Chapter 11

Alternative Energy Sources

BACKGROUND

I will now explore the alternatives to our reliance on fossil fuels as the dominant source of our energy needs. In this chapter we will explore the science of energy sources under the collective designation of “alternative” energy sources. By “alternative” one means alternative to direct use of fossil fuels or, more accurately, fuels that do not contribute to chemical changes in the atmosphere. The next chapter will focus on the economic tools, driving forces, and possible consequences of the transition to such fuels, and Chapter 13 will focus on the ongoing political processes involved in facilitating the transition.

Alternative energy sources are often divided into two main categories that share many similarities but attract and repel different constituencies: nuclear energy and sustainable energy sources. The term “sustainable” is often associated with energy sources that will last forever and will not have adverse, irreversible, climatic impacts on the environment—the two most problematic aspects of fossil fuels. Whereas the laws of physics tell us truly sustainable energy sources do not exist, we know we can do much better than we are currently doing with fossil fuels.

As reluctant as I am to stray outside the main topic of the book, I feel that this is the place to explore our relationship with the rest of the universe within the context of our global energy balance. Box 11.1 shows that our sun is a typical star (i.e., one referred to as in the middle of the “main sequence,” or neither newly born nor dying, in astronomy), about 5 billion years old, that derives its energy from the fusion of hydrogen to helium. Each of the billions of billions of “main sequence” stars in the universe derives its energy in a similar way. The hydrogen that serves as a fuel for this reaction was formed either directly or indirectly (through circulation from “dead” stars) in the big bang—the moment of creation. A star starts to die when the hydrogen in its core starts to run out—we (i.e., our sun) have about 5 billion years left.

Approximately 80% of the universe is composed of hydrogen. In principle, we can take a little bit of this hydrogen and try to mimic what the sun is doing—we are trying. As is mentioned in the box, the only “success” we have had so far with this process is in making bombs; we have not yet harnessed nuclear fusion for peaceful applications.
Earth was created at approximately the same time as the sun, but we are not an “independent” star—Earth’s core is not compressed enough to ignite a fusion reaction, and its chemical composition consists of the most stable nuclei; if it had been otherwise, life on Earth would not exist. Our core is compressed enough to sustain high temperatures, as high as the surface of the sun (not the sun’s core). In principle, we could tap this heat source if we could reach it. In Chapter 7 we saw that Earth’s interior hardly contributes anything to the global energy balance—life on Earth is confined to Earth’s surface and the energy balance is between us and the sun. Exceptions to this statement in the form of small ecosystems that develop around thermal vents near the surface of the ocean only serve to reinforce this general rule. We saw in Chapter 5 that to maintain approximately constant temperature, we radiate back into outer space all the energy we get from the sun. The property of the solar radiation that allows life-sustaining activities is the high “quality” of the radiation (short wavelength) coming in compared to what we emit back into outer space.

**Primary and Secondary Energy Sources**

Taking such a global perspective forces us to discuss energy alternatives in terms of primary sources and secondary sources. Primary sources include three forms of energy: nuclear energy that mimics the sun in using cosmological sources of energy that directly or indirectly were created with the creation of the universe, solar energy in its various forms, and geothermal energy resulting from heat leaks from Earth’s interior to the surface. Fossil fuels fall into these categories because they represent stored solar energy (the conversion took place in Earth’s earlier history). In spite of the law of conservation of energy discussed in Chapter 5 and our ability to convert energy from one form to another, not all forms of energy are equally useful for all applications. It is currently very difficult to devise cars with a nuclear reactor as the energy source. Our energy mix needs to reflect the targeted applications. Secondary energy sources shift energy production from distributed applications such as automobiles to centralized power stations that distribute power through an electric grid.

Centralized power stations generate electricity mainly, but not exclusively, by converting mechanical energy to electrical energy using electric generators. Electric generators are machines that convert mechanical power into an alternating-current electric power source. The physical principle that makes the generator work is based on the observation that if an electric conductor moves through a magnetic field, then electric current will flow in the conductor. The mechanical energy of the moving wire is converted into the electrical energy of the current flow. The mechanical energy comes from turbines that either convert the heat energy of steam in the same way as heat engines discussed in Chapter 5, generate their energy from falling water in waterfalls or dams, or generate their energy from wind.
Box 11.1

**WHERE IS ALL THIS ENERGY COMING FROM?**

The structure of atoms plays a key role in our discussion. In Chapter 11 I introduced the basic structure of nuclei that consists of positively charged protons and neutral neutrons bound together, as well as negatively charged electrons that orbit the nuclei. The number of protons determines the atomic number of the element and its place in the periodic table. In Chapter 3 we addressed how the very small nuclei can accommodate all these positively charged protons that have the same electric charge and thus tend to repel each other: neutral neutrons that do not contribute to the electrical force but strongly contribute to the strong nuclear force, which is an attractive force that operates only over the short intra-nuclear distances, keep the protons together. We observed there that for a given element, atoms with the same number of protons can accommodate different numbers of neutrons to stabilize the nuclei. Atoms of the same element with different numbers of neutrons are isotopes. In principle, we can bombard a nucleus and have all its protons and neutrons disperse to become independent particles. To accomplish that, we need energy: the minimum amount of energy required is the binding energy of that nucleus. Figure 11.1 shows the binding energy of various nuclei after we divide the total binding energy by the total number of protons and neutrons (collectively called nucleons). I show this as a function of the total number of nucleons, which we define as the mass number of the atom.

![Figure 11.1](image.png)

**Figure 11.1.** The binding energy per nucleon as a function of the total number of nucleons (adjusted to the binding energy of deuterium)
Arguably, Figure 11.1 is the most important figure in our understanding of the working of our physical world. This is a bombastic statement deserving some explanation, but first, how do we measure this energy? Today we can measure atomic masses very accurately using a mass spectrometer, which traces the trajectory of the atoms in magnetic and electric fields. As an example, Table 11.1 shows the mass of $^{12}\text{C}$, as well as the masses of neutrons, protons, and electrons. (The top number indicates the sum of protons and neutrons, and the bottom number indicates the number of protons or the atomic number.)

### Table 11.1.
Mass Balance of C-12

<table>
<thead>
<tr>
<th>Particle</th>
<th>Relative mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-12</td>
<td>12.0000</td>
</tr>
<tr>
<td>Proton</td>
<td>1.00728</td>
</tr>
<tr>
<td>Neutron</td>
<td>1.00867</td>
</tr>
<tr>
<td>Electron</td>
<td>0.00055</td>
</tr>
</tbody>
</table>

One atom of $^{12}\text{C}$ comprises 6 protons, 6 neutrons, and 6 electrons—so by summing up the components we get $6 \times 1.00728 + 6 \times 1.00867 + 6 \times 0.00055 = 12.099$. This number is obviously larger than 12.0000. What is the reason for this difference, and what are the units of mass we are using here? The units are normalized to the mass of $^{12}\text{C}$ that per the definition we set at exactly 12. If we now take 1 mole (back to Chapter 1) of each of the quantities of Table 11.1, then the units can be expressed in grams. If we take 1 mole ($6 \times 10^{23}$ atoms) of $^{12}\text{C}$, then it will weigh 12 g, but if we weigh the corresponding protons, neutrons, and electrons separately, then they will weigh 12.099 g. We can now use, for the difference in weight, Einstein’s famous formula (Chapter 5):

$$E = mc^2.$$

[11.1]

We will get $E = (0.099 \text{ g}) \times (1 \text{ kg/1000 g}) \times (3 \times 10^8 \text{ m/sec})^2 = 9 \times 10^{12} \text{ J} = 10^{10} \text{ Btu}$ (where $c$ is the speed of light $= 3 \times 10^8 \text{ m/sec}$).

This is the binding energy of the 6 protons and the 6 neutrons of 1 mole (12 g) of the $^{12}\text{C}$ nuclei. We divide this number by the number of nucleons and get the binding energy of $^{12}\text{C}$ per nucleon shown in Figure 11.1. To eliminate the need to introduce units that will express properties of individual atoms, the figure shows the binding energy relative to deuterium, which is a hydrogen isotope with 1 proton and 1 neutron. To put the strength of the binding energy in context, in 1999 the entire world’s energy use was $4 \times 10^{17} \text{ Btu}$. We
could have gotten this energy from assembling $4 \times 10^{17}/10^{10}$ moles of carbon, which weigh 480 tons, from its components. This amount of carbon is roughly equivalent to the amount of carbon in 5000 barrels of oil. The actual 1999 energy consumption was equivalent to 50 billion barrels of oil—10 million times more. The energy from this kind of assembling is the energy of fusion—we start with smaller nuclei and form bigger ones with a higher binding energy per nucleon. In terms of Figure 11.1, we climb from the left-hand side toward the middle. We actually use this kind of energy directly for destructive purpose, with the hydrogen bomb, and indirectly through the use of solar energy.

Let us go to the beginning—the beginning of the universe through the big bang. We have very good evidence that at that time (approximately 13 billion years ago) the universe comprised hydrogen and helium with the approximate ratio of 12 hydrogen atoms to 1 helium atom. The present average composition of the universe is not very different. This is obviously very different from the composition of Earth, which is dominated by heavier elements such as iron, silicon, oxygen, carbon, and so forth, but it is not very different from the present composition of our sun. The sun and all the other stars in the universe in their prime can perform nuclear fusion but have not yet exhausted the main fuel for this reaction.

The fusion reaction that fuels all the main sequence stars, including our sun, is the fusion of hydrogen to form helium in the core of the star:

$$4 \, ^1\text{H} \rightarrow ^4\text{He} + \text{energy.} \quad [11.2]$$

To ignite this reaction a star needs to have enough mass for gravity to compress its gas to temperatures that exceed 100 million degrees. Once ignition is achieved, the star gets its energy from the fusion reaction until the hydrogen in its core is exhausted. Our sun will exhaust its core hydrogen in about 5 billion years. When stars reach the last stages in their lifetime following the exhaustion of their core hydrogen, they climb up the fusion ladder in Figure 11.1 until they cannot ignite more fusion reactions—the exact end point will largely depend on how big they are. No matter how big they are, the end product of this is iron, the most stable nucleus. To fuse to a larger atom than iron, one needs to put great amounts of energy in the process. The only known mechanism to do that is through supernova explosions. These explosions take place at the death of very massive stars. Thus all the elements heavier than iron were formed long ago in such explosions. This brings us to the second way to get energy from changes in binding energy: start on the right-hand side of Figure 11.1, from the heavier elements such as uranium, and split them to form lighter elements. This process is the fission reaction, which will be discussed shortly.
**Present Distribution of Energy Consumption**

Table 11.2 shows the energy consumption and the percentage of electricity production globally and in four large countries. The percentage of the energy used as electricity looks small—but looks can be deceiving. The mechanical energy used in electric generators must be produced by getting it from a primary energy source in some way. Table 11.3 lists the main energy sources.

All the listed sources, except for hydroelectric, provide mechanical energy by boiling water to produce steam and using the resulting heat energy to drive turbines. The efficiency of conversion of heat energy into mechanical energy is limited by the second law of thermodynamics (Chapter 5) and depends on the temperature of the steam. The temperature and other conditions vary with the design of the generator, but typical conversion efficiency is about 33%. The world’s electricity production in 2000 was 13% of the total energy consumption. If we now take the heat equivalent of this, taking 33% as a typical efficiency, we get close to 40% of the total energy consumption. The rest of the energy is used for transportation, space heating, and

<table>
<thead>
<tr>
<th>Energy consumption (Btu)</th>
<th>Electricity production (% of energy)</th>
<th>Biomass (% of energy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>$9.2 \times 10^{16}$</td>
<td>15</td>
</tr>
<tr>
<td>Brazil</td>
<td>$7.35 \times 10^{15}$</td>
<td>16</td>
</tr>
<tr>
<td>India</td>
<td>$1.8 \times 10^{16}$</td>
<td>10</td>
</tr>
<tr>
<td>Japan</td>
<td>$2.1 \times 10^{16}$</td>
<td>17</td>
</tr>
<tr>
<td>World</td>
<td>$4.1 \times 10^{17}$</td>
<td>13</td>
</tr>
</tbody>
</table>

Source: World Bank.¹

<table>
<thead>
<tr>
<th>Coal</th>
<th>Hydroelectric</th>
<th>Natural gas</th>
<th>Nuclear</th>
<th>Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>53</td>
<td>6</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Brazil</td>
<td>3</td>
<td>87</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>India</td>
<td>71</td>
<td>13</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>Japan</td>
<td>22</td>
<td>8</td>
<td>23</td>
<td>31</td>
</tr>
<tr>
<td>World</td>
<td>39</td>
<td>17</td>
<td>18</td>
<td>17</td>
</tr>
</tbody>
</table>

Source: World Bank.¹
industrial production. However, not all electricity production is subject to the second law of thermodynamics. As we will see shortly, hydroelectric electricity production uses solar energy through the water cycle, which does not require conversion of heat to electricity and thus is not subject to the second law’s restrictions. Other forms of solar energy discussed shortly, such as wind energy and photovoltaic power, are not passing through a heat-to-electricity stage and thus are not subject to the thermodynamics restrictions. Presently, the contributions of wind and photovoltaic energy to the global electricity production are below 1%.

Aside from nuclear power, the alternative energy sources that play a significant role in the global energy options are, in one form or another, old sources of energy in use well before the Industrial Revolution and the subsequent discovery of fossil fuels. Nuclear power, in principle, can provide a global alternative to fossil fuels. However I will show it has very serious problems that must be overcome before we can put our global trust in it. There are many other options to utilize alternative energy sources currently in various stages of research, manufacturing, and penetration into the energy markets. Most of the new methods involve the use of solar energy, whereas two of them—geothermal power and tidal power—do not.

Table 11.4 lists the share of the main alternative energy sources in the mix. Excellent technical reviews of alternative energy sources can be found in the notes.²

Table 11.4.
Share of energy from renewable energy sources in 1997

<table>
<thead>
<tr>
<th></th>
<th>Renewables in total energy consumption (%)</th>
<th>Biofuels in renewable sources (%)</th>
<th>Hydroelectric in renewable sources (%)</th>
<th>Geothermal in renewable sources (%)</th>
<th>Direct solar in renewable sources (%)</th>
<th>Wind in renewable sources (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>14</td>
<td>80</td>
<td>16</td>
<td>2.8</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Developed countries</td>
<td>6</td>
<td>54</td>
<td>39</td>
<td>6.4</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>Developing countries</td>
<td>25</td>
<td>89</td>
<td>9.5</td>
<td>1.6</td>
<td>0.01</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Source: International Energy Agency.³
Life-Cycle Assessment

Before we proceed with the various possible alternative energy sources, it is important to outline the method now in use to address whether we are doing any good. In terms of environmental impact, are we putting more stresses on the environment by substituting for the fossil fuels as compared to the stresses using present technology? Life-cycle assessment (LCA) is rapidly becoming the dominant approach to assess environmental stresses with a global effort to create a life-cycle inventory (LCI) that can function as a global library for best practices. The analysis involves a cradle-to-grave assessment of environmental impacts including non-renewable resource depletion, greenhouse effect, air acidification, eutrophication (overfeeding of aquatic environments), human toxicity, and waste generation. The analysis follows the international standard International Organization for Standardization (ISO) 14000. Cradle-to-grave means it includes production, use, and disposal. As we will see shortly, the analysis is still a work in progress mainly because of the intricate interdependence of systems requiring often contentious boundary specification. In terms of alternative energy sources, the two most important impacts that should come out of the analysis are whether one produces more energy than one consumes and whether the CO₂ emission resulting from using the alternative energy is smaller than that emitted using an equivalent amount of energy from conventional sources. A third consideration, considerably important for nuclear energy, explores whether a new set of stresses, specific to the alternative energy, have a worse impact than the ones we try to remediate. The ongoing global research effort to develop alternative energy sources focuses on efficiency and price. Progress in LCA will redirect some of this effort to minimize adverse environmental impact. Because LCA evaluation requires detailed technical accounting of production, use, and disposal, it may be an effective tool for optimizing the various stages of the life cycle and thus also contribute to efficiency and cost. In the United States the government laboratory in charge of the development of alternative energy resources, the National Renewable Energy Laboratory (NREL), has a special section responsible for calculating the LCA of energy systems. Development efforts obviously change the LCA, so an effort to estimate dynamic LCA is given in Martin Pehnt’s paper.

Detailed accounts of LCA efforts for various energy systems will require a separate book that most likely will be obsolete by the time it is finished. The only current, controversial issue with serious policy implications is biomass use.

I will now proceed to describe the various forms of alternative energy sources.
Solar Energy

Solar energy is our most important primary energy source. We convert it in a variety of ways to energy used to fuel humans’ various needs. Solar energy is the primary energy for all the energy sources enumerated in Tables 11.2 and 11.3, except for nuclear energy. In the case of fossil fuels, the conversion took place long before humans appeared on Earth. Wood can be considered renewable and possibly sustainable if we plant new trees. Hydropower is used to create electricity, whereas the use of wood is usually confined to domestic use, such as cooking and boiling water. These two power sources will be discussed next.

Biomass

Biomass consists of food crops such as sugar cane, maize stalks, straw, and fiber crops that mainly consist of forest products such as firewood and charcoal. Wood is perhaps the oldest energy source. Until the Industrial Revolution and the subsequent discovery of fossil fuels to power various engines, wood was used for power generation since the discovery of fire. Many parts of the developing world still use wood this way. As we can see in Table 11.2, biomass in the form of wood and agricultural products still provides about 11% of the world’s energy supply. However, the geographic distribution of the use of wood as an energy source is very uneven—developed countries (United States and Japan) are hardly using any (with noticeable exceptions such as the Scandinavian countries), whereas the developing countries, represented by India, use it to satisfy a very significant fraction of their energy needs. Some African countries such as the Democratic Republic of the Congo, Eritrea, Ethiopia, Mozambique, and Tanzania use it to satisfy more than 60% of their energy needs. Most of the wood comes from forests. Globally, more than 50% of roundwood production is targeted for energy use; the rest is used for paper production and construction. The designation of wood as a renewable energy source is problematic. The ancient practice of going to the forest and chopping the wood without worrying what happens to the forest is still widely used in different parts of the world. In that sense it is not much different from using fossil fuels—as we burn the wood, we emit the same carbon dioxide that we emit by burning of fossil fuels. The issue here is accounting. Going back to Chapter 4 and Figures 4.1–4.2, where I enumerate the anthropogenic contributions to the carbon fluxes, we see 7.2 Gt-C/year are emitted by burning fossil fuel and 1.6 Gt-C/year are emitted through deforestation and other changes in land use. If we count wood burning in the same category as fossil-fuel burning, then we will be counting it twice. In principle, when we cut a tree and burn it, we are canceling the sequestration done by the tree throughout its lifetime. If we restore the forest, then the wood burning is truly a sustainable use of solar energy; if we do not, then it is not. Table 11.4 shows the situation in terms of changes in the global forest coverage in the four countries we follow throughout this chapter.
In addition to these four countries, Africa, with 17% of world forests, is losing coverage at a rate of 0.8%/year, South America with 23% of world forest coverage is losing at a rate of 0.4%/year, and Indonesia with 2.7% of world forests is losing its forests at a rate of 1.2%/year.

A fascinating, if somewhat controversial, book that enumerates the collapse of civilizations due to uncontrolled cutting of forest areas to supply energy and agricultural needs with no attempt to restore the forest is *Collapse* by Jared Diamond. One serious attempt to reduce deforestation for commercial use is to certify the forest area needed for the manufacture of the commercial products is used in a sustainable way. One credible certification program is run by the Forest Stewardship Council (FSC). However, less than 4% of world’s forest areas are certified.

**Ethanol**

This is probably the preferred biomass product used in the developed countries. Ethanol is the same alcohol we consume at parties. It is mostly produced for energy use by fermenting and distilling starch products. In the United States the main source is corn, and in Brazil it is sugar cane. It is used in the United States as additive to gasoline claimed to enhance the gasoline quality and reduce pollution. It is considered a sustainable fuel source because the corn (or the sugar cane) is replanted annually. There is a long-standing argument as to the energy audit of ethanol. Some claim that if you count all the energy needed to produce ethanol, then you exceed the energy content of ethanol, whereas others argue that about 30% is a net gain and thus it qualifies as an energy source. The political aspect of ethanol production is convoluted with thorny issues such as agricultural subsidies, energy security, and so on. The technique used to investigate such an issue is the LCA. Table 11.6, with data taken from a review by Harro von Blottnitz et al. summarizes the findings. The main conclusions out of this analysis are the following:

<table>
<thead>
<tr>
<th>Country</th>
<th>Total forest area (square miles)</th>
<th>Annual change 1990–2000 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>873,000</td>
<td>0.2</td>
</tr>
<tr>
<td>Brazil</td>
<td>2,100,000</td>
<td>−0.4</td>
</tr>
<tr>
<td>India</td>
<td>247,500</td>
<td>0.1</td>
</tr>
<tr>
<td>Japan</td>
<td>92,977</td>
<td>0</td>
</tr>
<tr>
<td>World</td>
<td>14,940,000</td>
<td>−0.2</td>
</tr>
</tbody>
</table>

*Source: UN Environment Programme.*
1. Make ethanol from sugar crops in tropical countries, but be careful in use of agricultural land because you are competing with food production and you are substituting crops so the CO$_2$ sequestration by the substituted crop need to be subtracted.

2. Further develop hydrolysis and fermentation of lignocellulosic residues (which include agricultural residues such as corn stover and bagasse [shown in Table 11.6], wood residues, and municipal paper waste) to ethanol.

3. Devote more research to the LCA results of grasses.

By some estimates ethanol production can substitute for significant fraction of current gasoline use (up to 30%). However, coupling energy production with food production is a problematic issue. Energy is a global commodity with approximately equal unsubsidized prices across the world. Poor countries do not have the purchasing power to fulfill their energy needs. They can find substitutes for fuels (which are not necessarily sustainable). If one allows food prices and energy prices to converge, then poor countries will suffer. Thus granting agencies emphasize research on ethanol production from waste material and weeds that do not compete with food production.

Other biomass-derived energy sources include biodiesel, a mixture of vegetable oil, animal fat, and other greasy products with diesel oil. Many cars are now designed to accommodate these kinds of brews.

One promising source for biofuel that does not compete with food production is derived from photosynthetic algae. Algae can grow at a high density with high yield for solar induced sequestration of carbon dioxides to yield a variety of oils that can be distilled for various applications.

### Table 11.6.

Bioenergy yield to fossil energy input ratios for bioethanol systems

<table>
<thead>
<tr>
<th>Biomass Source</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarcane (Brazil)</td>
<td>7.9</td>
</tr>
<tr>
<td>Sugar beet (Great Britain)</td>
<td>2.0</td>
</tr>
<tr>
<td>Corn (United States)</td>
<td>1.3</td>
</tr>
<tr>
<td>Molasses (India)</td>
<td>48</td>
</tr>
<tr>
<td>Molasses (South Africa)</td>
<td>1.1</td>
</tr>
<tr>
<td>Corn stover (United States)</td>
<td>5.2</td>
</tr>
<tr>
<td>Wheat straw (Great Britain)</td>
<td>5.2</td>
</tr>
<tr>
<td>Bagasse (India)</td>
<td>32</td>
</tr>
</tbody>
</table>

*Source: von Blottnitz et al. (2007).*
Hydropower

The primary source of energy that produces hydropower is the sun. In Chapter 7 we saw that about 70% of the solar energy that falls on Earth is falling on the oceans and this drives the water cycle in which water evaporates to form clouds that condense on land to form rain or snow that eventually flows back to the oceans. Some of this backflow comes through rivers flowing from high areas to low-lying areas. From an energy balance point of view, the sun provides the energy for water molecules to dissociate themselves from the binding forces of other water molecules in the liquid and provides the energy for these water molecules to move against the gravitational force of Earth to form clouds. We get this energy back when the water condenses in the clouds and responds to the gravitational forces to end up in as low an energy state as possible—at the end of the cycle, it is back in the ocean. We can directly intercept and convert some of this energy to electrical energy with waterfalls and dams. In both cases the force of the falling waterfalls against turbine blades causes the turbine to spin.

Efficiencies can be as high as 90%. Box 11.2 demonstrates quantitatively how much energy we can get from a waterfall.

Figure 11.2. Niagara Falls

Source: US Environmental Protection Agency (2009).
**Box 11.2**

**THE NIAGARA WATERFALLS**

**How Much Energy Can We Get from a Waterfall?**

Niagara Falls is the majestic falls on the Niagara River that connects Lake Erie with Lake Ontario on the border between Canada and the United States (Fig. 11.2). Within the continental United States, it is probably the most famous attraction for honeymooners that from the sight draw its energy for a lifetime of happiness. The falls provide a much more earthly form of energy used by both Canada and the United States to generate about 4 billion Watts of electric power. The falls consist of two cataracts: The Canadian falls (Horseshoe Falls) on the Canadian side of the river and the American Falls on the American side. The height of the Canadian falls is approximately 57 m (188 ft.) and that of the American Falls is about 55 m (181 ft.). These are gross heights that do not consider rock formations and other obstacles. The volume of water that flows through a cross section of the river is approximately 5520 m$^3$/sec (1 m$^3$ = 265 US gallons). About 50 years ago, the US and Canadian governments came to a landmark agreement to share this potential energy to generate electricity and still guarantee honeymooners and other tourists can enjoy the sight. In this agreement 2830 m$^3$ of water must fall over the falls during the tourist season during day time and about 1400 m$^3$ must fall during the night and off season. The remaining water should be equally divided between the two countries. The US government is diverting up to 1400 m$^3$ to a storage pool above the falls from which they derive power by letting it flow to power turbines below the falls.

The potential energy of this water flow (Chapter 5) is the weight × height. The energy units we want to get is in joules. If we want to get the energy in this unit, then we must use the other quantities in the same set of units: height in meters and weight in Newtons (N; see appendix 1 for conversion).

Therefore, 1 m$^3$ of water weighs 9800 N, so the potential energy of the water falling through the American Falls per unit time is

\[
1400 \times 9800 \times 56 = 0.8 \text{ billion J/sec},
\]

where 1 J/sec = 1 W of power.

This 0.8 billion W is considerably less than the generating capacity of power stations that can generate up to 2 billion W power. However, the water can also store power. Electric power, once generated, must be used immediately. However, there are big differences in
power use during peak consumption and during off-peak consumption, such as at night. When there is low demand, power can be used to lift the water from below the falls level to the storage pool above the falls for use when needed.

Wind

Winds are air movements resulting from uneven heating of the atmosphere by the sun. The direction and intensity of winds are directly influenced by the rotation of Earth and by the landscape. The kinetic energy of wind can be harnessed to drive an electric turbine in a similar way to the water turbine previously discussed. Probably the oldest known windmills can be found in ancient Persia (now Iran), dating from as early as the 7th century AD. More familiar to many of us are the ones found in Spain and Holland. These windmills did not produce electricity; they were mainly for milling grains and irrigation (Fig. 11.3). Today one is more likely to see landscapes with electricity-producing wind turbines such as the ones in Figure 11.4.

Figure 11.3. Reconstructed windmills near Consuegra, Castilla-La Mancha, Spain
Their use is increasing and there are still many untapped sites that can accommodate them.

**Photovoltaic Solar Cells**

Table 11.4 shows that solar cells currently contribute approximately the same amount of power to global energy use as does wind. The entry includes contributions from both photovoltaic solar cells and photothermal solar cells. The difference is that photovoltaic cells convert

<table>
<thead>
<tr>
<th>Year</th>
<th>Shipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>8363</td>
</tr>
<tr>
<td>1996</td>
<td>13,016</td>
</tr>
<tr>
<td>1998</td>
<td>15,069</td>
</tr>
<tr>
<td>2000</td>
<td>19,839</td>
</tr>
<tr>
<td>2002</td>
<td>45,313</td>
</tr>
</tbody>
</table>

*Source: US Energy Information Administration.*

**Figure 11.4.** Wind-turbine farm near Zaragoza, Spain
sunlight directly into electricity, whereas photothermal devices use a heat absorber to heat water used to drive a generator to produce the electric power.

**Ocean Thermals**

Oceans cover about 70% of the surface of Earth. Ocean thermal schemes are known by ocean thermal energy conversion (OTEC). The principle is simple—the average ocean surface temperature is about 25°C, which is sustained by solar irradiation, evaporative cooling, winds, and ocean currents. At a depth of about 1000 m, there is almost no direct solar input, and the temperature is a remarkably steady 5°C. While discussing energy in Chapter 5, we saw that whenever we have two heat reservoirs at different temperatures, one can convert some of the heat energy into work in the form of electricity. Almost all electrical generators work this way. The limiting efficiency for such a process is known as the Carnot efficiency (equation 5.5). If we know the ocean surface's high temperature and the deep ocean's lower temperature, then we will get a limiting efficiency of around 6.7%. This is a low conversion efficiency, and the construction costs of such a facility are high. Presently there are no commercial plants that operate on this principle.

**Wave Power**

Ocean waves are caused by wind as it flows across the sea. One can put an air chamber in the ocean, in which the oscillating motion of the waves induces water in the chamber to rise and fall, causing the air in the chamber to gain mechanical energy to drive an electric turbine. The Wavegen company operates a 500 kW facility off the Scottish coast that works on this principle.

**Nuclear Energy**

I will concentrate on the peaceful use of nuclear energy, in contrast to its military use in the form of nuclear weapons. As we will see shortly and in subsequent chapters, one cannot completely separate the two. If it was possible, nuclear energy would be playing a much more important role as an energy source. Currently, the peaceful use of nuclear energy is primarily in electric power generation and in the powering of large transportation systems, such as ships and submarines (some of them peaceful and some of them less so). For electrical power generation, nuclear energy is first converted into heat, most often in the form of steam, and the heat is used to drive a turbine that drives the generator. So in its simplest manifestation, the
use of nuclear energy as an alternative to fossil fuels boils down to a controlled use of nuclear power to boil water.

In the United States, after World War II, the control of nuclear power shifted from military to civilian authorities, with the stated intention of shifting the emphasis from military to civilian use—that is, from an instantaneous release of power to a controlled release of power. As we can easily see in Table 11.3, this shift was not very difficult for nuclear fission but is much more difficult for the more promising nuclear fusion. The meaning of “control” and the principles of the fission and fusion reactions, and their relation to Figure 11.1, are explained in Box 11.3.

Fission

The most important chemical elements that can undergo fission reactions are uranium and plutonium. The first is a natural element, whereas the second one is man-made. However, we need to revisit the discussion we had in Chapter 3 on the nature of isotopes. The atomic number of uranium (see the periodic table in Appendix 2) is 92. This means that uranium nuclei have 92 protons. Most natural uranium (more than 99%) has nuclei with 146 neutrons. We designate this isotope as $^{238}_{92}$U, where 92 stands for the number of protons (atomic number) and the 238 stands for the sum of the numbers of protons and neutrons (mass number). This isotope is not fissile. Around 0.7% of natural uranium consists of an isotope with 3 fewer neutrons: $^{235}_{92}$U. This isotope is fissile. Another fissile isotope of uranium now targeted for use in a relatively new design of nuclear reactor is $^{233}_{92}$U. The fissionable nucleus absorbs a neutron, and as a result, it splits into two lighter elements, more than one neutron, and a large quantity of released energy. The released neutrons can continue the process in a chain reaction described in Box 11.3. The control of the process means the control of the chain reaction. The chain reaction is sustained as long as the number of absorbed neutrons in a subsequent reaction is larger than in the preceding reaction. If we allow too many neutrons to escape, then we cannot sustain the reaction because of a shortage of neutrons, and if we do not have enough fissionable material, then the reaction will stop because of shortage of absorbers. Most of the fission products are unstable isotopes that further decay at various rates through emission of radioactive radiation. About 80% of the energy released in the fission reaction is heat; the rest is associated with the radiation. In a nuclear bomb the chain reaction is sustained by achieving a critical mass of fissionable material. In the case of a uranium bomb, this mass is about 10 kg. One achieves the criticality by a rapid joining of subcritical parts. In nuclear reactors the control is achieved through the use of control rods made of materials that capture the neutrons more efficiently than the fissionable material. Such materials are cadmium and boron. When the reactor is on, the control rods are out, ensuring that enough neutrons are available for the
sustained chain reaction, and when we want the reaction to stop, we insert the rods to decrease the number of neutrons below the level needed to sustain the chain reaction.

The typical yield of a fission reaction is 0.1%. This means that about 0.1% of the starting mass is converted to energy. If we take our typical 10 kg atomic bomb and assume it is made of pure U-235 and that all the uranium undergoes fission, then the amount of energy liberated can be calculated by using Einstein’s formula (equation 11.1; Chapter 5). Using the formula yields $E = 0.001 \times (10 \text{ kg}) \times (3 \times 10^8 \text{ m/sec})^2 = 9 \times 10^{13} \text{ J}$. This is approximately equal to the destructive power of 20,000 tons of conventional explosives.

**Fusion**

The energy yield of fusion reactions is approximately 0.4%–0.7%. The key to the ignition of a fusion reaction is very high temperatures: 20,000,000°C–100,000,000°C.

---

### Box 11.3

**Chain Reactions**

In many aspects this box is a continuation of Box 11.1. In Figure 11.1 we saw that the nuclei of heavy elements such as uranium are not very stable and given the opportunity they tend to split their nuclei to form lighter elements whose nuclei are more stable, releasing large amount of energy in the process:

\[
\begin{align*}
{^{141}\text{La}}_{35} + {^{90}\text{Br}}_{35} + 3{^0\text{n}} + \text{energy} \\
{^{235}\text{U}}_{92} + {^0\text{n}} & \quad \rightarrow \quad {^{141}\text{Ba}}_{56} + {^{92}\text{Kr}}_{36} + 3{^0\text{n}} + \text{energy} \\
{^{137}\text{I}}_{53} + {^{97}\text{Y}}_{39} + 2{^0\text{n}} + \text{energy}
\end{align*}
\]

Equation 11.3 shows three different possible splits. The elements produced here are lanthanum, bromine, barium, krypton, iodine, and yttrium. In addition to these elements, in each of these reactions, more neutrons are produced than are used in triggering the reaction.
Even in the sun, only the inner core reaches temperatures as high as this and so only there can fusion reactions take place. The temperatures are so high that the electrons of atoms are stripped away, forming what is called the fourth state of matter (after solid, liquid, and gas): plasma. The most stable materials on Earth liquefy at 4000°C and vaporize at 6000°C. At such high temperatures the atoms move so fast they can overcome the repulsive electrical forces that originate from the loss of the surrounding electrons, and they fuse. Once they fuse, their binding energy moves from left to right in Figure 11.1, and as a result they liberate a great deal of energy. Reaction 11.2 shows a simple example of such a collision that takes place in the sun and most other stars: four hydrogen atoms collide to produce helium. However, the chance of four atoms colliding is small, so it takes very high temperatures and very high concentrations of hydrogen for such a reaction to take place.

Another reaction that produces fusion, but requiring only two atoms to collide, is the deuterium–tritium reaction:

\[ _1^2 \text{H} + _1^3 \text{H} \rightarrow _2^4 \text{He} + _0^1 \text{n} + \text{energy.} \]  

This reaction is between two less-common isotopes of hydrogen: deuterium with one neutron (mass number 2) and tritium with two neutrons (mass number 3). Whereas hydrogen atoms are available in almost infinite amounts in the water of the oceans, deuterium is present in much lower concentrations (about 1 deuterium atom for every 6000 atoms of hydrogen). Tritium cannot be extracted but rather must be synthesized. The most common procedure is to make it from lithium using the following reaction:

\[ _3^6 \text{Li} + _0^1 \text{n} \rightarrow _2^4 \text{He} + _1^3 \text{H} + \text{energy.} \]

The supply of lithium is much more limited than that of deuterium. An alternative to this approach is to use only deuterium in what is known as the deuterium–deuterium reaction:

\[ _1^2 \text{H} + _1^2 \text{H} \rightarrow _2^3 \text{He} + _0^1 \text{n} + \text{energy.} \]

The availability of deuterium is not a problem here, but the ignition temperature in this case is considerably higher than for the deuterium–tritium reaction.

**Sustainability**

Sustainability also comes into play when we discuss nuclear energy. Like fossil fuels, nuclear energy, in a sense, is a stored energy—in this case storage is in the binding energy of the particular nucleus. One must discuss the availability of the element used to store the energy and the feasibility of retrieving this energy. In the case of fission energy retrieved from U-235, the issue is the availability of U-235. The supply of U-235, in terms of stored energy, does not exceed the
available supply of fossil fuels. A new, experimental, nuclear reactor called a breeder reactor operates on a different principle—it converts the much more abundant U-238 into the fissionable artificial element plutonium (hence it breeds the fissionable plutonium) by exposing the uranium to fast neutrons generated through fission of U-235. A different design—not yet commercially available—is the liquid-fuel thorium (Th) reactor in which Th-232 is converted to U-233. Thorium is more common than uranium, and this reactor is not expected to have the problems of waste and weapon conversion that uranium reactors suffer from.\textsuperscript{11}

As for fusion, the deuterium–deuterium reaction (11.6) does not pose a problem because the energy content in the available deuterium is so large. The much-easier-to-ignite deuterium–tritium reaction (11.4) is limited in usefulness by the amount of available lithium (equation 11.5) needed to produce the tritium.

\textit{Problems and Issues}

Table 11.3 shows that nuclear energy is playing an important role in the distribution of energy sources from which we derive our energy. Because it does not change the composition of the atmosphere, is it a desired solution to all our problems? Not exactly! Here again the old saying is valid—“If it seems too good to be true it probably is.” All our commercial nuclear power plants are fission reactors. The first ones were built in the Soviet Union and the United States in the 1950s. In the United States, 50 operating licenses were issued in the 1980–1990 period, whereas none were issued after 1996. Only 17 new applications were received since 2007. China is now considered the fastest growing nuclear industry, with the first operating reactor (Qinshan 1) operational since 1991. Eight new reactors entered commercial service in the period 2000–2005, with a target of two nuclear reactors per year for the next 17 years. So the 30\% of nonfossil energy in the United States shown in Table 11.3 comes from reactors about 20–50 years old. The trend in the rest of the world depends strongly on individual countries and is not as sharp as in the United States but is similar in its direction. Specifically, penetration of nuclear energy into developing countries is now accelerating as their economic development accelerates and with it the need for dependable energy sources. What were the causes for the inactivity in the United States and most other developed economies? It starts with simple economics to be addressed in the next chapter. Nuclear power plants are big: a typical size is 1000 MW of electrical production. Their costs are considerably higher than fossil fuel–based, traditional plants. In the 1970s the higher costs were justified by fast-increasing oil prices. In the period 1970–1985, the construction costs of nuclear power plants have increased by close to a factor of three in inflation-adjusted dollars, whereas the price of oil has decreased by almost the same ratio.
In addition, nuclear accidents such as the Three Mile Island disaster in the United States in 1979 and at Chernobyl in the Ukraine in 1986 did not endear the concept to the general public. About 50 years after the introduction of the first commercial nuclear power plants, no permanent solution exists to the problem of disposal of the highly radioactive nuclear waste, a by-product of these reactors. Discussions and plans are abundant, but agreed-on and functional solutions are in short supply.

Inspection of Table 11.3 reveals that currently nuclear power makes a significant contribution to the energy mix only in developed countries such as the United States and Japan. This situation is changing fast but not smoothly. The numbers for some European countries such as France are even higher. The contribution to the energy mix in developing countries is almost negligible. Economics plays an important part; trust is also very important. One cannot easily separate the stated intentions of a country to acquire or produce fissionable materials for energy use from the unstated plans to acquire nuclear weapons. Any activity by a country that does not belong to the relatively small club of countries that international treaties recognize as allowed to possess nuclear weapons raises suspicions of nuclear proliferation.

The situation is very different as to the use of fusion energy to generate electricity—we do not yet know how to do it. There is active research in this area with major expenditures by developed countries and international consortia. The potential payoff is great—if we achieve success via the more difficult deuterium–deuterium scheme, then we will never run out of the fuel source and there will be no spillover to destructive weapons applications, as well as no major problem associated with nuclear waste. It is easy to idealize solutions not put to test but within the two generations of our target transition time, the prospects are reasonably good.

**Other Alternative Energy Sources**

The incomplete list of alternative sources includes the following.

**Geothermal Energy**

In spite of the fact that Earth’s core is hot because of gravitational pressure and radioactive decay, very little of this heat permeates through Earth’s crust to reach the surface. We cannot yet penetrate the crust and generate heat from the mantle, but the heat can penetrate through cracks in the crust to form, in some locations, underground reservoirs of steam, hot water, and hot, dry rocks. If such reservoirs are accessible, then it is relatively simple to tap this energy and convert it into electricity using technology similar to the steam generators previously discussed. Currently, most of the appropriate sites for easy access are already in use, so the prospects for expansion are limited.
Lunar and solar tides were discussed in Chapter 8. Everywhere along the coastline, the differential gravitation attraction of land and water produces displacements that cause two daily high tides and low tides. One can capture this energy by retaining the water of high tide behind a dam and releasing the water during low tide in a way similar to a hydroelectric power facility. The required dams are much bigger than typical dams. A handful of tidal power stations around the world operate on a commercial basis. The best known (and probably the oldest) is on the Rance River in France. The facility went into operation in 1966 with a capacity of 240 MW. The difference between high and low tides there is about 8 m.

**Carbon Sequestration**

The complexities of the issues we are discussing here require that I appear to contradict myself from time to time. This is such an occasion. I have been showing repeatedly throughout this book that burning fossil fuels causes emission of carbon dioxide that results in chemical changes in the atmosphere, leading to the disruption of the atmospheric energy balance and climate change. Here I will show that the emitted carbon dioxide can be captured and stored in a way that prevents it from entering the atmosphere, and thus in principle, we can separate the energy use from its climate-altering consequences.

Such a possibility is particularly attractive when looking at the future use of coal. In the last chapter we saw that the world's coal reserves far exceed the reserves of oil and natural gas. Equally important, large coal reserves are located in the most populous countries, such as India, China, and the United States. Development of environmentally acceptable technologies for coal use would help these countries satisfy both energy security and the development of environmentally benign energy sources—an issue that will be further discussed in Chapter 14.

The removal of carbon dioxide from a gas flue or the air is not new. Such technology facilitates activities that require long underwater stay, such as scuba diving or submarine operations, and it is also required in the cleaning of natural gas pipelines. One of the most promising technologies currently used in commercial and pilot applications is passing the burned fuel through a water solution of a special class of compounds called amines. The amines are derivatives of ammonia. The formula of ammonia is \( \text{NH}_3 \): three hydrogen atoms bonded to a nitrogen atom. If we replace some of the hydrogen atoms with hydrocarbon chains, then we get amines. If we pass carbon dioxide through a water solution of some of these amines, then the reaction takes the following form:

\[
\text{CO}_2 + \text{H}_2\text{O} + \text{R}_3\text{N} \leftrightarrow \text{R}_3\text{NH}^+ + \text{HCO}_3^-, \tag{11.7}
\]
where R represents symbolically the hydrocarbon chains. This equation represents a similar dissolution mechanism to the dissolution of carbon dioxide in the oceans discussed in Chapter 4. The positive and negative ions form salts that can be separated from the flue. After separation, the salt is heated to drive reaction 11.7 back to the left to capture carbon dioxide and prepare it for long-term storage. Carbon dioxide is stored in the long term either deep underground in stable geological formations or deep in the ocean where the high pressure and low temperature can keep the gas in a condensed, isolated form similar to the methane hydrates discussed in the last chapter.

Currently the process is expensive and requires energy. Commercially it is used in a few demonstration plants. However, active research aimed at finding cost-effective and energy-efficient alternatives is pursued all over the world.

Cost

Renewable energy technologies are characterized by relatively high capital costs and low operation and maintenance costs. When determining fuel sources to use in the construction of new generating plants, the levelized cost determines which technology and energy source will be most cost-effective. Levelized cost considers capital, fuel, and operating and maintenance costs. In levelized costing, capital costs are amortized over the expected power output for the life of the plant.

The biomass power cost comes mainly from the burning of waste and does not include any credit for waste disposal costs. Wind power seems attractive, but the intermittent nature of the source requires storage.

Table 11.8.
Cost of renewable energy generating technologies estimated for 2016

<table>
<thead>
<tr>
<th>Technology</th>
<th>Levelized cost (2008 US$/MBtu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>29.5</td>
</tr>
<tr>
<td>Natural gas</td>
<td>24.4</td>
</tr>
<tr>
<td>Nuclear</td>
<td>35.0</td>
</tr>
<tr>
<td>Biomass</td>
<td>32.6</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>35.3</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>75.6</td>
</tr>
<tr>
<td>Solar photovoltaic</td>
<td>116.5</td>
</tr>
<tr>
<td>Wind</td>
<td>43.9</td>
</tr>
</tbody>
</table>

Source: US Energy Information Administration.10
The numbers in Table 11.8 are encouraging. Environmental impact is not included in the cost analysis. In the long term, the price of fossil fuels will continue to increase, whereas the capital cost of some of the renewable technologies will decline as a result of expanded markets and better technologies.

**BACK TO THE FUTURE**

As was discussed at the end of Chapter 9, the predictions of the anthropogenic contributions to climate change are based on the predictions of our socioeconomic development. The IPAT (I for impact, P for population, A for affluence, and T for technology) equation (9.1) captures these developments as population, gross domestic product (GDP), and terms relating to energy use. In Chapter 9 I addressed the issue whether, even in principle, we have a chance to avert a global disaster. In order to accomplish this I took two of the scenarios from the Special Report on Emission Scenarios (SRES) compilation—one that represents the business-as-usual scenario and the other a friendlier (to the environment) scenario—and superimposed these scenarios on recent changes in socioeconomic activities. In Chapter 9 we saw the results in terms of projected growth of population, GDP, and emissions. The main conclusions from the data from Chapter 9 were that until about 2020, it is almost irrelevant which scenario we follow—they all lead to about the same increase in CO₂ concentrations. The difference will materialize after 2020—approximate stabilization following the environmentally friendly B1 scenario and continuation of growth at an alarming rate for the business-as-usual A2 scenario. I have identified this bifurcation as the fork for our present decision making. The driving force for the bifurcation in Chapter 9 was population growth. I have also mentioned in Chapter 9 that the median United Nations future population estimates that have a credible accuracy record predict, mainly because of global trends for women's education and incorporation in the global workforce, the population dynamics will slowly follow a scenario very close to the B1 scenario. So we are in good shape? Not exactly.

Figure 11.5 shows there is no difference in the two scenarios in the projected energy use per person. However, because the A2 scenario predicts a population of 15 billion people at the end of the century whereas the B1 scenario predicts that the population will peak at around 8 billion in mid-century and then decline back to around 7 billion, there will be very large difference (by a factor of 2) in terms of total energy use.

Figure 11.6 predicts what kind of energy will be used. The business-as-usual A2 scenario predicts a slight improvement of use of nonfossil energy sources from about the present 15% to around 20%, whereas the B1 scenario predicts we will stabilize the atmospheric CO₂ concentrations through a reduction of the contribution of fossil fuels to about 50% or energy
Figure 11.5. Real and projected changes in global primary energy use per person (in units of billion joules per capita)

*Source: Tomkiewicz (2010).*

Figure 11.6. Real and projected changes in global use of nonfossil fuels

*Source: Tomkiewicz (2010).*
needs. This reduction in the contribution of fossil fuels to our energy mix, together with the projected reduction (scenario independent) in our energy intensity, will be enough to stabilize the atmospheric concentration of CO₂. Can we do this?

As was mentioned in the beginning of this chapter, the three components that dominate present nonfossil energy use are nuclear energy, hydroelectric energy, and the catch-all category the World Bank designates as combustible, renewable, and waste (CRW). The dominant users of CRW are underdeveloped countries that have neither fossil fuels nor the resources to import them. In its present form it is not a sustainable alternative to fossil fuels.

Figure 11.7 shows the history of the global use of nuclear energy and hydroelectric energy. The figure shows that the present annual growth rate of these energy sources is less than 2%. This slow growth for nuclear power followed a much more rapid growth for reasons discussed previously. This growth rate will not bring us to the required 50% reliance on nonfossil sources required under the B1 scenario.

Direct solar-energy conversion methods, such as wind power, photovoltaic, and photothermal, are emerging technologies presently buried within the noise in the global statistics of energy use (see Table 11.4). However, the statistics are based on past and present use. The future looks a bit brighter. Figure 11.8 shows the global accumulated installed capacity of wind

![Figure 11.7. Changes in global use of nuclear and hydroelectric energies (expressed in exajoules)](image)

Source: Tomkiewicz (2010).
turbines. We notice the scale on this figure—it is again a logarithmic scale (used before in Chapter 9). We need such a scale when things move fast. A straight line on such a scale indicates a constant growth rate. Analysis of Figure 11.8 indicates that starting in 1990 the growth rate is approximately constant at about 20% per year. A 20% growth rate means a doubling time of 3.5 years. Photovoltaic cells follow similar growth dynamics. Simple arithmetic shows that with this growth rate we can easily approach the B1 scenario and stabilize the atmosphere. The obstacles for these scenarios will be explored in the next two chapters.

Figure 11.8. Changes in global accumulated installed capacity of wind turbines

Source: Tomkiewicz (2010).