# 5

# Renewable Energy



Among the several generalizations about energy that were emphasized in Chapter 3 were two points that are especially pertinent in considering renewable sources: first, that each of the various forms of energy can be transformed into an alternative form; and second, that all the forms that we have available came originally from sunlight. That is to say that given some attention to geological time scales, all energy is solar energy.

What then is the distinguishing feature that allows us to label some forms of energy as renewable? It has little to do with the ultimate source and everything to do with the time scale of regeneration. If the time required for

*The Challenge of Climate Change: Which Way Now?*
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 ISBN: 978-0-470-65498-9

transformation is measured in hours, days, or months, time duration that is short relative to human lifetimes, we consider the source to be renewable. If on the other hand the time required is long as measured by our experience, we class the supply to be non-renewable. Thus, since formation of the fossil fuels occurred over eons of geological time, they are non-renewable; whereas plant growth via photosynthesis, and changes in wind or tides, are classed as renewable because the transformations of solar radiation into these forms occurs in a matter of hours, days, or months.

This understanding of what is or is not renewable is important as a framework in which to evaluate some claims for renewable status when the moves are political and/or economically motivated. By mid-2009, 28 US states and the District of Columbia had set quotas requiring a percentage of an electricity provider's energy sales or installed capacity to come from renewable resources.[1] To provide economic incentives there are federal tax breaks and extensive new grants and loans available for those installations that fit under the rubric of renewable. Further benefits that go with this designation are *renewable energy credits* which could become salable if proposed national standards become law.

With billions of dollars at stake, lobbyists have been pressing legislators to expand the boundaries of definition and have been able in some states to include as renewable such sources as waste coal and methane from coal mines, and old tires. Other pressures on legislators are to consider the burning of garbage as a renewable process and some want to include nuclear energy under such a title. Recalling that the purpose of moving toward renewable energy is to limit the release of carbon dioxide ($CO_2$) by reducing our dependence on fossil fuels, this chapter will adopt a narrower view on what energy should be considered renewable. We exclude waste coal and methane from coal mines and nuclear fuels as coming from a finite supply. Garbage and recycled tires can be allowed to the extent that they are in fact shown to be a reliable and ongoing supply. Our focus in the sections that follow will be on the technical and planning aspects of transition from our current status.

One should ask first: where do we stand today? Again we turn to Department of Energy (DOE) data[2] for an answer. As shown pictorially in Figure 5.1, only 7% of all US energy consumption was classed as renewable in 2007. That relatively small segment of the pie can further be subdivided: biomass sources that include wood as well as waste make the largest contribution (53%), hydroelectric power is next (36%), leaving just 10% of all renewable energy attributable to wind and geothermal sources, and only 1% to solar conversion to heat and electricity.

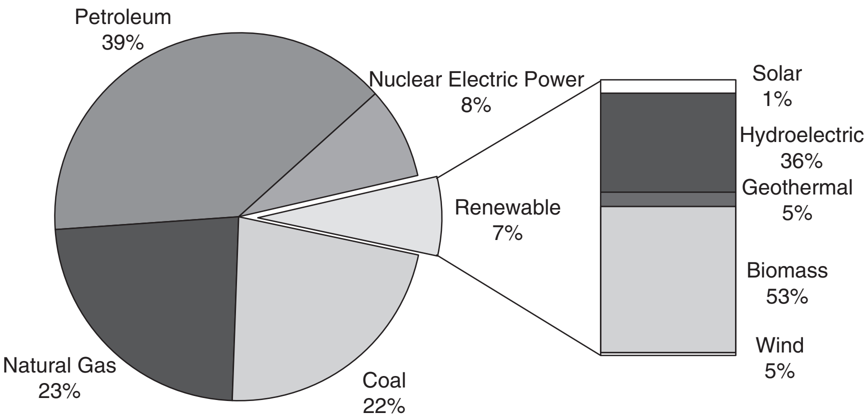


**Figure 5.1** US renewable energy consumption, 2007.
*Source*: US Department of Energy, Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels

The distribution is somewhat different if attention is shifted to international use.[3] Here hydroelectric power is even more predominant, accounting for about 66% of the total world-wide renewable energy. Combustion of materials of biological origin and crops fermented into alcohol produce some 22%, and wind about 5%. World-wide the conversion of solar radiation into useful energy accounts for 7%, a noticeable increase over the fraction in the US data. A bar graph comparing these magnitudes is shown in Figure 5.2, where geothermal sources are also included for comparison. Geothermal energy is obtained by tapping into steam and hot water heat under the surface, but it is not renewable in a strict sense because the sources are finite reservoirs that can be used up in time. By the same token, nuclear energy that is based on fission is not renewable since uranium is a finite resource. Biological materials are certainly renewable in each growth cycle, although their eventual combustion returns to the atmosphere the $CO_2$ that was extracted to make possible the growth.

## 5.1 Hydroelectric Power

The use of water wheels to harvest the energy flowing in streams, rivers, and waterfalls is very old indeed. Such wheels were even of use in the US late into the nineteenth century until they were replaced by steam engines

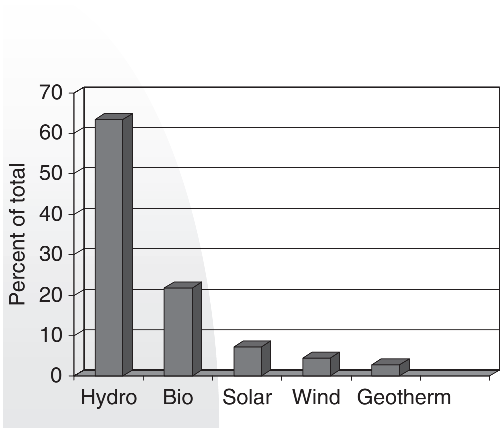


**Figure 5.2** World renewable energy, 2009.
*Source*: US Department of Energy, 2008 Renewable Energy Data Book

and electric motors. Today the water flow is usually held behind large dams and released in a controlled manner to drive turbines linked to generators for electricity. The full capability of a dam (called capacity) is not usually realized because the release of water is governed by added constraints related to supply, maintenance, and irrigation needs. The fraction of the capacity that is actually used is called the *load factor*, expressed as a percent. Table 5.1 lists the capacity and the actual delivery of power for each of the nine nations that are the largest producers of hydroelectric power. The sum of capacity in the table is 542 GW, but this total is not all that could be extracted globally from water power, and dams are being built in many parts of the world to augment the supply. One estimate has the total possible capacity at about 3,000 GW.

The greatest rate of growth in hydro power is found today in China, where the Three-Gorges Project will be the largest in the world. Also in China, the recently completed Xiowan Dam is the world's tallest with water storage capacity equal to all the Southeast Asia reservoirs combined. This dam is one of eight under construction on the upper half of the Mekong River. At the same time Laos has started construction on a series of 23 dams hoped to be completed by 2010 on the lower part of the same river. A recent United Nations (UN) study has expressed concerns that the concomitant changes in

**Table 5.1** Hydroelectric capacity by country.

| *Country* | *Capacity GW* | *Load Factor Percent* | *Delivered GW* |
|---|---|---|---|
| China | 145 | 37% | 54 |
| Canada | 89 | 59% | 53 |
| Brazil | 69 | 56% | 39 |
| USA | 80 | 42% | 34 |
| Russia | 45 | 42% | 19 |
| Norway | 28 | 49% | 14 |
| India | 34 | 43% | 15 |
| Japan | 27 | 37% | 10 |
| France | 25 | 25% | 6 |

river flow will affect biodiversity, damaging the ecosystem which is home to dozens of rare birds and edible marine species.[4]

Whether one looks at the human costs of displaced populations or pays attention to the ecological consequences of dam building, the negative effects must be weighed against the alternatives. With appropriate mitigation of the worst consequences, dams may be worth both these costs if they are compared to the world costs of expanding coal-fired power plants in rapidly growing industrialization. The ideal perfect should not be the enemy of limited improvement.

## 5.2 Biofuels

There are several major sub-categories of processes that produce products that fall under the title of biofuels. They may use as raw materials woody plant growth from well-established and long used materials such as farm crops, trees grown for this purpose, or forest and field leftovers. New crops such as switchgrass to be grown on otherwise unused fields, or algae harvested in artificial ponds, have also been proposed for this use. Whatever the specific source, the simplest technological treatment is controlled combustion in a furnace; it yields a hot gaseous product (consisting mainly of steam, $CO_2$, and attendant nitrogen from the air used for combustion) that can be used to drive a turbine and generate electricity in a conventional manner. This route does not, however, yield the desired liquid fuel that is needed for transportation use, nor does it reduce the greenhouse gas (GHG) burden in the atmosphere.

To manufacture a combustible liquid fuel the plant material can be: (i) chemically treated and/or fermented to produce alcohols; or (ii) chemically and/or catalytically converted into hydrocarbons similar to diesel fuel. The first of these alternatives is already in use on a large scale and indications are that it will continue to be important for some years to come. It includes corn and sugar cane grown explicitly for the purpose of conversion into ethanol as a gasoline fuel additive. It also includes a longer range objective: that of converting non-food cellulosic growth into such a fuel. Cellulose is a complex sugar that is a major component of virtually all growing plants, but it is not easily fermented. It must first be broken down by chemical or enzymatic means to produce simple sugars that can then be converted to alcohol.

Biological conversion of crops to fuels has been known since Weizmann's research, by which he was able to produce the butyl alcohol (butanol) and acetone that were badly needed by Great Britain during the years of the First World War. The production method was less than profitable, however, when the exigencies of war subsided and the process was abandoned. More recently, British Petroleum (BP) and Dupont are exploring an updated variation of this process to produce a fuel that they are calling *biobutanol*.[5] They hope to be in large-scale production by 2013, though this may be an overly optimistic projection.

The processes that are already in use, based on fermentation of corn or sugar crops, are very sensitive to national political needs and international ramifications. They provide excellent examples of the intense interaction of technical development, economic benefits to interested parties, and policy decisions. In Brazil, where petroleum is expensive and sugar is cheap, fermentation of sugar cane has been and is today the foundation of their gasoline industry. In the US, ethanol made from corn supplied about 9% of the country's market for liquid fuels in 2009, and the percentage is growing in order to meet the Federal Fuels Standard that mandates an increase from 9 billion gallons in 2008 to 36 billion gallons by 2022.[6] Anticipating the need to meet the new requirements, several large oil companies have entered the field. Sunoco, for example, has purchased an existing factory that is expected to supply 25% of the ethanol that they need to blend into gasoline.[7]

Whether starting from sugar cane or corn syrup, the fermentation process is technically well developed and subsidized in the US by federal grants to farmers and refiners. The benefit of a biofuel is to be sought above all in its reliance on domestic farms to replace imported petroleum, but this objective has been a subject of controversy ever since questions were raised by Pimentel and Patzek.[8] These authors considered the energy used in: (i) raising the crop, (ii) running farm machinery, (iii) irrigating, grinding, and transporting the crop, and (iv) finally fermenting and distilling the ethanol from the water mix; they concluded that more energy is used to produce ethanol in this way than is subsequently released by the ethanol as fuel. Vigorous counter-arguments by representatives of the industry and by reports from the US Department of Agriculture and Argonne National Laboratory reached an opposite conclusion and blamed the discrepancy on Pimentel's use of outmoded data that does not reflect current practice.

The major criticisms of this commitment to ethanol have been two-fold. The first is that the large-scale use of corn to make fuel has caused the price of corn to rise dramatically, thereby hurting all consumers but especially the poor in other parts of the world who depend on US food exports. The second complaint is an outgrowth of the price rise, that it leads farmers throughout the world to convert grasslands and forests into crops. These land clearing practices introduce significant amounts of greenhouse gases into the air, and the changes in landscape remove some of the very active sinks for $CO_2$ that the world depends on each growing season. One estimate[9] is that the carbon emissions that result from the clearing of tropical forests in places like Brazil, Indonesia, and the Congo now accounts for 17% of all global emissions contributing to climate change.

Searchiger has calculated[10] that burning corn ethanol as fuel produces twice the GHG emissions as gasoline that is alcohol free, if the emissions from land conversion are included in the count. He argues that there is no benefit to the use of biofuels when the full cost to the environment is included in the accounting. This position has been accepted by the California Air Resources Board (CARB),[11] which is charged with putting into practice California's fuel standard, which requires a 10% reduction in GHG emissions from transportation fuel by the year 2020. The federal government is also likely to be drawn into this controversy, since a 2007 law requires the Environmental Protection Agency (EPA) to calculate "life cycle greenhouse gas emissions" for renewable fuels.

To circumvent some of the difficulties associated with the use of food crops to make liquid fuels, there is research in progress that would use non-food crops (i.e. cellulosic feedstocks) as raw materials for ethanol manufacture or to form other fuel components. The intention is to generate these feedstocks from perennial crops grown specifically for this purpose, sited on marginal lands to prevent competition with food production.[12] Steps in this direction are supported by the 2007 US legislative mandate for 16 billion gallons of cellulosic ethanol by 2022, as well as by the European Union's directive that 10% of all transport fuel in Europe should come from renewable resources by 2020. Congressional passage of the 2008 Farm Bill further addressed biofuels and provided subsidies for the production of cellulosic ethanol and biodiesel fuel to the extent of $1 per gallon for refiners and $45 per ton of biomass for growers. This federal tax credit was allowed to expire at the beginning of 2010, making these processes much less attractive economically. In addition much of the overseas market dried up when the European Union put in place tariffs on all biofuels.

The second of the sub-categories of processes that produce liquid fuels, those that focus on hydrocarbons as their goals, are as yet untested on any scale beyond the laboratory. The processes that are currently being studied as candidates for large-scale expansion[13] are based on a variety of chemical steps that convert the oils extracted from plants or algae into compounds similar to those found in petroleum products. These could be used as gasoline, diesel fuel, or jet fuel, depending on the detailed conditions of the conversion steps. Plans for the works in progress, with target dates as early as 2011 to 2016, call for factories with capacities to produce 100 million gallons of fuel annually at prices that would be competitive with petroleum at $60 per barrel. Exxon-Mobil, for example, has announced an intention to invest $900 million over a 5-year period to develop a process to produce refined liquid fuels from algae.

Yet another variation on this theme is based on a high-temperature chemical gasification of the raw material to produce an intermediate gas called *syngas* (short for synthesis gas). In turn, the so-called syngas (a mixture of hydrogen and carbon monoxide) is reacted further to form the desired hydrocarbons catalytically. One can also think of this process as a technique for storing, first in syngas form and then in hydrocarbon fuel, part of the chemical energy that was located in the plant raw material by photosynthesis. With this in mind, we will discuss the features of this process further in Chapter 6 on energy storage.

Whatever the details of processing, it should be added in assessing the potential benefits of using so-called *biomass* as a raw material that any biomass is a bulky solid with quite high water content. The relative costs of shipping and drying mitigate for processing plants that will be close to the biomass source and thus tends to constrain the size (and efficiency of scale) of the manufacturing facility.

What may emerge to be the most telling argument in the debate around biofuel alternatives is presented very sharply by Cambell, Lobell, and Field.[14]

They addressed directly the two current alternatives for biomass use: (i) conversion to ethanol to power internal combustion vehicles; or (ii) conversion to electricity to power battery electric vehicles. Their life cycle assessments compared the transportation distances and greenhouse gas reductions that would be achieved from commitment of land area to one of these choices, accounting for energy needed to grow the feedstock and convert it to either electricity or ethanol, as well as the energy needed to manufacture and dispose of vehicles. They found that "one can travel farther on biomass grown on a hectare of land when it is converted to electricity than when it is converted to ethanol." The results of their work also show that GHG emissions are less when the electricity route is followed in preference to the alcohol route, even when land use impacts are left out of the calculations. Other indirect advantages of the electric route may come from the easier connection with other renewable sources such as solar and wind power, or even greater benefit from centralization if $CO_2$ sequestration ever becomes accessible.

## 5.3 Wind Power

As with water power, the use of wind to drive windmills has a long established history. What is new is the advanced machine technology linked to electricity generation that offers more efficient collection of the energy. The energy collected by a windmill is very sensitive to wind velocity (it varies with the square of the velocity; i.e., a velocity reduction in half has the effect of cutting the energy collection to a quarter). As a result it is essential to place windmills at sites of frequent high winds. As illustrated in Figure 5.3 the preferred locations in the US are in the center, north, and west of the country, as well as along the Atlantic and Pacific coastlines.[15] Wind velocities also vary with time of day and season of the year, typically peaking in summer and falling to a low in mid-winter. As a result, wind farms only deliver a fraction of their rated capacity, typically about a third. This means in effect that one cannot depend on wind energy alone, but must plan on integration with other more dependable sources.

As of the year 2007 the installed windfarms in the US had a cumulative capacity of about 18 GW of power. This was increased to 25 GW in 2008, and grew further to 35 GW by the end of 2009, aided by federal tax credits and investment incentives as well as state laws that mandate that some fraction of local power come from renewable sources.[16] Plans are in place for

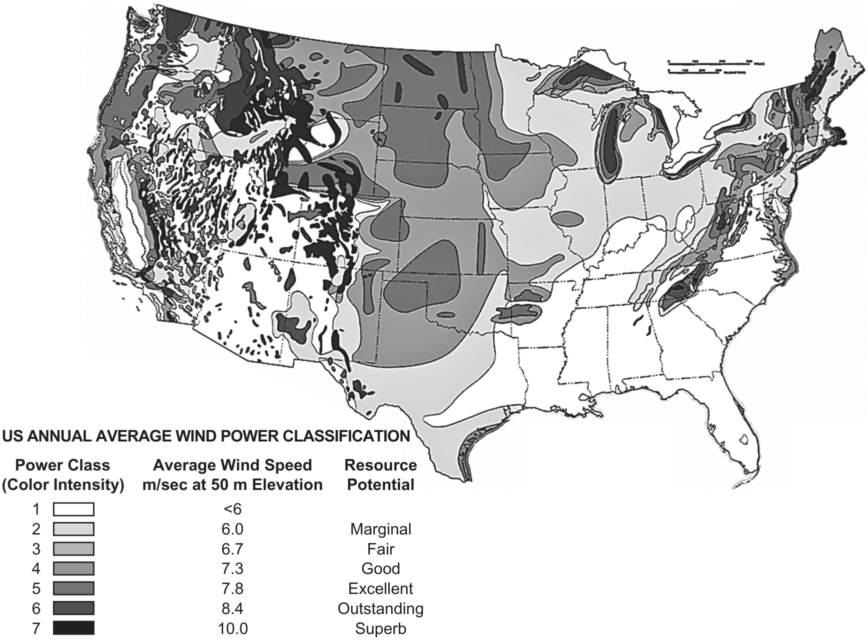


**Figure 5.3** US wind power resources at 50 m elevations.
*Source*: US Department of Energy, National Renewable Energy Laboratory, Wind Energy Resource Atlas of the US

sizable expansions both on land and in offshore locations. The US pattern of growth in generating capacity from this source is shown in Figure 5.4 for the years 1981–2008.[17]

In the UK about 2.5 GW of wind power currently exist, an additional 8.5 GW have been approved but are not yet built, and further increase of 22 GW have been proposed to be developed by installing 7,000 new wind turbines. If all goes according to this plan, the total capacity will be 33 GW, a very significant addition to the 75 GW which currently exist in the UK from coal, gas, nuclear, and hydro power. The goal set by the European Commission is to obtain 20% of its electricity from renewable sources by 2020; Denmark has already reached that target. From 2006 on, China has been making huge investments in green technologies, aiming to increase massively energy generation from wind, solar, and other renewables by 2020.[18]

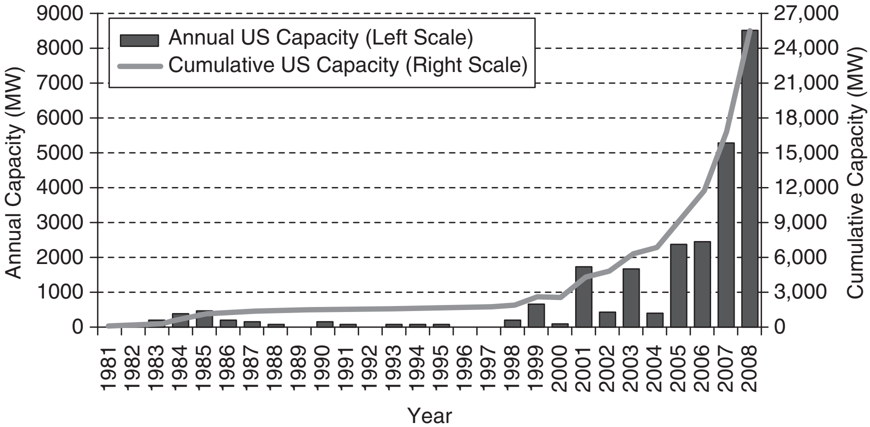


**Figure 5.4** Growth of US wind electricity generating capacity.
*Source*: US Department of Energy, Energy Information Administration, Office of Coal, Nuclear, Electric and Alternate Fuels

## 5.4 Power from Tides and Waves

The harvesting of electric power from ocean waves was seriously proposed[19] as early as 1974, but the outcome can be easily summarized: the source has always been available and never been used because the investment has always been considered to be too large to justify the savings in energy. Today the picture is changing as energy costs rise and the threat of global warming is ever present. Scruggs and Jacob[20] reported on a finding of the US Electric Power Research Institute (EPRI) that the potential ocean wave energy in the US is comparable to energy currently generated by conventional hydro power. They also cited an estimate by the Carbon Trust in the United Kingdom to the effect that their economically viable offshore resource amounted to about 14% of their current national demand.

To find suitable locations at which to extract energy from the sea, one seeks low wave frequencies and high amplitude waves. This means that deeper waters are preferred to shallow beaches and western shores are typically better than those that are east facing. Waves form in deep water and their energy dissipates as they approach a shore; at depths less than 20 m the energy is less than one-third of that carried by the wave in deep water. As of 2009 existing installations are off the coasts in Portugal (rated at 2.25 MW), Spain (1.4 MW), and Oregon (2 MW). There is as yet no agreement on the best design, and the various test units are small and use different technologies and geometric arrangements. They are typically tuned to work best with a given wave frequency, but real waves exhibit random behavior over a range of frequencies, and statistical expectations and close control are needed to optimize an entire system.

Although tides and waves both present forms of water power, they exhibit several important differences. For one, tidal power is the only form of energy that derives directly from the motion of the moon about the earth and the movement of planet earth as it orbits the sun. These relative motions produce gravitational shifts that periodically change the water levels that we recognize as high and low tides. The size of the tidal fluctuations at any given location depends on the changing positions of the moon and sun relative to our planet, but also on the shape of the coastline, the slope of the continental shelf, and the shape of the sea floor.

Because a tidal energy generator uses this phenomenon to generate energy, tidal power is highly predictable and practically inexhaustible. It does, however, vary sharply with geography and the location for tidal energy generation should be chosen with water level height or tidal current velocity in mind, typically at the mouths of bays and rivers or between land masses. One type of arrangement, called a *barrage*, is in essence a dam built across a tidal estuary; it holds back water to store it for its potential energy and releases the stored supply through turbines when the energy is needed. A major tidal power station of 240 MW capacity, the largest barrage in the world, has been operating in La Rance, France, since 1966. In Britain a huge 2 GW capacity barrage is planned to utilize by 2028 the 15 meter tide on the Severn River. The capital cost is estimated to be $29 billion, expected to offer long-term returns with minimum maintenance cost and a projected savings of over 19 million ton of coal each year. However, blocking the mouth of an estuary can have significant ecological effects similar to those that occur at any large dam, changing local marine life and vegetation. An alternative approach harvests the kinetic energy in the moving water by placing turbines directly into a moving stream. One such, for example, with a capacity of 1.2 MW and billed as the world's largest tidal turbine, was installed in 2008 in Northern Ireland's Strangford Lough.

The distinction made between tides and waves should be emphasized again with regard to their dependability, because whereas tides are predictable over short and long time scales, wave action depends to a great degree on driving winds. As a consequence, energy recovered from wave action will suffer from the same irregularities as that recovered via wind turbines.

## 5.5 Direct Use of Solar Energy

The point has been made and emphasized before that all renewable energies either directly or indirectly use solar radiation as an original source. Thus wind is created by the sun unevenly heating the air. Rain and snow, which flows to all rivers, form when the air is cooled sufficiently to cause previously evaporated water to condense and precipitate. But when we speak of solar energy, we mean direct use of the sun's radiation as opposed to indirect use via wind or waves.

The direct use of sunlight is by one of two transformations: (i) the sun's radiation can be used to generate heat in whatever fluid is designated to be the carrier; or (ii) radiation can be absorbed in photovoltaic (abbreviated PV) cells that directly convert the energy to electricity. The direct conversion to electricity is accomplished by specially designed silicon cells that absorb light and put out an electric current, but cheaper substitutes for silicon based on cadmium telluride thin films are also being worked on, as are methods that use reflectors to focus more sunlight on a smaller collector area.

In residential use the solar energy is usually collected by heating a circulating fluid. The carrier is hot water that is then passed through piping for internal space heating or bathing. For industrial applications that can efficiently use high-temperature heat, the working fluid can be a molten salt that gives up its energy to create steam for power generation. In this case focusing mirrors have been suggested in order to cover a wider area for collection of sunlight, which is reflected in the direction of a central receiver.

To encourage research and development in this arena governments have provided incentive policies for PV cells. These include tax benefits that serve to refund part of the investments needed to build and install systems, as well as constraints on utilities that require them to buy PV electricity from producers. In response the largest utility in New Jersey announced in 2009 a plan to install 80 MW of PV collectors over a 4-year period.[21] In Germany, California, and Florida governments have introduced a so-called "feed-in tariff" which sets the price of the electricity sold to the utilities above the going market price.[22] It is estimated that by the end of 2008 about 90% of the PV-generating capacity was tied into the utility electricity grid. The political purpose of these subsidies is to promote greater national energy independence and facilitate start-up and growth in an industry not yet ready to compete until it reaches the necessary economies of scale. The immediate effect of scale can be seen by recalling that PV cost was as high as $25 per watt in 1979. Current costs of silicon flat panel modules are priced at about $5 per watt, increasing to $6.4 per watt with included installation charges in 2009. To cite some typical figures,[23] a new 80 kW rooftop solar array installed in a Philadelphia factory is reported to cost $536,000, corresponding to $6.7 per watt, but after federal and state grants and rebates, along with depreciation tax credits, the net cost (including a new roof) is reduced to $195,000, giving an installed cost of $2.4 per watt. A comparison study by Greg Nemet[24] concluded that 43% of the drop in cost in the 22 years since 1979 was attributable to economies of scale. He associated another 35% of the reduction to progress in research and development.

One scheme that can improve collection efficiency of solar cells uses reflectors to pick up radiation over a larger area. This reduces cost, because the reflecting collector is less expensive than an equivalent area of solar cells. Whereas silicon flat panel modules with included installation charges are priced at about $6.4 per watt, the system with reflecting collectors is reduced in price to about $3 per watt. Estimates by those within the industry[25] are understandably very optimistic, expecting that as manufacturing costs fall, PV plants will be able to compete with more standard electricity generation by 2014, even without the current US federal incentive of a 30% investment tax credit. Nevertheless, to put these estimates in context it should be noted that the total accumulated world-wide capacity of PV production was about 15 GW in 2009, half of which was in Germany and around 10% in the US. This means that as of that date the entire PV megawattage amounts to less than 0.5% of the world installed electricity generating capacity.

As is so often the case when new high-tech devices enter the market, the cost of PV conversion is still too high to compete with conventional alternatives except for special situations where sites are too far removed from a supply grid, or in areas with abundant sun and high costs for electricity such as in parts of California, Japan, or Hawaii. On the other hand, the cost of solar thermal power is competitive with clean coal (without sequestration) and is less expensive than nuclear power for small-scale installations. Comparison numbers from a recent National Research Council report[26] on each of these alternatives for generating electricity are given in Table 5.2, where the listings are energy costs per kW used for an hour (cents/kwh). Given these numbers, it is not surprising that coal burning accounts for 49% of US electricity generation, natural gas for 21%, and nuclear power for 20%.

Ignoring for the moment all questions of economics and costs, there is yet another consideration that puts power from PV sources into sharper perspec-

**Table 5.2** Costs of US electricity in 2005.

| *Source* | *Cents/kwh* |
|---|---|
| Conventional Coal | 4 |
| "Clean Coal" (without Sequestration) | 7 |
| Nuclear | 11 |
| Solar Thermal | 8 |
| Solar Photovoltaic | >24 |

tive as a possible replacement for current sources of energy for electricity generation. We should ask: how much surface area would need to covered by silicon cells to obtain a useful amount of electric energy from the sun via PV? Allowing for reflection, cloud cover, weather, and the many vagaries during the year, the energy that reaches the surface of our world averages about 200 W/m$^2$ (watts per square meter). We might expect current PV conversion to be 10% efficient and supply 20 W/m$^2$ as electricity.

One recent estimate[27] projected that by 2050 the US could be using existing PV technology for 69% of total electricity consumption, i.e., 700,000 MW. A simple ratio of these numbers leads to the area requirement of 35 trillion square meters or approximately 14,000 square miles. Allowing for space between the PV modules and making room for auxiliary equipment, service vehicles, and adjacent connectors and carriers of electricity, one might reasonably double the area required to 28,000 square miles, an area equivalent, for example, to 23% of the total area of the state of New Mexico. This area requirement is certainly not a trivial consideration, but the overall picture might improve if the collectors could be sited exclusively in desert areas where the incident radiation could be expected to yield more than 20 W/m$^2$, or if the collectors' efficiency for energy conversion were to increase significantly. Given such improvements the plans would still need to take into consideration the costs of power transmission over long distances to the consumers.

If instead we focus attention on a single home with say 100 m$^2$ of useful roof area, the same 20 W/m$^2$ could supply 2 kW of power, enough to meet the monthly electricity demand of the average US household; however, this monthly estimate is an average over day and night, rain and shine, and would not be sufficient at times of peak demand when supplemental sources would have to be called upon. One way or another each of the renewable energy sources are intermittent. This will lead us into Chapter 6, where attention is to be paid to options for storage of energy.

## 5.6 Nuclear Energy

It was noted above that nuclear energy is not fully renewable since the uranium supply is finite, but whatever its proper category, nuclear power has some obvious advantages among the possible ways to generate electricity. Since they do not burn hydrocarbon fuels, operation of these plants does not produce any $CO_2$. Above all, nuclear power is a known technology. In France some 80% of all electricity generation comes from nuclear plants, and in the US more than a hundred commercial reactors generate almost 20% of the country's electric power right now. In spite of that not a single new plant has been ordered and built in the US in over three decades. The lack of any new moves in this regard was a response to increased costs of construction as well as heightened fears of radiation hazards following the 1979 Three Mile Island accident in the US and the 1986 explosion in Chernobyl, Ukraine. In addition there has been ongoing discomfort with the current above-ground storage of nuclear wastes, currently being held at multiple sites scattered all over the US. A proposed unification to a single underground site in Yucca Mountain in Nevada has been delayed for decades by geological uncertainties, changing performance expectations, and local political opposition.[28] Now, after some $10 billion has been spent on risk assessment studies, it appears from plans for the 2010 federal budget[29] that a new strategy for nuclear waste disposal will replace the earlier idea to use the Yucca Mountain site.

Today, with the rising public concern over global warming, we may be entering a period of nuclear revival.[30] In 2008 the Nuclear Regulatory Commission had applications for permission to build 34 new plants, and Congress has provided loan guarantees and insurance against regulatory delays. The implementation of such guarantees is yet another source of controversy, however, because major delays and cost overruns have in the past been common in reactor construction.[31] With government guarantees any private sector losses would have to be covered from the US Treasury. In spite of this easing of impediments, it must be recognized that new construction of nuclear plants takes many years from design to construction to completion.

As a remedy to fossil fuel use, this avenue is not an available short-term fix and should properly be thought of as an intermediate-term target.

Expansion of nuclear capacity is also being planned abroad. China had announced plans 3 years ago to move from a capacity of 9 GW to 40 GW by 2020; they have now stepped up their expected development in this area to aim for 70 GW capacity by 2020 and 400 GW by the year 2050. If the Chinese meet their targets for 2020, they estimate that nuclear power will still only provide about 10% of their electricity needs. Aware of the hazards associated with this industry, China has requested experts from the International Atomic Energy Agency for staffing and training help.[32]

## 5.7 Geothermal Energy

Below the thin layer of our planet on which humans live, the world is hot and has been so from the time of its origin to the present. To the extent that we have access to this huge thermal reservoir it can provide a sustainable source of energy, but in most locations it is cut off from us by an insulating crust. In places where the crust is thin or broken, generally near tectonic plate boundaries, we can and do harvest energy by passing steam or hot water through the underground reservoirs and using the energy to drive electrical generators or to provide thermal space heating. As of 2007, the world-wide electricity generating capacity from this source was about 10 GW, and the estimated thermal heating amounted to an additional 28 GW, both quite small in comparison to conventional fossil fuel sources.

To access deeper pockets of heat and locations elsewhere away from tectonic boundaries it is necessary to drill through layers of rock and earth, usually to depths of several miles below the surface. Such techniques have been developed for petroleum production, but the costs of drilling have until now discouraged this endeavor. The investment in so-called *enhanced geothermal systems* will become more attractive as other fuels become more expensive and the reduction of $CO_2$ release more pressing. In fact concentrations of $CO_2$ are present in some of the hot gases under the crust, but they can be recycled back into the same holes from which they were released. In one variation of this approach, pressurized water is injected deep in the ground with the object of cracking the rock that is trapping underground heat; however this process has been associated with local earthquakes. A 2006 project in Switzerland had to be stopped when many thousands of seismic events were recorded and felt during 6 days of water injection, and the project was shut down permanently in 2009 in response to the determinations in a Swiss government study.[33] A similar 2009 project in California[34] has raised earthquake fears among residents because it is designed to drill over 2 miles (3.2 km) below the surface. Elsewhere, in New Zealand and Germany, geothermal projects have caused subsidence of the bordering lands.

In spite of these cautionary tales, the advantages of geothermal energy are very significant: the supply is virtually inexhaustible, it is available at all times of the day and all seasons of the year, and the cost of production is low except for the initial drilling investment. And above all, this source promises to reduce the overall greenhouse gas burden, and there is still hope that a practical operation might work in a less populated area.

## 5.8 Indirect Emissions and Hidden Costs

The full effects of any change are not always apparent. When the California Air Resources Board had the task of evaluating the addition of alcohol to gasoline, for example, their finding was determined not merely by the immediate carbon release from the combustion of the fuel, but crucially by a secondary effect: the emissions that came from the land conversion that followed the economic pressures created by the new demand for crops to be fermented. The realistic assessment called for an overall view in context, recognition of the subsequent and indirect effects on the overall carbon balance. A similar evaluation is needed for each and every proposed step toward climate control.

A point of particular sensitivity in this regard has been raised in relation to nuclear power.[35] At first glance, it appears that a nuclear reactor does not produce $CO_2$ at all, that the fission of uranium produces only "green" energy in the form of steam that is used to drive turbines and thus generate electricity. A closer examination of the full process must recognize, however, that the production of uranium and/or plutonium is not without energy input. First, the uranium ore must be dug from its source. Then the uranium 235 isotope must be concentrated, originally via gaseous diffusion and more recently by using high-speed centrifuges. Finally, the uranium must be transformed into oxide pellets and fuel rods suitable for insertion into the reactor core. Each of these steps demands energy input, in some cases using fossil fuels, in other steps using electricity generated by combustion of fossil fuels. The full effect is surely to release $CO_2$ into the atmosphere, but the extent of this release is not generally documented, perhaps because of its association with weapon uses of uranium, and as a consequence it is not easy to estimate. In the book cited above, Helen Caldicott indicated that the creation of nuclear electricity produces one-third as much $CO_2$ as a similar-sized conventional plant that burns natural gas. She cautioned, however, that a still greater ratio of fossil fuels will be needed in the future as the quality of available uranium ores decreases.

Yet another uncertainty in this arena arises from the possible recovery of uranium by reprocessing spent fuel. To date this has not been part of the US nuclear plant protocol, although it is done in other nations, notably France. Such reprocessing will become increasingly attractive if and when the cost of newly refined uranium rises, but of course this mode of chemical recovery will also require an investment of energy. Furthermore, as with any natural resource the cost depends on ease of availability, and conversely, additional amounts become economic to recover as the price goes up. Data on reserves of uranium oxide have been published by the DOE[36] and are shown in Figure 5.5 as proved, estimated, and speculative reserves for each of three costs per pound. As points of reference, it should be noted that the price of uranium oxide has varied since 1981 from a low of $10 to a high of $43 per pound.

The costs of implementing change are not always directly expressed in terms of construction dollars or operating dollars. Any change, for example, that calls for increased demand in irrigation for agriculture or in cooling water for power generation will have to deal with water supply issues. Depending on location, a large growth in demand could trigger water shortages, costs that are great even if not directly expressed in simple monetary terms. Robert F. Service has reported[37] on studies that say 98 gallons of irrigation water are required on average to produce each gallon of alcohol via the corn fermentation process. This translates into an increased irrigation need of at least 2 billion gallons per day if US farms are to produce enough crops to meet the congressionally mandated production of alcohol and other advanced biofuels. To put these figures in perspective, they may be compared to the water needs of more conventional power generation: for the same energy production, corn ethanol irrigation requires at least 30 times as much water as a power plant burning natural gas.

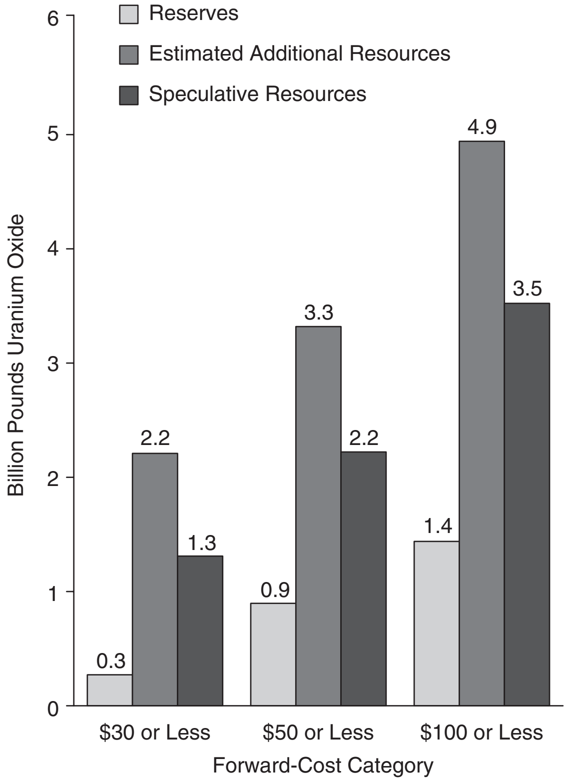


**Figure 5.5** Reserves and resources of uranium oxide at various prices.

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