has been a relatively static business, characterized by slow, incremental change, limited competition, and some of the lowest rates of research and development of any major industry. But that is now changing. Concern about climate change and rising energy prices have sparked a nascent transformation of the energy business, with engineers, entrepreneurs, and investors who would have been focused on the Internet and biotechnology a decade ago now focused on energy. Their skills, energy, and commitment to solving one of the world's greatest problems is likely to prove as revolutionary as their great-grandparents' work to build a carbon-based economy a century ago.

Rebuilding the global energy system will be expensive, but it can also be transformative. And its sheer scale would create thousands of new businesses and millions of jobs for decades to come. At a time of serious economic troubles, volatile oil prices, and instability in many fossil fuel producing regions, building an efficient, low-carbon energy system can become an engine of economic recovery, job creation, and international cooperation. Climate change, energy security, and economic development should be viewed, in the words of Common Cause founder John Gardner, as "breathtaking opportunities disguised as insoluble problems."[5]

Darling National Wind Farm in Cape Town, South Africa.

* All dollar amounts are expressed in U.S. dollars unless indicated otherwise.

Avoiding Catastrophe

Over the past half-million years, the world's climate has seen four ice ages and four warm periods separating them. Over that vast sweep of time, extensive glaciers have engulfed large swaths of North America, Europe, and Asia and then retreated; thousands of species were displaced, and the shapes of coastlines were 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]

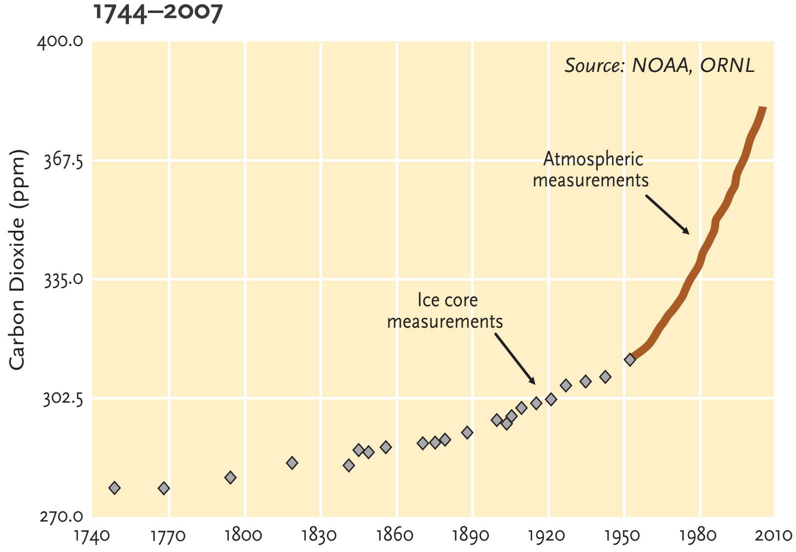
In 2007, the atmospheric concentration of CO_2 passed 384 parts per million (see Figure 1), and it is already at the equivalent of 430 parts per million if the effect of other greenhouse gases is included.[2] Humanity is at risk of creating a climate unlike any it has seen before, unfolding at an unnatural, 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.

Only recently have scientists understood that changes in the concentration of CO_2, methane, and other less common greenhouse 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 the Earth's orbit and orientation to the sun—providing, for example, just enough added energy to warm the planet over thousands of years, increasing the concentration of CO_2 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] According to scientist James Hansen, "More warming is already in the pipeline, delayed only by the great inertia of the world's oceans. And the climate is nearing dangerous tipping points. Elements of a perfect storm, a global cataclysm, are now assembled."[4]

Scientists project that in the decades immediately ahead, the capacity of the Earth and its oceans to absorb carbon emissions will decline, while vast changes in the world's ecosystems

Figure 1. Atmospheric Concentration of Carbon Dioxide, 1744–2007



Sea ice clogs the gap between iceberg B-15A, right, and B-15J, left, on October 21, 2003. B15 was the world's largest recorded iceberg until it broke up after calving from Antarctica's Ross Ice Shelf in March 2000.

Brien Barnett, National Science Foundation

may further accelerate warming. Recent studies show that frozen soils in the Arctic contain vast quantities of carbon—60 percent more than was previously estimated and equivalent to one-sixth of the carbon now in the atmosphere.[5] Melting tundra could release millions of tons of carbon dioxide as well as methane—a greenhouse gas 25 times more powerful than CO_2—causing additional warming.[6]*

Another tipping point may lie in the Arctic Ocean, where the year-round ice cap has been shrinking dramatically and unexpectedly in recent years, and may disappear entirely in the summer months within the next decade. This will cause an enormous change in the Earth's energy balance, with more of the sun's light and heat being absorbed, raising temperatures further in the northern hemisphere.[7] This 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.[8]

Exactly when the world will reach such a tipping point—or whether it already has—is not known. But it is 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.[9] And 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 21st century.[10] The uneven and disruptive nature of these changes could set off additional crises as conflict both within and between societies undermines their stability.

In 2007, the combustion of fossil fuels released nearly 30 billion tons of carbon dioxide to the atmosphere—more than a million tons every hour—with coal and oil contributing roughly 40 percent each and natural gas accounting for the rest.[11] The manufacture of cement released nearly another 350 million tons, while deforestation and agriculture combined contributed roughly 1.6 billion tons.[12] Annual fossil-fuel carbon emissions have increased fivefold since 1950 and the rate of

* Units of measure throughout this report are metric unless common usage dictates otherwise.

increase has actually accelerated since 2002.[13] Today, fossil fuels provide four-fifths of the energy that powers the global economy.[14]

Burning fossil fuels on this scale is a vast and risky experiment with the Earth's biosphere. The United Nations Framework Convention on Climate Change, adopted in 1992, commits nations around the globe to preventing dangerous climate change. Precisely identifying that point is difficult, but the 2007 report of the Intergovernmental Panel on Climate Change (IPCC) as well as more recent assessments by James Hansen and W.L. Hare of the Potsdam Institute suggest that the increase in the global temperature must not exceed 1.5 to 2 degrees Celsius above pre-industrial levels.[15] (The increase so far is just under 0.8 degrees Celsius, with some additional increase locked in as the greenhouse gases already in the atmosphere have their full impact.[16]) This requires preventing the atmospheric concentration of CO_2 from exceeding 450 parts per million and a long-run goal of returning the concentration to 350 ppm—below the current level.[17]

The bottom line is clear: to keep the world's climate within the range it has occupied for at least a million years, recent emission trends will need to be quickly reversed. The current emissions trajectory would take the atmospheric concentration to 650 ppm or beyond by the end of the century. The scenarios published in the 2007 IPCC report indicate that in order to stabilize the climate, global greenhouse gas emissions must peak before 2020 and be reduced by 40–70 percent by 2050, eventually falling to zero.[18] The goal of reducing global emissions by half by 2050 has been adopted by the European Union and was endorsed by industrial country leaders at the G8 Economic Summit in Japan, giving it political as well as economic significance.[19] How rapidly carbon dioxide emissions need to fall during this period depends on how quickly emissions of the other key gases are reduced; recent estimates range from a 50-percent reduction to eliminating CO_2 emissions entirely by mid-century.[20]

Table 1. Global Energy Use and Carbon Dioxide Emissions, 2007 and Two Scenarios for 2050

Indicator	2007	2050 Business as Usual	2050 Stabilization Scenario
CO_2 concentration (parts per million)	384	~550	<450
Population (billion)	6.7	9.2	9.2
Energy use (billion tons oil equivalent)	12.0	23	16
Energy-related CO_2 emissions (billion tons)	29.9	62	15

Source: See Endnote 21 for this section.

The magnitude of the challenge is obvious when the emissions path needed to avoid catastrophic climate change is compared with the current trajectory.[21] (See Table 1.) The U.S. Department of Energy forecasts that both world energy use and carbon emissions will grow nearly 50 percent by 2030—an average rate of 1.7 percent per year.[22] This would take emissions to more than 40 billion tons in 2030 and, assuming continued growth at that rate, to 62 billion tons in 2050—nearly four times the annual emissions that would be needed to keep the peak CO_2 concentration below 450 parts per million.[23]

The challenge is made particularly difficult by the fact that the energy needs of developing countries such as India and China have accelerated in recent years as they have 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 emissions, and they are responsible for more than 60 percent of the total CO_2 that fossil fuel combustion has added to the atmosphere since the Industrial Revolution began in the early 19th century.[24] But this picture is changing rapidly, particularly in China, where since 2002, emissions growth has accelerated to a remarkable 10 percent annual rate.[25]

As recently as 2004, China was not expected to pass the United States in CO_2 emissions until 2030; however, data now indicate that this threshold was crossed in 2007 if cement-related emissions are included.[26] China barely trailed the United States in emissions from fossil fuels in 2007, and the two together account for fully 40 percent of global emissions.[27] (See Table 2.) Emissions are also growing quickly in other parts of the developing world, particularly elsewhere in Asia and in the Middle East, where rapid population growth, rising oil wealth, and low, subsidized energy prices have led to skyrocketing energy demand.[28]

Providing energy services for the much larger global economy of 2050 while reducing CO_2 emissions to 15 billion tons will require an energy system that is very different from today's.[29] For the world as a whole to reduce its emissions by at least half by 2050, today's industrial countries will need to cut theirs by more than 80 percent.[30] According to most official assessments, including that of the IPCC, getting there depends on some combination of a three-pronged strategy: reducing energy consumption through new technologies and lifestyles, shifting to carbon-free energy technologies, and capturing and storing the CO_2 released when fossil fuels are combusted. A variety of combinations of these three options can in theory do the job.[31] It is now time to develop a coherent strategy—and to shape policy and investment accordingly.

Emissions from oil will be limited by supply constraints. Production of conventional crude oil is expected to peak and begin declining within the next decade or two.[32] By 2050, output could be a third or more below the current level.[33] This will require that transportation fleets shift rapidly to other energy options, the most promising of which are electricity (produced from renewable energy), advanced biofuels, and compressed natural gas. 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 likely to grow. But its potential to be used efficiently for cogeneration of heat and power will limit its contribution to emissions.

Unfortunately, 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" fossil fuels such as tar sands and oil shale, which at recent oil prices have become economically viable. Unless the development of these dirty fossil fuels is deliberately curtailed in favor of renewable alternatives, it will be imposible to reach the declining emission trajectories that scientists say are needed.

Table 2. Energy-Related Carbon Dioxide Emissions, Selected Countries, 1990 and 2007

Country or Region	CO_2 Emissions 1990	CO_2 Emissions 2007	CO_2 Emissions, Per Capita 1990	CO_2 Emissions, Per Capita 2007	CO_2 Emissions, Per $ GDP 1990	CO_2 Emissions, Per $ GDP 2007
	(billion tons)		(tons)		(kilograms per $1,000 GDP (PPP))	
United States	4.8	6.1	18.7	19.2	823	437
China	2.3	5.9	2.0	4.4	2,523	844
European Union-27	3.6	3.8	7.6	7.6	514	258
India	0.6	1.5	0.8	1.2	898	503
Japan	1.0	1.2	8.3	9.7	446	290
Africa	0.6	1.2	1.0	1.2	864	595
Others	9.0	10.2	–	–	–	–
World	**22.0**	**29.9**	**4.2**	**4.3**	**863**	**460**

** Does not include emissions resulting from gas flaring, cement making, or land use change.*

Source: See Endnote 27 for this section.

Coal-fired power plants currently supply more than 40 percent of the world's electricity, and their large contribution to CO_2 emissions has led policymakers and industrialists to focus on carbon capture and storage (CCS) so that those plants can be compatible with a low-carbon economy.[34] Such plants would be 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 carbon dioxide then separated from the other gases, or it can be burned directly in a super-critical pulverized plant that also allows the capture of as much as 90 percent of the CO_2. Four CCS projects are in operation in Algeria, Canada, Germany, and Norway.[35] The facilities in Algeria and Norway simply capture carbon dioxide that is extracted together with natural gas. The small project in Weyburn, Canada, on the other hand, gasifies coal, extracting CO_2 and injecting it underground. While these technologies are advancing, together with advances in modeling and monitoring of geological sites, full-scale commercial CCS systems are still a long way off. And a vast physical infrastructure will be needed to capture, move, and store the emissions from even a fraction of today's fossil fuel combustion.

The United States, European Union, Japan, and China have all launched government-funded CCS programs in the last few years, but the pace of these efforts is surprisingly lethargic given the urgency of the climate problem and the fact that much of the power industry is counting on CCS to allow them to continue burning massive amounts of coal. A 2007 study by the Massachusetts Institute of Technology concluded that the U.S. Department of Energy's main program to demonstrate the feasibility of large-scale CCS is not on track to achieve rapid commercialization of key technologies.[37] Locating, testing, and licensing large-scale reservoirs where CO_2 can be stored is a particularly urgent task. Also problematic is the fact that CCS will be water- and energy-intensive, which will limit its attractiveness in many regions.

It will take at least a decade to develop and test large-scale CCS technology, which means that it will be the 2020s or 2030s at the earliest before significant numbers of low-carbon coal plants can begin to be built. How large a role CCS ultimately plays in a low-carbon economy will depend on how rapidly the technology develops, how much it costs, and whether governments and industries are able to successfully mobilize the massive infrastructure investment that will be required. In the meantime, James Hansen and Al Gore have both called for a moratorium on building new coal-fired power plants until CCS can be included.

A Convenient Truth

In 2001, as U.S. Vice President Dick Cheney was assembling the Bush Administration's energy policy proposals, he described saving energy as a "moral virtue" not worthy of serious consideration alongside more robust energy options such as offshore oil drilling and nuclear power.[1] Cheney's quick dismissal of the demand-side approach to meeting energy needs reflects a widespread neglect of efficiency by policymakers and investors since energy prices fell dramatically in the 1980s.

But as energy prices recently reached all-time highs, the consensus of expert opinion has shifted decisively. Reducing the amount of energy wasted and increasing the amount of economic output that can be produced with a given amount of energy is now considered the most economical way of reducing dependence on fossil fuels. The monetary savings associated with boosting energy productivity are often sufficient to justify the investment even if the world were not facing a climate crisis. Given the urgency of the climate problem, that is indeed a convenient truth.

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 advanced steadily, a trend that accelerated dramatically when energy prices soared in the 1970s. In the United States, the economy has grown 165 percent since 1973, while energy use rose just 34 percent, allowing the nation's energy productivity to double during the period.[2] Germany and Japan, starting with higher productivity levels, have achieved comparable increases.[3] But even today, well over half of the energy harnessed worldwide is converted to waste heat rather than being used to meet energy needs.[4]

This suggests enormous potential to improve energy productivity in the decades ahead, and broader trends will boost that effort. Many technologies are becoming more and more efficient—from steelmaking to automobiles—and in recent decades, the economies of most industrial countries have centered the bulk of their economic growth on light industry and the service sector, with energy-intensive industries such as smelting metals and manufacturing petrochemicals falling as a share of the total economy. Even larger opportunities are found in developing nations, where energy productivity tends to be lower and much of the basic infrastructure is still being built. However, this potential will be offset in some countries in the short term by the fact that they are entering an infrastructure- and energy-intensive stage of economic development.

Smart Car, manufactured by Daimler AG.

In China, for example, energy growth suddenly accelerated in 2002—with the bulk of the growth coming from energy-intensive industries needed to build the factories, roads, buildings, and other pillars of an industrial economy.[5] This abruptly ended two decades of impressive energy productivity gains in which China's energy use and emissions had grown much slower than the economy as a whole. As a result, China's CO_2 emissions nearly doubled between 2002 and 2007, passing the United States (if cement emissions are included) two decades before the International Energy Agency had projected this would occur.[6]

The dramatic acceleration of energy growth in China has alarmed the country's leaders, who are concerned about the economic, security, and environmental implications of soaring energy demand. The country's 11th Five-Year Plan, adopted in 2006, calls for a 4 percent annual increase in the country's energy productivity; new efficiency standards have been adopted and energy subsidies reduced.[7] With the right policies in place, rapid economic growth can speed the introduction of a new generation of efficient electric motors, air conditioners, automobiles, power plants, computers, aircraft, and buildings.

Light bulbs are a case in point. Compact fluorescent lamps (CFLs), first developed in the early 1980s, have been catching on as an alternative to the incandescent bulb introduced to the mass market by Thomas Edison in the late 19th century. CFLs represent a remarkable advance in energy efficiency—producing nearly four times as much light for each watt of power consumed.[8] Until recently, CFLs were expensive and did not meet the needs of many lighting applications, but two decades of miniaturization of components, improvements in the quality of light produced, and reductions in manufacturing costs have largely closed the gap with incandescents, and sales are soaring.[9]

Compact fluorescent lamp (CFL).

© AZAdam (Flickr Creative Commons)

Although CFL technology was developed in the United States and has been dominated by European and U.S. firms, most of the bulbs are now manufactured in China where they have become nearly ubiquitous. Chinese production of CFLs tripled from 750 million units in 2001 to 2.4 billion in 2006.[10] In the United States, sales rose from 21 million units in 2000 to 397 million in 2007.[11] The CFL share of the lighting market varies widely, from 80 percent in Japan, to 50 percent in Germany, to 20 percent in the United States.[12] Around the world, the use of CFLs will continue to rise as governments implement lighting efficiency standards that promote their use and in some cases virtually prohibit the sale of incandescent bulbs.

In the meantime, several other new lighting technologies are under development, including a semi-conductor device known as a light-emitting diode (LED) that is as much as 90 percent more efficient than an incandescent. Currently deployed for a range of specialized forms of lighting, including stoplights and electronic devices, LEDs are still too expensive for widespread use. However, costs are falling, and engineers are developing a range of new LEDs that will have much wider application.

The greatest potential for energy savings lies in the most basic element of the energy economy—buildings—which consume about 40 percent of global energy and emit a comparable share of CO_2 emissions.[13] About half of this energy use is for space and water heating, and the rest is associated with the production of electricity for lighting, space cooling, and powering appliances and office equipment.[14] With technologies available today, such as better insulation, more-efficient lighting and appliances, improved doors and windows, and heat recovery ventilators, the fossil energy needs of buildings can be reduced by 70 percent or more, with the additional investment paid for via lower energy bills.[15] Further gains can be achieved by designing and orienting buildings so that they can benefit from natural heating, cooling, and daylighting.

The advent of cheap energy enabled modern buildings to work in spite of nature rather than with it. But it is possible to reduce demand in existing buildings by insulating them appropriately, controlling unwanted air infiltration, and improving performance for space and water heating, lighting, ventilation, and air conditioning. There is a substantial gap between economic potential and commercial reality in the buildings sector, and since the 1970s, national, state, and local governments have imposed energy building codes to close that gap. But in recent years, those codes have themselves fallen short of driving the kind of advances that are possible.

Studies show that for new construction, the integration of design with multiple energy-efficiency measures can reduce energy use to half or less that of a comparable conventional building, as new offices from New York City to London to Berlin have demonstrated.[16] Potential savings in India, China, and elsewhere could be even greater. India, for example, has no mandatory efficiency codes for commercial buildings, and most building contractors have not been trained to install insulation.[17] But greener buildings are on the way in India as well. One of the largest green commercial developments in the world is under construction outside of Delhi; it is expected to exceed international energy performance standards.[18]

"Green buildings" that minimize the use of energy as well as other environmental impacts have attracted growing attention around the globe in recent years. In the United States, green certification is now highly sought by builders of new commercial buildings, setting off a wave of advances by architects, engineers, and builders. The U.S. Green Building Council, which developed a popular set of voluntary standards, now includes more than 15,000 member organizations.[19] Efforts are under way to strengthen the energy efficiency requirements within these standards. Canada, India, and other nations are meanwhile developing their own standards.

European countries are moving particularly rapidly and with greater government support, sparking a green building boom. The Passivhaus Institute in Germany, which began developing criteria for highly efficient houses in 1990, has built more than 6,000 living and commercial units that consume about one-tenth the energy of standard German homes.[20] In China, the Ministry of Housing and Urban-Rural Development has established a goal of making new city buildings 65 percent more efficient than existing buildings are, and the State Council has established a tax and feebate system for energy hookups that encourages better efficiency.[21]

Green buildings in Berlin, Germany.

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As peak energy loads for lighting, heating, and cooling decline, so does the required size of fans, boilers, and other equipment, providing additional savings. The modest remaining energy needs can be met with renewable energy. In 2008, the European Parliament called for "all new buildings needing to be heated and/or cooled be constructed to passive house or equivalent non-residential standards from 2011 onwards, and a requirement to use passive heating and cooling solutions from

Energy-efficient windows at Lawrence Berkeley National Laboratory, California.

2008."[22] This goal is awaiting implementing laws in member states.

As energy efficiency improves, each unit of energy is cheaper, so consumers may choose to use more energy or to spend this savings on additional goods that require energy. The resulting rebound effect is measured by the difference between projected and actual energy savings that result from an increase in efficiency.[23] This can be countered with progressively stronger efficiency standards or with technology advances that offer the potential to break the mold. Case studies in the United States have concluded that energy savings in energy-efficient commercial buildings—from schools to office towers—have frequently been greater than projected.[24]

Even greater savings can come from "zero-energy" or "zero-carbon" buildings that produce all of their energy on site with renewable energy, emitting no CO_2. (Most buildings will need to have an energy supply from outside to meet peak demands at particular times of the day and year, but are considered zero net energy if they produce as much energy as they consume over the course of a year.) The United Kingdom has mandated that all new homes built after 2016 and all commercial buildings built after 2019 be zero-carbon.[25]

In developing countries, energy use in buildings is growing particularly rapidly as people move into improved homes and acquire amenities such as heating, cooling, and refrigeration. In China, buildings already account for 23 percent of energy use, and with 300 million people—equivalent to the entire U.S. population—expected to move to cities in the next decade, the largest construction boom in history will unfold in the coming years.[26] How these buildings are constructed will profoundly shape CO_2 emissions in China for decades to come.

Another large opportunity for advancing energy productivity can be found in the extensive use of combined heat and power (CHP), also known as cogeneration. In most power plants today, two-thirds of the energy contained in the plant's fuel is converted into waste heat or lost in the transmission process.[27] In the United States, the waste heat from power plants is equivalent to all of the energy consumed in Japan.[28] By integrating power generation with factories and buildings, high-temperature waste heat can be used to produce electricity, or, in another configuration, the waste heat from power generation can be used for industrial and building heat, increasing total energy efficiency from 33 percent to as high as 80–90 percent.[29]

Some of the world's first power plants employed CHP, and while it has since fallen out of favor in most nations, some have pursued it aggressively since the early 1980s. Finland and Denmark obtain 40 and 50 percent respectively of their electricity from CHP, far above the levels found in countries such as the United States (8 percent) and Germany and China (12 percent each).[30]

It is estimated that CHP in Europe reduced annual CO_2 emissions by 57 million tons between 1990 and 2005, accounting for 15 percent of European emissions reductions.[31] If most industrial countries were to aggressively pursue CHP, it would eliminate the need for new coal plants and allow many older plants to be gradually shut down. At today's energy prices, much of the investment can be justified in energy savings alone. The United States could get 150 gigawatts, or 15 percent of its power, from the unused waste heat from heavy industry as well as from manure, food industry waste, landfill gas, wastewater, steam, gas pipeline pressure differentials, fuel pipeline leakages, and flaring. This is as much power as the entire U.S. nuclear industry produces.[32]

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.[33] If these gains are extended to 2050, the growth in world energy use could be held to roughly 50 percent above current levels, rather than the doubling that is projected under most business-as-usual scenarios. This large difference is equivalent to the combined current energy consumption of the European Union, Japan, and North America.[34] By fully exploiting all of the opportunities described above, the world could likely do even better than that.

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. And additional gains can be made by altering the design of cities—for example, by increasing the role of public transport, walking, and cycling while reducing dependence on automobiles.

No-Carbon Energy

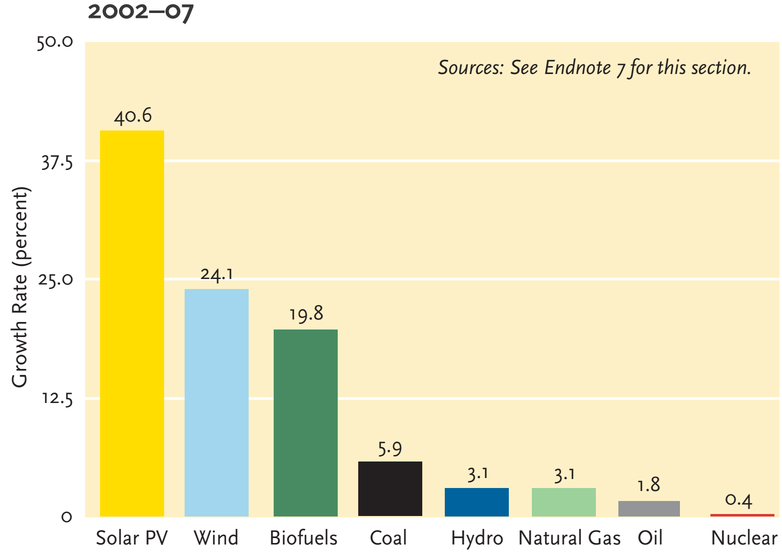
No matter how efficiently energy is used, substantial reductions in carbon dioxide emissions will require the simultaneous and rapid introduction of carbon-free sources of energy. One option that is gaining increased attention these days is nuclear power, which already plays a major role in some countries but faces considerable obstacles to its expansion in the decades ahead.[1] (See Sidebar 1.) The more robust carbon-free energy option is renewable energy, including solar, wind, biomass, and geothermal energy. In the longer run, ocean energy—from tides, waves, currents, and thermal convection—is another strong possibility.

Assessments of the potential of renewable energy to replace fossil fuels over the next few decades vary widely, with skepticism running high among many energy executives. 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."[2] That view is outdated and inaccurate: rapidly advancing technologies are making a growing number of renewable energy options economically competitive in today's markets, and the pace of progress continues to accelerate. This, combined with the vast scale of the renewable energy resource base, holds the potential for what can only be described as an energy revolution.

Modern renewable energy technologies have been advancing steadily since the late 1970s, with modest government support and industries that were concentrated in a handful of countries. But in the past five years, renewable energy has entered a super-charged stage of growth. Soaring energy prices combined with new government policies and concern about climate change have spurred a growing army of small and mid-sized companies and a wide range of investors who are pouring tens of billions of dollars into an array of promising renewables technologies.[3]

Coal-fired power plants generate 40 percent of the world's electricity and account for a third of global CO_2 emissions.[4] Replacing existing plants—and those being planned—with renewable power would make a big dent in the world's climate problem.[5] Renewable energy sources already supply nearly one-fifth of the world's electricity. While most of this comes from large hydropower, which is grow-

Figure 2. Average Annual Growth Rates by Energy Source, 2002–07



ing very slowly, wind capacity is expanding at 24 percent per year and solar at over 40 percent, rivaling the computer and mobile phone industries.[7] (See Figure 2.)

Since 2000, wind power has gone from a tiny niche electricity supplier to become a significant force in the global power business. Deploying giant multi-megawatt wind turbines made by companies such as General Electric, Siemens, Vestas, and Gamesa, the wind industry is now booming.[8] Total generating capacity is estimated to have passed 100 gigawatts in early 2008, double the amount in 2004.[9] An industry that was dominated by California and Denmark in the 1980s, and by Germany and Spain in the 1990s, is now flourishing in the world's largest power markets, including China, India, the United States, and the European Union.

In 2007, wind power represented 40 percent of new generating capacity installations in Europe and 35 percent in the United States.[10]

Sidebar 1. What About Nuclear Power?

Nuclear power is a largely carbon-free energy source that could in theory help phase out fossil fuels. At the beginning of 2008, there were 372 gigawatts (GW) of nuclear generating capacity, providing roughly 15 percent of the world's electricity. But nuclear power has been plagued by a range of problems, from safety concerns, to radioactive waste disposal, to the diversion of technologies and fuel for the manufacture of nuclear weapons.

Nuclear construction starts peaked in the 1970s with an average of 25 GW annually, falling to an average of less than 5 GW in the last five years. Over the past decade, global nuclear capacity has expanded at a rate of less than 1 percent a year. In 2006 and 2007, the world added 3 GW of nuclear capacity, compared with 35 GW of wind capacity over the same two-year period. By the end of 2007, some 34 reactors were being built worldwide, but 12 of these units have been "under construction" for 20 years or more. In Western Europe, only Finland and France are building nuclear plants. In the United States, one problem-plagued plant is being built; it has now been under construction for more than a quarter century.

The combination of concern about climate change, high natural gas prices, and a large dose of new government subsidies has recently revived interest in nuclear power. Several companies are developing 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 of the newer nuclear plants are being built in Europe, and several are under construction in China. In the United States, 23 applications have been filed for construction and operating licenses since 2004; however, only four of these include actual plant designs, and all are dependent on federal loan guarantees. The $18.5 billion that Congress has so far made available for loan guarantees is only enough to support two plants.

The largest hurdle facing the nuclear industry is the one that crushed it in the 1980s: economics. In the United States, it is now estimated that nuclear plants cost twice as much as a coal plant to build and five times what a natural gas plant costs. A study by a Keystone Center panel composed of academics, energy analysts, and industry representatives estimated the full cost of new nuclear power at 8–11 cents per kilowatt-hour, which is more than coal, natural gas, biomass, and wind-powered generators. For nuclear power to be economical, the industry will need to build large numbers of standardized plants, but new orders are coming sporadically, and utilities are pursuing an array of new designs, which is likely to keep costs stubbornly high. And because of the large capital requirements and long lead times, nuclear plants face a risk premium that other generators do not—a risk that will be exacerbated by tight financial conditions in the years ahead. In Finland, ground was broken in 2005 on the first new European reactor in a decade; three years later, it is two years behind schedule and $2 billion over budget.

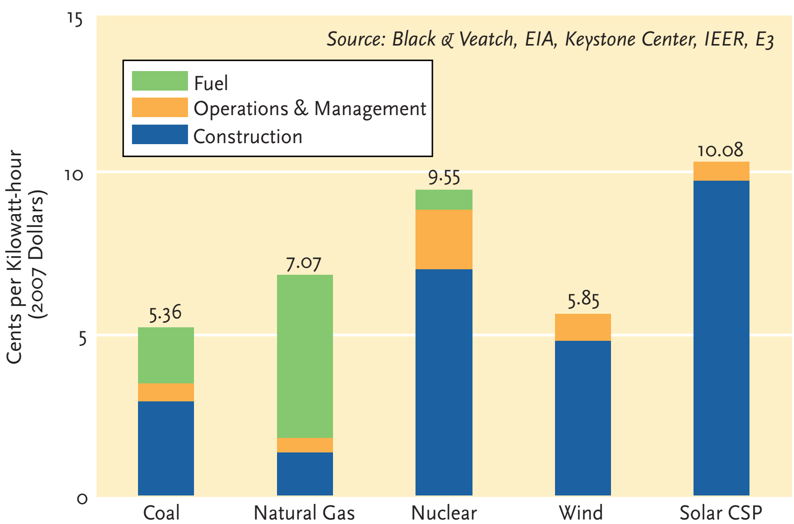
Energy planners will also have to reckon with the scale and pace of construction that would be needed to make a serious dent in the world's climate problem. MIT researchers estimate that 1,000–1,500 new reactors would be needed by 2050 for nuclear to play a meaningful role in reducing global emissions—a construction pace 20 times that of the past decade and five times the peak level in the 1980s. Speed, however, is not one of nuclear power's virtues. Planning, licensing, and constructing a single nuclear plant typically takes 10–15 years, and completion deadlines are frequently missed. Due to the dearth of orders in recent decades, the world currently has limited capacity to manufacture many critical nuclear components. Rebuilding that capacity will take a decade or more. In the United States, it is estimated that it will be 2012 at the earliest before a construction license is approved, and that the first plant will not begin operating until 2020 or beyond. By the time a significant number of plants come on line in the late 2020s or early 2030s, they will largely be replacing today's plants, which will by then be ready for retirement.

Source: See Endnote 1 for this section.

Further growth will come from offshore wind farms, which are expected to expand rapidly in the coming decade. And this torrid growth appears likely to continue as more and more governments follow the leaders and implement wind-friendly electricity laws. As the industry grows, it invests in ever more efficient wind technologies, driving costs down. In the United States, wind power now costs just under six cents per kilowatt-hour on average—less than natural gas and roughly even with coal.[11] (See Figure 3.)

The solar industry is starting from a smaller base but is growing even more rapidly than wind power. Annual production of solar cells (semiconductors that turn sunlight into electricity) rose 41 percent in 2006 and 51 percent in 2007.[12] Cumulative installations of solar cells have grown more than fivefold over the past five years, spurred by strong incentive programs in Germany, Japan, and Spain.[13] This growth has fueled a powerful wave of innovation in a technology that was invented only in the 1950s. From Silicon Valley, California, to Munich, Germany, and Shenzen, China, scores of companies are pursuing an extraordinary array of approaches to improving solar cell design and lowering costs.

Figure 3. Cost of Electricity Generation by Source



Solar power still requires significant subsidies, but the Prometheus Institute projected in 2007 that as the industry scales up, installed system prices for large projects will fall 50 percent by 2010, to $4 per watt (without incentives) in the best locations.[14] Solar cells are deployed mainly on rooftops where they provide power for homes, businesses, and public institutions, with excess power fed into the local grid. In regions such as California and Italy that combine high electricity prices and ample sunshine, solar power is expected to fall to less than 25 cents per kilowatt-hour, becoming cost-competitive with the retail price of electricity within the next three years.[15]

Even as solar cells enter the mainstream, attention has focused on using solar thermal energy through large concentrating solar power (CSP) plants. Built mainly in deserts, these plants provide wholesale electricity that is transmitted to cities and industries via high-voltage power grids, in the same way most power is today. A wide range of CSP plant designs are being pursued; most rely on mirrored parabolic troughs or dishes to concentrate the sun's heat, which is then transferred to water or another fluid, with the resulting steam used to spin a turbine and produce electricity. These plants produce power in much the way that conventional coal or nuclear plants do, but they operate at lower temperatures and pressures, which permits cost reduction.

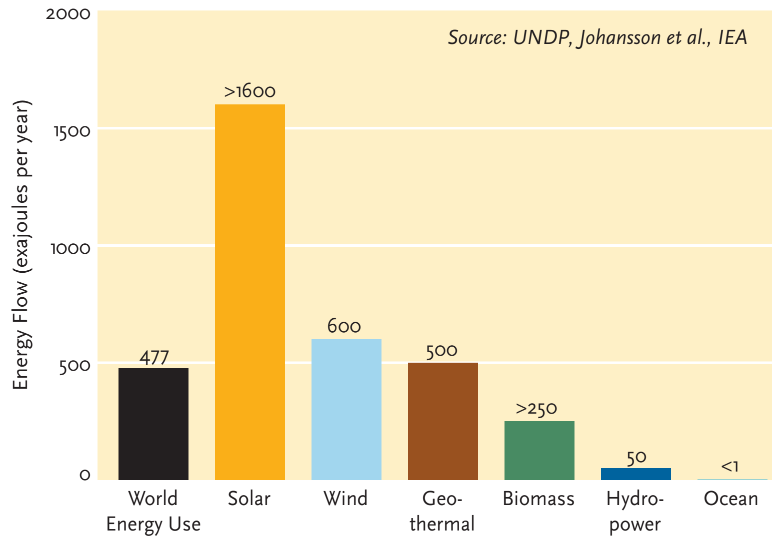
The world's first modern CSP plant was built in California's Mojave Desert in the late 1980s, but it was not until the past few years that the technology experienced a dramatic renaissance.[16] More than a dozen projects with a combined capacity of over 4 GW are under contract in the southwestern United States alone, and another 3 GW in other countries including Spain, China, Egypt, and Israel.[17] Costs are still relatively high at 10 cents or more per kilowatt-hour, but because the industry is in the early part of a very steep learning curve, costs are expected to fall rapidly in the next 5–10 years. New plant designs continue to emerge, including a Pacific Gas and Electric project that will use 800 megawatts of solar cells rather than thermal systems.[18]

Geothermal energy—heat from deep in the Earth's crust—is another large potential source of electricity. Geothermal power currently provides just 10 GW of power worldwide, with much of it in the United States, the Philippines, and Mexico.[19] But a new generation of enhanced geothermal technologies is now being developed that makes it possible to tap a much larger geothermal resource base. Advanced geological sensing and drilling techniques developed by the oil industry are being combined with new heat exchanger materials and systems. By piping water into porous geological structures 1 to 10 kilometers beneath the Earth's surface and then bringing the heated water back to a plant at the surface, electricity can be generated. The Massachusetts Institute of Technology has estimated that the United States alone has at least 100 GW of geothermal potential, mainly in the western states, and similar potential undoubtedly exists in many other countries.[20]

As renewable energy technologies have advanced, attention has turned to the adequacy of the resource base available to meet the large and growing demands of the global economy. Many are skeptical that these relatively dispersed and often variable energy sources can meet such vast energy needs. They need not be worried. The sunlight alone that strikes the Earth's land surface in two hours is equivalent to total human energy use in a year.[21] 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 flux of energy will ever be needed by humanity. With improved technologies, greater efficiency, and lower costs, renewable energy could one day replace all the carbon-based fuels that are so vital to today's economy.[22] (See Figure 4.)

Several studies have assessed the scale of the major renewable resources and what their practical contribution to the energy economy might one day be.[23] (See Table 3.) In the case of wind power, the Pacific Northwest Laboratory found that the land-based wind resources of the U.S. states of Kansas, North Dakota, and Texas could meet all of the nation's electricity needs, even with large areas excluded for environmental reasons.[24] The U.S. wind resource base is not limited to those states, however, and beyond the land-based resource, offshore wind offers enormous potential—enough in the case of northern European countries such as the Netherlands and the United Kingdom to in principle provide all of their electricity.[25] China's wind resources alone are sufficient to provide more electricity than the country currently consumes.[26]

Figure 4. Estimates of Available Energy Resources Using Today's Technology



Solar energy represents an even larger resource. A study by the National Renewable Energy Laboratory in the United States identified 159,000 square kilometers of land in seven southwest states that are suitable for CSP plants—representing nearly 7,000 GW of generating capacity, or nearly seven times the nation's existing capacity from all sources.[27] One-fifth of U.S. electricity could be produced on a 1,500 square-kilometer plot of land slightly larger than the city of Phoenix.[28] While some regions such as northern Europe do not have sufficient solar resources to meet more than a fraction of their energy needs, other areas could become major exporters of solar energy. North Africa, for example, has a vast solar resource, and plans are being laid to

Table 3. Estimates of Potential Contribution of Renewable Energy Resources

Energy Source	Potential Contribution
Concentrating solar power (CSP)	Seven states in the U.S. Southwest could provide more than 7,000 GW of solar generating capacity—nearly seven times U.S. electric capacity from all sources.
Solar water heaters	Could easily provide half the world's hot water.
Rooftop solar cells	Could provide 10 percent of grid electricity in the United States by 2030.
Wind power	Could easily provide 20 percent of world's electricity; offshore wind farms could meet all of the European Union's electricity needs.
Geothermal heat	Could provide 100 GW of generating capacity in the United States alone.
Wave and ocean thermal energy	Contribution could be on same order of magnitude as current world energy use.

Source: See Endnote 23 for this section.

build solar power plants that would transmit electricity to Europe.[29] An area covering less than 4 percent of the Sahara Desert could produce enough solar power to equal global electricity demand.[30]

On average, wind and solar power require less land to provide a given amount of power than hydropower or coal do. And sometimes, renewable energy requires no land at all. Mounting solar electric generators on just half of the United States' suitable rooftop area could provide 25 percent of the nation's electricity, according to one estimate.[31] Solar cells could also be deployed atop outdoor parking lots, the median strips along highways, and other currently unused spaces. Renewable energy also has a big advantage when it comes to a resource that is more limited than land is: most forms of renewable energy have minimal water requirements compared with fossil fuels and nuclear power, and as water scarcity grows, the significance of that advantage will increase.

In contrast with fossil fuels, almost every country has large-scale domestic sources of renewable energy—including many developing countries that have no oil resources. Africa, Australia, China, India, the Middle East, and the United States all have vast amounts of solar energy.[32] Iceland, Indonesia, and the Philippines are rich in geothermal energy.[33] And scores of countries are rich in biomass waste materials that flow from their farm and forest industries.

Designing a New Energy System

For all of their abundance, integrating renewable energy resources into an energy system that was designed around fossil fuels presents challenges. Fossil fuels have the advantage of being concentrated and easily stored, and the energy industry has spent decades building up an energy delivery system—including massive pipelines, high-voltage transmission systems, and local distribution networks—that is matched to those fuels. Renewable energy sources are more dispersed, many are available only part of the time, and the best resources are often a long distance from where energy is consumed. These characteristics have not been a significant impediment to providing as much as a fifth of the power from wind in some areas of Europe, but in order to de-carbonize the energy economy, additional innovation will be needed.

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 air conditioning and electronics proliferate and as new technologies allow electricity to be used to power motor vehicles and to heat and cool homes efficiently using ground-source heat pumps. Electricity also happens to be the output of the largest and most easily replaced contributor to carbon dioxide emissions: coal-fired power plants. It is therefore fortuitous that solar, wind, geothermal, and biomass are all able to produce electricity.

From the generator's viewpoint, the main disadvantage of most of these electricity sources is their variability—wind and solar, for example, produce on average only 25–40 percent of their rated capacity, depending on the technology and site.[1] Variability 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 the supply of electricity varies when conventional power plants are shut down unexpectedly. So variability is not a new concept, though dealing with it does take planning and a willingness to strengthen weak electricity grids and to make adjustments in grid operation as penetration levels rise.

As reliance on coal is reduced in the decades ahead, it is likely that many regions will need to move well beyond the 20-percent threshold for wind, solar, and other variable power sources. To do this, they can pursue some combination of four strategies: 1) add local generating capacity using combined heat and power (CHP) systems, including advanced technologies such as microturbines and fuel cells that can be turned on and off as needed; 2) integrate variable sources with digital smart grids that are more flexible in their ability to balance demand and supply; 3) develop the capacity to store energy economically so that it is available when needed—with options such as pumped hydro, compressed air, and advanced chemical batteries and fuel cells; and 4) selectively add a new generation of efficient, low-cost gas turbines to provide spare backup power.

Power companies in some regions have already gained experience in operating grids that obtain a sizable share of their electricity from wind energy. Denmark generates about 20 percent of its electricity with the wind, and occasionally wind energy meets more than 100 percent of peak demand on the country's west coast.[2] Four German states produced more than 30 percent of their electricity with wind power in 2007.[3] And in the U.S. state of California, renewables make up more than 30 percent of the portfolios of some large utilities.[4] Utilities in these regions have balanced supply and demand through interconnection of grid systems over large regions, using hydro reservoirs as temporary storage, increasing the use of gas turbines to meet peak demand.[5]

These tools help utilities regulate the electricity supply, but there is more they can do on the demand side as well. New technologies have made it possible to predict and even control the level of power demand, saving money for consumers while better matching supply and demand.[6] But unleashing the full potential of efficiency and renewable energy will require upgrading the early 20th century electricity grids that provide no feedback between consumer and producer and require a physical visit just to read the meter. Kurt Yeager, who directs the Galvin Electricity Initiative, an effort dedicated to promoting digital grids, compares today's electromechanical power grids to a railroad on which it takes 10 days to open or close a switch.[7] New digital grids include electronic controls that smoothly integrate electricity consumers with all types of power plants—large, small, and variable—and with electricity storage facilities.

Wind farm near San Jacinto Peak, southern California.

© Wayfinder_73 (Flickr Creative Commons)

Digital grids allow the electricity system to operate much the way the Internet does—as an electronically controlled network that responds instantly 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 available. Consumers can monitor their power use with electronic meters and choose to have their appliances turned off at times of day when prices are high.

The Pacific Gas and Electric utility in California is in the process of installing 9 million smart meters for its customers, while Europe is projected to have 80 million smart meters installed by 2013.[8] When starting from scratch, smart grids are cheaper than conventional systems, and they are already being deployed in regions of sub-Saharan Africa that are being electrified for the first time.[9] And digital grids will allow higher levels of reliance on variable generators.[10]

Some utilities are already making the transition to greater reliance on renewable energy. Danish power company DONG, which has hundreds of wind turbines connected to its system, is making conventional power plants more flexible so they can be turned down, or even off, when the wind is blowing. "In the old times," explains Chief Executive Anders Eldrup, "wind power was just something we layered on top of our regular production. In the future, wind will provide a big chunk of our baseload production."[11]

In order to qualify for capacity credits earned when power is generated during peak periods, some wind farm operators have begun exploring the use of compressed air storage in underground steel pipes or geological formations. One company plans to mount a compressor under the structure that houses the generating components, and to send the com-

Solar energy towers in Seville, Spain.

pressed air down the tower, where it will be stored underground.[12] 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.[13]

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.

Electricity grids can be made even more robust and reliable by adding more micro-power generators that are connected to the local grid and reduce dependence on distant power plants. Small-scale gas turbines, Stirling engines, and fuel cells can provide large amounts of electricity, with the waste heat available for use in the buildings in which they are located.[14] And unlike the large power plants that dominate today's power system, micro-generators will be able to respond quickly to shifts in demand.

Tapping the full potential of renewable energy will also require expanding the high-voltage transmission system in many parts of the world. This is particularly true in sun-rich North Africa, which is not far from Europe in distance but currently lacks sufficient electrical connections. In the United States, electric utilities have underinvested in transmission for decades, and the existing grid is not well matched to the onshore renewable resource base, which lies mainly in the Great Plains and Desert Southwest, distant from the nation's population and industrial centers. Plans have been laid to build a new National Electrical Superhighway using high-voltage, direct current lines costing $100 billion or more.[15] The concept is being promoted by everyone from former vice president Al Gore to energy tycoon T. Boone Pickens, but will require national leg-

Wind turbine mechanic at work in Germany.

© Vestas Wind Systems A/S

islation to cut through the thicket of federal and state jurisdictions now in place.[16]

Over time, stronger, smarter grids and a new wave of generators will gradually reduce the need for the baseload coal and nuclear plants that typically provide one-third to one-half or more of the generating capacity on today's power systems.[17] The Combined Power Plant, a project that links 36 wind, solar, biomass, and hydropower installations throughout Germany, has already demonstrated that a combination of renewable sources and more-effective control can balance out short-term fluctuations and provide reliable electricity without any traditional baseload power plants.[18] In a recent interview, S. David Freeman, former general manager of the Los Angeles Department of Water and Power, said, "I'm a utility executive that ran major utilities, and I can tell you there is no reason why the electric-power industry can't be all renewable."[19] A report by the German Aerospace Center (DLR) concluded that renewable energy sources could generate at least 40 percent of the electricity in most of the world's 20 largest economies by 2030.[20]

The U.S. Department of Energy (DOE) produced a detailed study in 2008 showing that wind power alone could supply 20 percent of U.S. electricity by 2030.[21] The DOE scenario relies on 305 gigawatts (GW) of wind farms—up from roughly 25 GW at the end of 2008—that would be spread widely across the country, including 54 GW of offshore wind generators. To make this possible, extensive new transmission lines will need to be built, and the industry's manufacturing capacity will need to expand, but the DOE analysts concluded that both of those are readily achievable with sufficient private and public support.

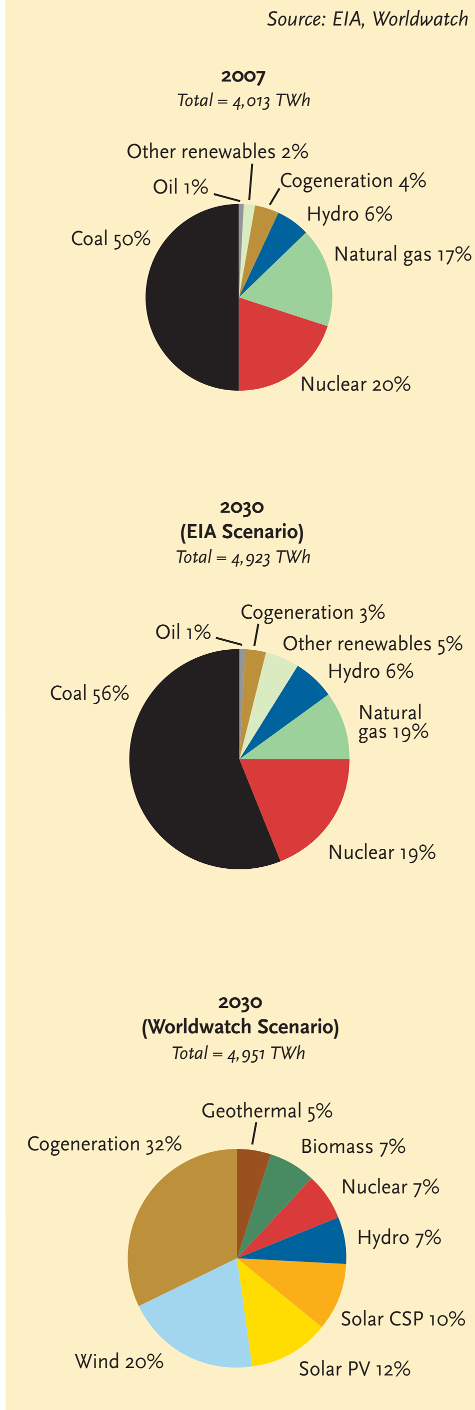
As of late 2008, the U.S. wind industry was well ahead of the DOE study's projected development pace, and will only need to double the current rate of annual installations to reach the 16 GW that would need to be added in 2022 under the DOE scenario.[22] The benefits of achieving this goal would include 250,000 new jobs and reducing CO_2 emissions by 825 million tons in 2030—virtually stopping the growth in emissions from the power sector.[23]

To illustrate what a low-carbon power system might look like, we have sketched out a scenario for the United States in 2030.[24] (See Figure 5.) We assume that improved energy efficiency will cut the rate of electricity demand growth to 0.5 percent per year, compared with the U.S. Energy Information Administration's (EIA's) forecast of a 1 percent growth rate, and actual growth in the 1990s of 2.4 percent per year. However, we also assume that by 2030, half of the energy needs of cars and light trucks will be met by the grid, increasing the demand for power by 10 percent. Based on technologies that are already available or soon will be, our scenario includes a diverse mix of solar, biomass, geothermal, wind energy, and cogeneration (small, efficient generators located in industries and buildings), with hydropower and nuclear retaining a modest role. The EIA, on the other hand, projects that coal will still provide over half the country's electricity in 2030—causing CO_2 emissions from the power sector to continue rising.[25]

In the Worldwatch scenario, emissions from the U.S. power sector would be 90 percent lower than they are today. Notably, no single renewable resource would need to provide more than 20 percent of the country's electricity. A stronger grid, extensive cogeneration, and modest storage would allow such a system to operate reliably with only a fraction of the inflexible baseload plants that dominate today's power industry. And if this scenario is feasible for the United States—which has the world's largest electricity system—then something similar is possible in most countries, with some achieving a low-carbon power system somewhat earlier and others a bit later.

Low-carbon electricity is central to a low-carbon energy economy, but by itself, it is not enough. Reducing motor vehicles' heavy dependence on oil is another key step, and the most promising near-term strategy is shifting to a new generation of electric and hybrid vehicles. Because of the efficiency of electric motors, it is estimated that half of motor vehicle energy needs in 2030 could be met with just a 10-percent increase in the power supply.[26] Electricity planners believe that plug-in vehicles would also increase the stability of the grid: they could be recharged during off-peak periods and produce power for the grid at times when demand is high and other resources are not available—replacing some of the expensive natural gas-fired "peaking

Figure 5. U.S. Electricity Generation by Source, 2007 and Two Scenarios for 2030



Note: "Other renewables" includes wind, biomass, geothermal, municipal solid waste, solar CSP, and solar.

plants" that utilities now have to rely on. A smart grid would, of course, be needed for this to work most efficiently. The timetable for this transition has accelerated dramatically in the past few years as General Motors, Nissan, and Toyota have all announced plans to quickly bring plug-in cars to the market.[27]

Natural gas will also play an important role in the transition to low-carbon energy. Natural gas produces half the carbon dioxide per unit of energy that coal does, and because it can be used far more efficiently, natural gas permits as much as a 75 percent reduction in CO_2 emissions compared with coal. Ironically, then, the road to low-carbon energy actually involves increased use of natural gas over the next few decades—providing a less carbon-intensive transition fuel in applications where affordable renewable alternatives are not yet available. Natural gas resources have not been as heavily depleted as oil has, and analysts believe that substantial production increases are possible in the coming decades.[28] In the United States, which has moved much further down the depletion curve, production is now increasing sharply as the industry uses new technology to exploit extensive gas reserves found in shale rock in several parts of the country.

Natural gas should be viewed as a premium fuel with an economic value that matches or exceeds oil and with an environmental profile that gives it a solid advantage over other fossil fuels. But much of the natural gas used today is effectively wasted—burned to produce low-temperature heat to warm buildings and heat water, or consumed in an inefficient single-cycle power plant. In order to reduce CO_2 emissions, both of those applications can be reduced substantially—as buildings are made more efficient; as solar energy, ground-source heat pumps, and biomass provide much of the energy for space and water heating; and as the least efficient natural gas-fired power plants are closed. This would free up large amounts of natural gas to fuel a new generation of high-efficiency CHP plants, particularly the distributed micro-power systems that could become ubiquitous in commercial and residential buildings.

The ability to integrate new low-carbon 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 in the transport sector, ethanol is being added to gasoline in many countries. Brazil has made a particularly significant step toward flexibility by widely adopting cars that can be run on any mixture of ethanol and gasoline; drivers can make instant purchasing decisions based on the relative prices of the two fuels.[29] And natural gas can be gradually supplemented with methane biogas collected from landfills, livestock feedlots, and sewage treatment plants, which would have otherwise been released into the atmosphere. In Germany, methane biogas is already being added to the country's natural gas pipelines.[30]

In the longer run, the natural gas that currently courses through the world's gas pipelines may be replaced by hydrogen that is produced from a broad range of renewable resources—some of it coming from wind and solar electricity produced in off-peak hours. During the transition, hydrogen can be mixed with natural gas—a blend known as hythane—in the world's gas pipelines.[31]

Jumpstarting a Revolution

If a low-carbon energy economy is possible, the next question is how we get there from here. The road ahead will be long and expensive, but it has become a bit clearer thanks to the trailblazing initiatives of pioneering governments and companies over the past few years. A successful transition will nonetheless require a powerful combination of government policy changes, steady technological progress, and the rechanneling of private investment.

It is instructive to remember that 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 crude oil became widely used for lighting in the late 19th century, the idea that it would become a dominant energy source—let alone reshape the global economy—was inconceivable.

In 1907, only 8 percent of U.S. homes had electricity, Henry Ford had produced about 3,000 vehicles in his four-year-old factory, and the mass-produced Model T wasn't yet introduced.[1] Similarly, when Thomas Edison introduced his improved lightbulb, skeptics dismissed it: "Everyone acquainted with the subject will recognize it as a conspicuous failure," said the president of the Stevens Institute.[2] Few would have imagined that by the mid-20th century, virtually every American home—and billions of others around the world—would have electricity and lighting, and that the automobile would redefine lifestyles and the economy.

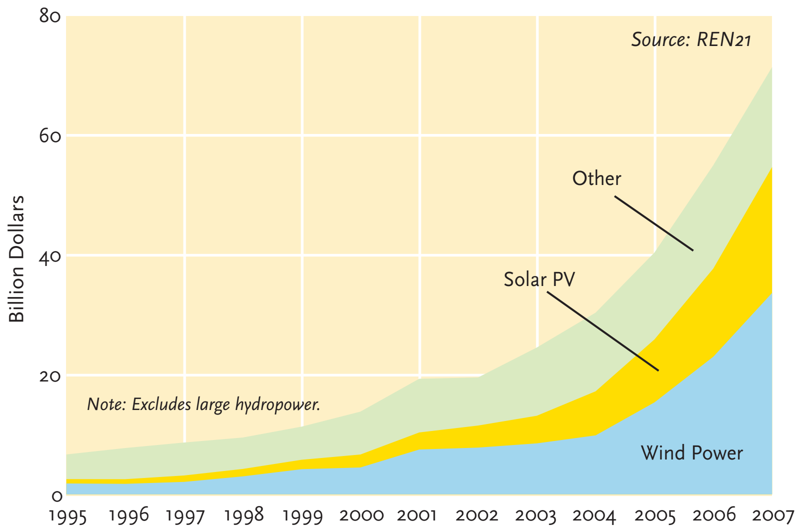
Most economic transitions begin as almost imperceptible ripples that build into transformative waves. Dominant technologies and businesses are protected by a network of institutional and political support that effectively resists change. As a result, developers of new technologies and businesses must start by finding a niche market to exploit, meeting specialized needs at a higher cost. 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 speeds up as the economic advantage flips.

According to conventional wisdom, the energy sector is far from such a transformation. New renewable energy sources, including solar, wind, geothermal, and biomass, represent less than 4 percent of the total energy supply, and in 2008 total U.S. government support of renewable energy research and development (R&D) came to little more than $650 million—about the amount the government spent in Iraq in a single day.[3] 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.

Rapid growth has turned the new energy industries into lucrative businesses, with demand outrunning supply and profits soaring. An estimated $71 billion was invested in new renewable electric and heating capacity in 2007, up from just $20 billion in 2002.[4] (See

Figure 6.) Some of the world's leading corporations have made major investments in renewable energy, including Applied Materials (solar PV), BP (wind and solar PV), General Electric (wind), DuPont (biofuels), Goldman Sachs (wind and concentrating solar), Mitsubishi (wind), Royal Dutch Shell (wind, hydrogen, and solar PV), Sharp (solar PV), and Siemens (wind).[5]

Figure 6. Annual Investment in New Renewable Energy Capacity, 1995–2007



Corporate R&D on clean energy technologies reached $9.8 billion in 2007.[6] This is 15 times U.S. government spending on renewable energy R&D in 2008.[7] A single company, Vestas Wind Systems, spent $169 million on R&D in 2007, while the U.S. government spent just over $50 million on wind R&D.[8] Even these comparisons understate private R&D, which is often embedded in commercial projects, and they 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 $13.2 billion in 2007, 42 percent above the 2006 level and 13 times the 2001 level.[9] By early 2007, these investments had helped create 253 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.[10]

These tiny firms may be the real game changers, 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 has become the hottest new sector for entrepreneurs and investors. Venture capitalists typically make money by investing in technologies with small market shares but high growth potential. They like the energy sector because of its vast size—far larger than the I.T. sector—and the fact that there is a huge gap between the sluggish ways of the incumbent energy companies and the game-changing innovations being pursued by hundreds of upstart challengers.[11] 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.

The best example is solar 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 few years, price trends temporarily reversed their usual downward course.[12] But the industry is planning to increase its manufacturing capacity as much as eightfold over the next three years, and dramatic price declines are expected, spurring the industry to develop new applications and markets that would not be feasible today.[13]

Beyond the advance in technology, the economics of renewable energy will further improve as the scale of production grows—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.[14] This is good news for clean energy industries: the manufacture of wind turbines has doubled in just the past three years, while the manufacture of solar cells has doubled in the last two.[15]

The combination of falling technology costs and rising fossil fuel prices has taken renewable energy to the threshold of economic competitiveness. Wind power is already less expensive than natural gas-fired power in the United States and nearly even with coal—even without accounting for the cost of CO_2 emissions.[16] Solar power is on track to be economical both in wholesale grid and local retail markets within the next five years.[17] As these thresholds are crossed, they will fuel additional growth, expanding markets, reducing the need for government subsidies, and driving additional technology development and job creation.

Advancing technology and rising energy prices have created an extraordinarily favorable market for new energy systems. But reaching a true economic tipping point will require new public policies and strong political leadership. Energy markets virtually everywhere are regulated, heavily subsidized, 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 internalizing environmental costs by 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 increase in average oil prices from $30 in 2003 to nearly $100 in 2008 has had on petroleum consumption.[18] That increase is equivalent to a CO_2 price of $170 per ton; by comparison, the October 2008 price of an emission allowance in Europe was € €23.5 ($32) per ton.[19] This suggests that any carbon pricing system likely to be politically feasible in the next decade or so would have a relatively minor impact on energy investment decisions. To be effective, climate policy will need to address not just the price of emissions but the failures of energy markets that limit the ability of prices to send a clear signal.

The neoclassical economic model 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. 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 economic 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.[20] Without them, most markets would work inefficiently if at all.

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 one 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.

In a traditionally regulated system, where a utility produces and distributes electricity at a fixed rate of return, profits are determined in part by the amount of power sold. This naturally makes such utilities proponents of demand 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 via simple 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 governments are moving quickly in that direction. Average auto efficiency standards, for example, have recently been increased to 47 miles per gallon in Japan and 49 mpg in Europe.[21] Meanwhile, the U.S. Congress tightened its standard to 35.7 miles per gallon by 2015, up from the 27.5 mpg standard that has been in place for the past two decades.[22]

Another approach to requiring efficiency can be seen in the law passed in Australia in 2007 to phase out the use of most incandescent light bulbs, which would be replaced by compact fluorescent bulbs that are four times as efficient.[23] Since then, several other countries have also committed to phasing out incandescent bulbs.[24]

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 26 states in the United States now have binding "renewable portfolio standards" requiring that specified amounts of renewable electricity be added to their grids.[25] In Spain, a 2006 update of building codes requires all new buildings to incorporate solar water heaters.[26] As of April 2008, the state government of Baden-Wurttemberg, Germany, requires that 20 percent of new buildings' heating requirements be met with renewable energy.[27] And 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.[28]

Such mandates are essential for patching some of the holes in a market economy, but they are at best blunt instruments that cannot by themselves harness the full power of the market to effect change. While they ensure that minimum standards are met, they give no incentive for achieving the best possible efficiencies and the lowest possible emissions. One way to provide that kind of incentive is to decouple 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.[29] (See Figure 7.)

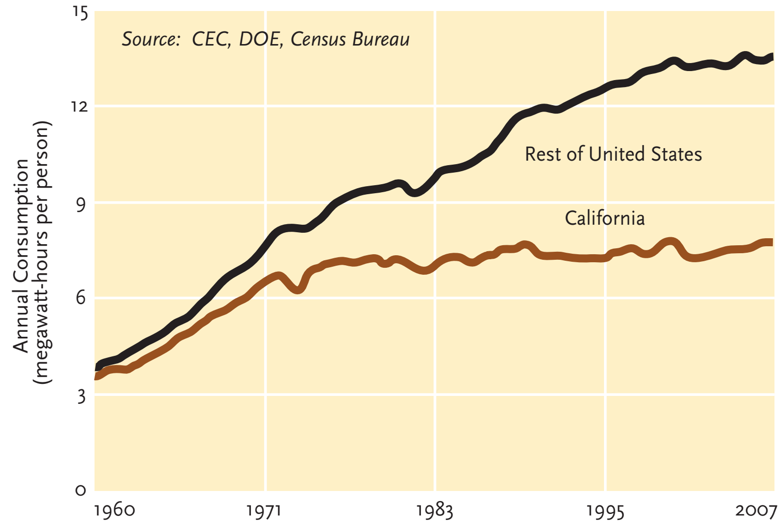
Spurred by the recent rise in fuel costs—and consequently in power prices—electric utilities have taken a fresh look at energy efficiency as a strategic investment, something that was last in favor in the 1980s. This time, the utilities and their regulators are working together, looking for ways to align the utilities' profit motives with what is needed to reduce customers' power bills and reduce power plant emissions. Duke Energy has estimated that utility efficiency programs will be 10 percent less expensive than any new source of supply, and has requested that the North Carolina Utility Commission allow it to earn a return on 90 percent of the costs avoided via its efficiency investments.[30] The California Public Utilities Commission has made similar recent adjustments, and Pacific Gas and Electric plans to invest $1 billion in improved energy efficiency.[31]

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.[32] 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.

European governments have developed another economic tool to spur investment in renewable energy. In 1979, the Danish government ordered utilities to give small wind turbines access to the electric grid and to pay a higher price for the renewable electricity they purchased. This law and successive regulations that established set purchase prices for renewable power stopped utilities from thwarting potential competitors, and over two decades they reduced Denmark's dependence on fossil fuels and made the country a leading generator of wind and biopower.[33]

Germany and Spain adopted similar market-access laws (called feed-in tariffs, or renewable energy payments) in the 1990s, and they too moved quickly into the leading ranks of renewable energy development.[34] 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, which by international standards has a mediocre endowment of renewable resources,

Figure 7. Electricity Use Per Capita in California and Rest of United States, 1960–2007



has increased the renewable share of its electricity supply from just under 5 percent in 1998 to over 14 percent today.[35] This reduced CO_2 emissions from the nation's power sector by 79 million tons in 2007—enough to cut emissions from the power sector by 18 percent and total national emissions by nearly 10 percent.[36]

Other countries with a larger renewable resource base are entering the market at a time when renewable energy technologies are more mature. They should, with the right policies, be able to move even faster. China's renewable energy markets have grown far more rapidly in the past few years than European markets did at their peak growth rates in the 1990s. In the United States, the market for wind turbines has tripled in the past three years, and the market for solar power is right behind.[37]

The economic opportunities presented by the booming market for new energy technologies have dramatically increased political support for these alternatives, which in turn is driving further growth. This dynamic can be seen clearly in the United States, where governors in states such as Iowa, Michigan, Ohio, and Pennsylvania are working to revive their economies by attracting the solar, wind, bioenergy, and electric car industries. By 2006, the U.S. renewables industry had created 386,000 jobs, compared with 82,000 jobs in the coal industry.[38] Worldwide, the renewables industries had created 2.3 million jobs by 2006.[39] (See Table 4.)

Table 4. Estimated Employment in the Renewable Energy Sector, 2006

Renewable Energy Source	World*	Selected Countries	
Biomass	1,174,000	Brazil	500,000
		United States	312,200
		China	266,000
		Germany	95,400
		Spain	10,349
Solar Thermal	624,000-plus	China	600,000
		Germany	13,300
		Spain	9,142
		United States	1,900
Wind	300,000	Germany	82,100
		United States	36,800
		Spain	35,000
		China	22,200
		Denmark	21,000
		India	10,000
Solar PV	170,000**	China	55,000
		Germany	35,000
		Spain	26,449
		United States	15,700
Hydropower	39,000-plus	Europe	20,000
		United States	19,000
Geothermal	25,000	United States	21,000
		Germany	4,200

**Countries for which information is available.*
***Under the assumption that Japan's PV industry employs roughly as many people as Germany's PV industry.*
Source: See Endnote 39 for this section.

Growing political support for green energy provides further evidence 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 has 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, the International Energy Agency, and others estimate is needed to reverse the tide of climate change?[40]

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? As negotiations continue on the international climate agreement that will follow the first commitment period of the Kyoto Protocol, which ends in 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 time is growing short.

The world has not yet reached the political tipping point that would ensure the kind of economic transformation that is required. But there are growing indications that it is near. In the summer of 2008, T. Boone Pickens, a prominent Texas oil tycoon, proposed deploying massive wind farms in the Great Plains to provide at least a fifth of U.S. electricity.[41] A couple of weeks later, former vice president Al Gore proposed shutting down all uncontrolled U.S. coal-fired power plants within a decade and replacing them mainly with renewables.[42] Then, in early October, Google proposed ending coal-fired generation in the United States by 2030, spending $4 trillion to replace it with efficiency and renewables, with the goal of making renewables cheaper than coal.[43] In a speech announcing the plan, Google CEO Eric Schmidt said, "I'm a computer scientist, and computer scientists love scale problems."[44]

A week later, the International Energy Agency, which has for decades dismissed

Jumpstarting a Revolution

World's largest solar energy plant, in California's Mojave Desert.

NREL

renewables as niche sources of energy, called for these sources to supply half of global electricity by 2050. "Governments need to do more," said Executive Director Nobuo Tanaka. "Setting a carbon price is not enough. To foster a smooth and efficient transition of renewables towards mass market integration, renewable energy policies should be designed around a set of fundamental principles, inserted into predictable, transparent, and stable policy frameworks [in order to] make the energy technology revolution happen."[45]

The biggest question for the world's climate is whether the energy revolution in industrial nations will take hold in developing countries as well. China has already passed the United States in annual CO_2 emissions, and the developing world as a whole is on course to produce the majority of global emissions within the next decade. Conventional wisdom holds that developing countries are too poor and lack the technical sophistication to adopt state-of-the-art energy systems. While superficially convincing, this argument misses the fact that although the new energy systems are different—and will require adaptation by both governments and the private sector—they are in the end better matched to the indigenous resources and capabilities that most developing countries possess. Renewable technologies and efficiency will allow developing countries to increase their reliance on indigenous resources and reduce their dependence on expensive and unstable imported fuels. Around the world, new energy systems could become a huge engine of economic development and job creation, opening vast economic opportunities for developing countries. And the total cost in the long term will likely be less than following the current, carbon-laden path.

China is beginning to show the way forward. Even as it continues to build coal-fired power plants at the fastest pace in human history—roughly two per week—the country has suddenly emerged as a clean energy leader.[46] New laws enacted since 2004 have jumpstarted the energy-efficiency and renewable energy industries in China, in some cases creating new industries from scratch. China now leads the world in solar water heating, small hydropower, and the manufacture of efficient CFL light bulbs.[47] It was among the top producers of solar cells and the third largest installer of wind turbines in 2007, and is on track to lead both sectors by 2010.[48] China is meanwhile making great strides in its efforts to be a leader in green buildings and green cars—persuading U.S. billionaire Warren Buffett in 2008 to invest $230 million in BYD, a Chinese battery manufacturer that plans to mass market a hybrid electric car.[49]

Other developing countries lack many of the extraordinary capabilities that China has demonstrated. But if China shifts away from its coal-based energy path to one that favors efficiency and renewables, it will have an enormous impact on the global economy, and will inevitably pull other countries into its orbit. Developing countries that pay little attention to what happens in Europe or the United States may be more influenced by the policy choices made in Beijing. And the dramatic cost reductions in renewable energy technologies that China is likely to spur will make it much easier for developing nations to adopt those technologies.

Tipping points are easier to decipher in retrospect than in advance. No one can say for sure whether the substantial shifts in energy markets and energy policies over the past few years are the precursors to a revolution. Just as the events of the past few years have surprised us, so will those ahead. And the financial crisis now breaking over the global economy will likely have profound impacts on energy markets.

Even with those substantial caveats, the evidence presented in this report suggests that when historians look back on 2008, they will conclude that a 21st-century energy revolution was well under way. Whether they will also be able to say that the world was able to avert catastrophic climate change will be determined by the decisions we make in the decade ahead. Urgency and vision are the twin pillars on which humanity's hope now hangs.

Endnotes

The Road to Low-Carbon Energy

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