CHAPTER 1

ALTERNATIVE SOURCES OF ENERGY

1.1 INTRODUCTION

Since humankind's beginning, the ability to harvest and convert energy has been a means of survival. However, this has never been as evident as in recent years. When the industrial revolution in Europe caused an evolution of society and areas of larger population density, people realized that factors such as comfortable housing and energy could be important to the development of a country. Fossil fuels became essential products of a modern society, and new strategies were developed to guarantee their uninterrupted supply.

Since then, our population has grown—and so has its demands for industrial goods. On a planet of unaltered size and resources, this has had predictable consequences. Bloody wars, new frontiers, international agreements, and optimized use of resources are a few of the results. With the exhaustion of the planet's energy resources, the continuation of such effects can easily be foreseen.

Long ago, the need to generate large amounts of electrical energy and the realization that larger power plants were more efficient than smaller ones encouraged the construction of huge power plants. Examples include Itaipu Binational in Brazil, Guri in Venezuela, Sayano-Shushensk in Russia, and Churchill Falls in Canada. A more recent example is the plan for construction of the largest

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(18 GW) hydropower plant in China, Three Gorges Dam. However, some of these areas are affected by immense floods, massive power transmission lines and towers, air pollution, modified waterways, devastated forests, large population densities, and wars. Because of this trend in development, distances to energy sources are increasing, material capacities are reaching their limits, fossil reserves are being exhausted, and pollution is becoming widespread. New alternatives must be devised if humanity is to survive today and for centuries to come.

1.2 RENEWABLE SOURCES OF ENERGY

Earth receives solar energy as radiation from the sun, and it receives it in a quantity that far exceeds humankind's use. By heating the planet, the sun generates wind, rain, rivers, and waves. Along with rain and snow, sunlight is necessary for plants to grow. The organic matter that makes up plants is known as *biomass*, and biomass can be used to produce electricity, transportation fuel, and chemicals. Plant photosynthesis (essentially, chemical storage of solar energy) creates a range of biomass products, from wood fuel to rapeseed, that can be used for heat, electricity, and liquid fuels.

Hydrogen can also be extracted from many organic compounds, as can water. Hydrogen is the most abundant element on Earth, but it does not occur naturally in a gas. It always combines with other elements, such as with oxygen to make water. Once separated from another element, hydrogen can be burned as a fuel or converted into electricity.

The sun also powers the evapotranspiration cycle, which allows water to generate power in hydro schemes—the largest source of renewable electricity today. Interactions with the moon produce tidal flows, which can produce electricity.

Although humans have been tapping into renewable energy sources (such as solar, wind, biomass, geothermal, and water) for thousands of years, only a fraction of their technical and economic potential has been captured and exploited. Yet renewable energy offers safe, reliable, clean, local, and increasingly cost-effective alternatives for all our energy needs.

Research has made renewable energy more affordable today than it was 25 years ago. Wind energy has declined from 40 cents per kilowatthour (kwh) to less than 5 cents. Electricity from the sun through photovoltaics (which literally means "light electricity") has dropped from more than $1 per kilowatthour in 1980 to nearly 20 cents/kwh today. Ethanol fuel costs have plummeted from $4/gallon in the early 1980s to $1.20 today.

Renewable energy resource development will result in new jobs and less dependence on oil from foreign countries. According to the federal government, the United States spent $109 billion to import oil in 2000. If we fully develop self-renewing resources, we will keep the money at home to help our economy.

There are some drawbacks to renewable energy development. An example is solar thermal energy, in which solar rays are captured through collectors (often, huge mirrors). Solar thermal generation requires large tracts of land, and this affects natural habitat. The environment is also affected when buildings, roads, transmission lines, and transformers are built. In addition, a fluid often used for solar thermal generation is toxic, and spills can occur. Solar or photovoltaic cells are produced using the same technologies as those used to create silicon chips for computers, and this manufacturing process also uses toxic chemicals. In addition, toxic chemicals are used in batteries that store solar electricity through nights and on cloudy days. Manufacturing this equipment also has environmental effects. So even though the renewable power plant does not release air pollution or use fossil fuels, it still has an effect on the environment.

In addition, there are production problems. All the solar equipment production facilities in the world make only enough cells to produce about 350 MW of electricity, just enough for a city of 300,000 people. California alone needs about 55,000 MW of electricity on a sunny, hot summer day. Producing that electricity by solar means would be about four times more expensive than if it were produced in a natural gas–fired power plant.

Wind power, too, has its downside, involving primarily land use. For example, the average wind farm requires 17 acres to produce 1 MW of electricity (about enough electricity for 750 to 1000 homes). However, farmers and ranchers can use the land beneath wind turbines. Wind farms can cause erosion in desert areas, and they affect natural views because they tend to be located on or just below ridgelines. Bird deaths also result from collisions with wind turbines and wires. This is the subject of ongoing research. But ultimately, combined with energy efficiency, renewable energy can provide everything fossil fuels offer in terms of energy services: from heating and cooling to electricity, transportation, chemicals, illumination, and food drying.

Energy has always existed in one form or another. It can be transformed into other forms of energy, but it cannot be created or destroyed. For example, the energy in a flashlight's battery becomes light energy when the flashlight is turned on. Food, the most natural stored chemical energy, resides in fat tissues and cells as potential energy. When the body uses that stored energy to do work, it becomes kinetic energy. Telephones transform a voice into electrical energy variations, which flow over wires or are transmitted through air. Other telephones change this electrical energy into sound energy through speakers. Cars use stored chemical energy in fuel to move, and they change chemical energy into heat and kinetic energy. Toasters change electrical energy into heat and light energy. Computers, television sets, and DVD players change electrical energy into coordinated types of mechanical movement and image and sound energy to reproduce the ambient of life.

In all such transformations of energy, intermediary transformations are involved. For example, consider the case for a home computer. Electricity allows self-organization of the main processor, according to a preestablished program, to convert ventilator movement to the cooling process for the main processing unit and the motherboard. The alternating current (ac) source power is converted into integrated direct current (dc) power to feed peripheral plates. After many electromagnetic processes, the monitor produces a luminous energy on-screen. Many processes and intermediary sources are integrated into a simple computer. They produce heat, light, movement, and circulation of electrical current to make it an impressively organized machine. This diversity of energy forms is an example of the changes happening in power systems.

1.3 RENEWABLE ENERGY VERSUS ALTERNATIVE ENERGY

A renewable energy source cannot run out and causes so little damage to the environment that its use does not need to be restricted. No energy system based on mineral resources is renewable because, one day, the mineral deposits will be used up. This is true for fossil fuels and uranium. The debate about when a particular mineral resource will run out is irrelevant in this context. A renewable energy source is replenished continuously.

Renewable energy sources—solar, wind, biomass (under specific conditions), and tides—are based directly or indirectly on solar energy. Hydroelectric power is not necessarily a renewable energy source because large-scale projects can cause ecological damage and irreversible consequences. Geothermal heat is renewable but must be used cautiously to guard against irreversible ecological effects.

There is no shortage of renewable energy because it can be taken from the sun, wind, water, plants, and garbage to produce electricity and fuels. For example, the sunlight that falls on the United States in one day contains more than twice the energy the country normally consumes in a year. California has enough wind gusts to produce 11% of the world's wind electricity.

Clean energy sources can be harnessed to produce electricity and process heat, fuel, and valuable chemicals with less effect on the environment than fossil fuel would cause. Emissions from gasoline-fueled cars and factories and other facilities that burn oil affect the atmosphere through the greenhouse effect. About 81% of all U.S. greenhouse gases are carbon dioxide emissions from energy-related sources.

At the International Climate Convention in Kyoto (1997), it was agreed that the developed nations of the world must reduce their greenhouse gas emissions. The European Union (EU) committed to reducing emissions of carbon dioxide (CO_2) by 8% from 1990 levels by the year 2010. The United States was to reduce emissions by 6% and Japan by 7% (see Table 1.1). These agreements are laid down in the Kyoto Protocol and aim for a society that uses renewable energies, not fossil fuels.

It is understandable that the world worries about emissions because our environment is unable to absorb them all. Table 1.2 lists some renewable sources of energy and their approximate production, or absorption, of CO_2 per kilowatthour.

Because every source is more or less intensive in what it produces, special measures have to be considered when considering global energy solutions. These include availability, capability, extraction costs, emissions, and durability. Table 1.3 shows indicators of renewable energy technologies, and Table 1.4 illustrates the intensity and frequency characteristics of some renewable sources.

TABLE 1.1 Kyoto's Pledged Emission Reductions in Selected Countries

Country	Emission Reduction (%)
Australia	−8
Canada	+6
Croatia	+5
EU	+8
Hungary	+6
Iceland	−10
Japan	+6
New Zealand	0
Norway	−1
Poland	+6
Russian Federation	0
Switzerland	+8
Ukraine	0
United States	+7

Source: Depledge, J., 2000. Tracing the origins of the Kyoto Protocol: an article by article textual history, UNFCCC/TP/2000/2, UNFCCC, Bonn.

Ironically, the atomic energy industry seems to be profiting from concerns about greenhouse gases and global climate change. Nuclear energy does not emit greenhouse gases, but its waste is stored in long-lasting containers and thrown into the sea in underground caves. Nevertheless, in the developed northern hemisphere, nuclear energy has little political or social support. The United States has not built a single reactor since the accident at Harrisburg, Pennsylvania, in 1979. In addition, there are no moves toward expanding nuclear power generation in any European Union member state that already has nuclear power stations. On the contrary, there is support for reduction in and closure of their atomic programs. Eight Western European countries (Denmark, Iceland, Norway, Luxembourg, Ireland, Austria, Portugal, and Greece) have never had a nuclear energy program and have instead

TABLE 1.2 Emission of CO_2 per Kilowatthour by Renewable Sources of Energy

Renewable Source	Emissions of CO_2/kWh (g)
Waste incineration	600
Biogasifier	−3800
Biomass	−4000
Photovoltaic cells	120
Wind turbine	10
Hydraulic power station	25
Nuclear power station	55
Gas-fired power station	400
Coal-fired power station	1160

Source: Ref. [1].

TABLE 1.3 Indicators of Renewable Energy Technologies

Renewable Energy Technology	Volatility (Approx. Time Variation)	Resource Availability	Range of Generation Cost (EU cents/kWh)	Preferred Voltage Level of Grid Connection (kV)
Biogas	Year	High	5.18–26.34	1.30
Biomass	Year	High	2.87–9.46	1.30, except cofiring
Geothermal electricity	Year	Low: country-specific	3.34–6.49	10.110
Large hydro power				
Run-of-river power plants	Months	Low	2.53–16.37	220.380
Storage power plants	Months	Low	Not considered	220.380
Small hydro power	Months	High	2.69–24.93	10.30
Landfill gas	Year	Low	2.50–3.91	1.30
Sewage gas	Year	Medium	2.85–6.24	1.30
Photovoltaics	Days, hours, seconds	High	47.56–165.32	<1
Solar thermal electricity	Days, hours, seconds	Low:country-specific	12.48–66.97	1.30
Tidal	12 hours	High	Not considered	10.380
Wave	Weeks	High	9.38–45.16	10.380
Wind				
Onshore	Hours, minutes	Low:country-specific	4.63–10.80	30.380
Offshore	Hours, minutes	Low:country-specific	6.09–13.39	110.380

Source: Ref. [1].

favored the alternative programs of renewable energy (see Figure 1.1). Outside Europe, only China, South Korea, Japan, Taiwan, and South Africa aspire to expand the share of nuclear power generated in their countries.

Today, the atomic energy industry is targeting developing countries, and the Kyoto Protocol is paving the way. The protocol provides for the use of “flexible instruments,” which were introduced so that wealthy nations could achieve their emission reductions in other countries by paying royalties to compensate for pollution levels. One instrument is the Clean Development Mechanism (CDM). The CDM facilitates the financing of clean technologies (through investment in solar energy, wind turbines, hydroelectric power stations, and energy-saving

TABLE 1.4 Intensity and Frequency Characteristics of Renewable Sources

System	Major Periods	Major Variables	Power Relationship	Comment	Approximate Time Variation
Direct sunshine	24 h, 1 y	Solar beam radiance $G_b^*(\mathrm{W}/m^2)$, beam angle from vertical q_z	$P \propto G_b \cos\theta_z$; $P_{\max} \cong 1\,\mathrm{kW}/m^2$	Daytime only, highly fluctuating	Hours to seconds
Diffuse sunshine	24 h, 1 y	Cloud cover, perhaps air pollution	$P < \sim 300\,\mathrm{W}/m^2$	Significant energy, however	Day
Biofuels	1 y	Soil condition, solar radiation, water, plant species, wastes	Stored energy, $10\,\mathrm{MJ}/kg$	Many variations, linked to forestry and agriculture	Year
Wind	1 y	Wind speed u_0 nacelle height above ground z, height anemometer mast h	$P \propto u_0^3 \dfrac{u_z}{u_h} = \left(\dfrac{z}{h}\right)^b$	Highly fluctuating, $b \approx 0.15$	Minutes to hours for wind farms
Wave	1 y	Reservoir height H_s, wave period T	$P \propto H_s^2 T$	High power density $\approx 50\,\mathrm{kW}/m$ across wavefront	Week
Hydro	1 y	Reservoir height H, water volume flow rate	$P \propto HQ$	Established resource	Months
Tidal	12 h, 25 min	Tidal range R, contained area A, estuary length L, depth h	$P \propto R^2 A$	Enhanced tidal range if $L/\sqrt{h} \approx 36,000\,\mathrm{m}^{1/2}$	12 h
Geothermal	None	Temperature of aquifer or rock formation, hence temperature difference from ambient	$P \propto (\Delta T)^2$	Very few suitable locations for electricity generation	None

Source: Ref. [2].

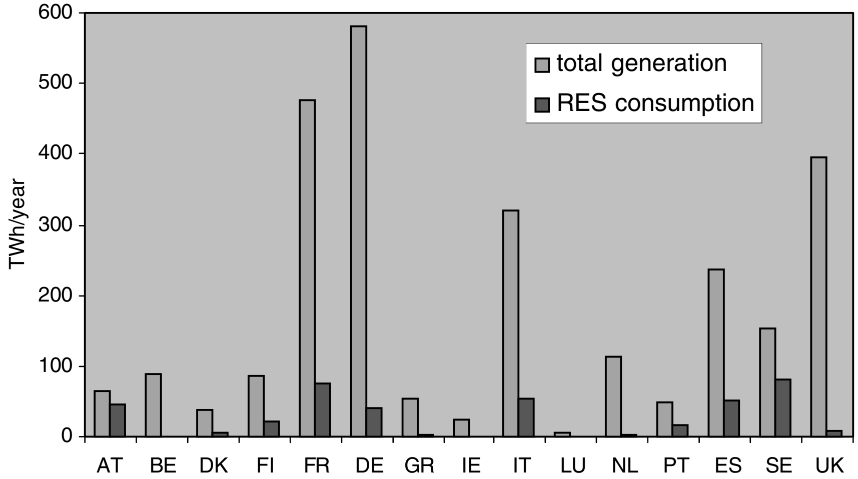

Figure 1.1 Electricity generation from renewable energy versus total electricity consumption in european countries, 2001. (From Ref. [2].)

technologies) and the transfer of these technologies from the northern to the southern hemisphere. Wealthy nations can use emission reductions achieved via the CDM to meet their Kyoto commitments, but the same cannot be said with respect to developing nations. Developing countries gain access to clean, endemic sources and compromise their future in much the same way as did the northern hemisphere. Is this the ideal win–win solution? The atomic energy industry claims that nuclear energy can be used as an effective solution in the struggle to prevent climate change.

From socioeconomic and environmental points of view, renewable energy increases supply security, has the lowest environmental effect of all energy sources, allows for local solutions, and offers sustainable energy development worldwide. Renewable energy also offers wider opportunities for investment, avoided fuel costs, CO_2 emissions savings, and new jobs. Generally speaking, renewable energy technologies are important because of the income that results from manufacturing, project development, servicing, and in the case of biomass, rural jobs and income diversification for farmers.

1.4 PLANNING AND DEVELOPMENT OF INTEGRATED ENERGY

Many studies show that the global wind resource technically recoverable is more than twice as much as the projection for the world's electricity demand in 2020. Similarly, theoretical solar energy potential (see Chapters 5 and 6 for solar thermal and solar photovoltaics, respectively) corresponds to almost 90,000,000 Mtoe (million tonne oil equivalent) per year, which is almost 10,000 times the world total primary energy supply [3]. The rapid deployment of renewable energy technologies, and their wider deployment in the near future, raise challenges and opportunities regarding their integration into energy supply systems.

The planning and development of integrated energy must consider the environment itself, the existence of energy sources, system needs, and local needs where it is desirable to install a renewable energy source. The capability of the grid supply, the electrical and mechanical behavior of the load, the distributed generation sources, and the effects on the regional economy define how successful the investment may be.

1.4.1 Grid-Supplied Electricity

The thickness, and hence cost, of conducting cables is inversely proportional to the voltage of power; therefore, high voltages are preferred for electricity supply along transmission and subtransmission lines. The practical limits relate to safety issues, especially sparking and insulation at high voltage. In practice, the voltage of long-distance transmission is 50 to 750 kV. Local area distribution is 6 to 50 kV, and supply to consumers is 100 to 500 V. Internally, in equipment, it is 3 to 48 V.

Grid electricity is converted from the primary source by:

- Moving wires in magnetic fields (Faraday effect)
- Photovoltaic generation with sunlight (photovoltaic effects)
- Chemical transformations as in fuel cells and batteries (electrochemical effects)

Transformation between transmission voltages is easiest and cheapest with alternating current (ac to ac). Transforming between direct currents (dc to dc) or between ac and dc is possible using electronic interfaces, which have become increasingly reliable and cheaper because of solid-state power electronics. Transmission with ac power has more loss per unit of distance than with dc power because of stray capacitances and inductances along lines, which increase current losses. Nevertheless, the ease of transformation means that the majority of power transmission is accomplished with high-voltage ac up to 350 km. The economic facilities of high-voltage dc transmission systems favor distances greater than 500 km.

To regulate power, voltage, speed, and frequency, each method depends on matching, instantaneously, load to generation. Generation is distinguished by its economic and physical ability to vary to match load. Examples are:

1. Base load generation (difficult or expensive to vary; e.g., nuclear power, large coal, and large biomass)
2. Peaking generation (easier to vary quickly but may be expensive; e.g., gas turbines and fuel cells)
3. Standby generation (easy to increase generation rapidly from off or idling modes; e.g., diesel, fuel cells, and gas turbines)

4. Intermittent generation (e.g., run-of-the-river hydro, wind, and most renewables, except biomass and geothermal)

Note that fuel cells can be used as peaking or standby generation; this depends on the availability of hydrogen or fuel gas and the maximum excess power that can be withdrawn from the cell without overly compromising its useful life. The same note is applied to reservoir hydropower, which may be either base (plenty of water) or peaking (limited water) load. Note also that intermittent does not mean unpredictable availability but guarantees that load always equals generation.

1.4.2 Load

It is important to realize that electricity users do not want electricity alone. They want a service, such as transportation (vertical or horizontal), lighting, water, welding, motor movement, communication, or warmth. The success of the electricity supply must be judged by the availability, quality, and cost of the service. The quality of a service (e.g., heating or water supply) tends to be measured by an intensive parameter (e.g., temperature or pressure) and the availability of that parameter. The cost of the service is measured by an extensive parameter (e.g., energy or kilowatthours) linked to its availability. The desire for the service presents a demand on the grid system, which power engineers see as load.

Ordinary consumers use the name of the service (e.g., television) for the function and never expect to use the word *load*. It is most efficient to use the word *demand* for the desire of consumers for service and the word *load* for the consequent electricity consumption. This subtle distinction is maintained in this book.

Satisfactory service can be maintained without the continuous consumption of electricity. For instance, water of a satisfactory temperature can be supplied from a previously heated tank. If the value of the intensive parameter is maintained (i.e., shower temperature), the consumer is satisfied even if electrical supply is interrupted. A demand that is satisfied by intermittent power is an *interruptible load*, also called a *switchable load*. If load and tariff management are used to optimize a power system (e.g., to increase the penetration of renewable energy), it is quite acceptable to use it to induce new trends in energy use.

1.4.3 Distributed Generation

Distributed generation (DG) is the application of small generators, typically 1 to 10 MW, scattered throughout a system to provide electrical energy closer to consumers. Current DG power sources include hydropower, wind, photovoltaics, diesel, fuel cells, and gas turbines. Renewable and other generators located downstream in a distribution network and involving small, modular electricity generation units close to the point of consumption are defined in this book as DG.

In this section we provide a qualitative analysis of the issues that drive the effects of DG on a transmission system. More technical details and deeper insights are dealt with in Chapter 13, where we also define the services that DG can provide to distribution systems. In this section, the transmission services that DG is technically capable of providing are identified, and guidelines are developed to enable DG to participate in markets for these services.

Studies, reports, and experts in the field of DG [3–6] refer broadly to the benefits that DG can provide to transmission and distribution systems. The amount of generation relative to system total load, or penetration, is the most important factor in determining the influence of DG on transmission operation. A single 2-MW generator may have a considerable effect on the operation of a distribution system but go entirely unnoticed on a transmission system. On the other end of the spectrum, if a fully mature DG market supplies 30% or more of total customer load, the effect and importance to transmission operation will be undeniable. A tougher question is: What are the effects at penetration levels between the two extremes, and how should they be treated in respect to system control and economic valuation? This is addressed by focusing on (1) localized transmission benefits that a relatively small penetration of well-sited DG can provide, and (2) the benefits to the larger transmission system that can feasibly be achieved by growing DG penetrations.

Among the services DG can provide to the distribution system are capacity support, contingency capacity support, loss reduction, voltage support, voltage regulation, power factor control, phase balancing, and equipment life extension. DG can be defined as generation located at or near a load. *Combined heat and power* (CHP) is associated with prime movers that provide shaft power to generators and encompasses two broad categories: reciprocating engines and turbines. (Fuel cells may soon make a significant entrance on the CHP stage as well, but they are not yet ready for prime time.) CHP systems (also known as *cogeneration*) are generally developed by a user to avoid the purchase of power from the grid or by the energy service provider that retails the power to the site.

CHP is considered a subset of DG and can be used when there is a potential for profitable use of thermal energy. CHP is an energy cascade that captures energy normally rejected as part of a process. In the traditional case, steam is raised with a boiler on-site, and power is purchased from the local utility. The thermal energy in the steam is then employed for another use.

1.5 RENEWABLE ENERGY ECONOMICS

To meet the demand for a broad range of services (e.g., household, commerce, industry, and transportation needs), energy systems are needed. An energy supply sector and the end-use technology to provide these energy services are also necessary. In the United States, European Union, Russia, and Japan, the electricity supply system is composed of large power units—mostly fossil-fueled and centrally controlled—with average capacities of hundreds of megawatts. Conversely, renewable energy sources are geographically distributed and if embedded in distribution networks, are often closer to customers and therefore subject to smaller losses.

In the power sector, most utilities have limited experience interconnecting numerous small-scale generation units with their distribution networks. Complicating matters, the possible level of renewables penetration depends on the existing electrical infrastructure. For example, transporting to land the power produced by a large offshore wind farm is (economically) possible only where sufficient electricity grid capacity is available. In some locations, new electricity infrastructures have been set up to provide high penetration levels of up to 100% electricity from renewables.

Distributed electricity generation, close to the end customer, differs fundamentally from the traditional model of a large power station that generates centrally controlled power. The DG approach is new and replaces the concept of economy of scale (using large units) with economy of numbers (using many small units), although it has yet to prove itself.

Far from being a threat, DG-based renewable energy can reduce transmission and distribution losses as well as transmission and distribution costs, provide consumers with continuity and reliability of supply, stimulate competition in supply, adjust prices via market forces, and be implemented in a short time and with scalonated resources because of its modular nature. The International Energy Agency alternative scenario (WEO, 2002; WEIO 2003) predicts savings of about 40% for the transmission grid and 36% for the distribution grid because of the increased use of DG. This is a significant and driving argument when recent blackouts in the United States, Brazil, and Italy are taken into account.

1.5.1 Calculation of Electricity Generation Costs

When calculating generation costs, a distinction must be made between existing and potential plants. For existing plants, the running costs (short-term marginal costs) are relevant only for the economic decision as to whether to use the plant for electricity generation. Conversely, for new capacities, long-term marginal costs are important [2].

Existing Plants Annual running costs are split into fuel costs and operation and maintenance (O&M) costs. *Fuel costs* are a function of the fuel price of the primary energy carrier and efficiency. *O&M costs* refer to electricity output, hence must be coupled with full-load hours. In general, one average operation time (full-load hour) is taken for each technology band. Analytically, generation costs for existing plants are given by

$$C = C_{\mathrm{var}} = C_{\mathrm{fuel}} + \tilde{C}_{\mathrm{O\&M}} - R_{\mathrm{heat}} = \frac{p_{\mathrm{fuel}}}{\eta_{\mathrm{el}}} + \frac{C_{\mathrm{O\&M}}}{H_{\mathrm{el}}} \times 1000 - p_{\mathrm{heat}} \frac{\eta_{\mathrm{heat}}}{\eta_{\mathrm{el}}} \frac{H_{\mathrm{heat}}}{H_{\mathrm{el}}} \tag{1.1}$$

where C = generation costs per kilowatt [euros (€)/MWh]

C_{var} = running costs per energy unit (€/MWh)

C_{fuel} = fuel costs per energy unit (€/MWh)

$\tilde{C}_{\mathrm{O\&M}}$ = operation and maintenance costs per energy unit (€/MWh)

R_{heat} = revenues gained from purchase of heat (€/MWh)

p_{fuel} = fuel price primary energy carrier (€/MWh$_{\text{primary}}$)
p_{heat} = heat price (€/MWh$_{\text{heat}}$)
η_{el} = efficiency—electricity generation
η_{heat} = efficiency—heat generation
H_{el} = full-load hours—electricity generation per annum (h/yr)
H_{heat} = full-load hours—heat generation per annum (h/yr)

The full-load hours represent the equivalent time of full operation for a year. This is calculated for a power plant by dividing the amount of electricity generated per year by the plant's nominal power capacity. For theoretical cost–resource curves, this reflects an important aspect: the suitability of sites. In the case of wind energy, the full-load hours are determined by the wind speed distribution and the rated wind speed of the machines. Knowing the expected full-load hours, the quantity of electricity to be generated can be calculated. Hence, costs per unit are determined. The number of full-load hours divided by the number of hours in a year (8765 hours, on average) equals the system capacity (dimensionless).

New Plants Electricity generation costs consist of variable costs and fixed costs. Generation costs are given by

$$C = C_{\text{var}} + \frac{C_{\text{fix}}}{q_{\text{el}}} = \left(C_{\text{fuel}} + \frac{C_{\text{O\&M}}}{H_{\text{el}}} \times 1000 - R_{\text{heat}} \right) + \frac{1000\, I(\text{CRF})}{H_{\text{el}}} \qquad (1.2)$$

where C = generation costs per kilowatthour (€/MWh)
C_{var} = running costs per energy unit (€/MWh)
C_{fix} = fixed costs (€)
q_{el} = amount of electricity generation (MWh/yr)
$C_{\text{fix}}/q_{\text{el}}$ = fixed costs per energy unit (€/MWh)
C_{fuel} = fuel costs per energy unit (€/MWh)
$\tilde{C}_{\text{O\&M}}$ = operation and maintenance costs per energy unit (€/MWh)
R_{heat} = revenues gained from purchase of heat (€/MWh)
I = investment costs per kilowatt (€/kW)
CRF = capital recovery factor, $= \dfrac{z(1+z)^{\text{PT}}}{[(1+z)^{\text{PT}} - 1]}$
z = interest rate
PT = payback time of the plant (years)
H_{el} = full-load hours—electricity generation per annum (h/yr)

Fixed costs occur whether or not a plant generates electricity. These costs are determined by investment costs (I) and the capital recovery factor.

Investment Costs Investment costs differ according to technology and energy source. In general, investment costs per unit of capacity for renewable energy systems are higher than for conventional technologies based on fossil fuels. Also, differences exist among renewable energy technologies (e.g., investment costs per unit of capacity for small hydropower plants are generally at least twice those for wind turbines).

Investment costs decrease over time and are usually derived annually. It is usual to consider renewables as having zero fuel costs, apart from biomass (biogas, solid biomass, and sewage and landfill gas), so running costs are determined by operation and maintenance costs only. Therefore, the running costs for renewable energy systems are normally low compared with those of fossil-fuel systems.

Capital Recovery Factor The capital recovery factor allows investment costs incurred in the construction phase of a plant to be discounted. The amount depends on the interest rate and the payback time of the plant. For the standard calculation of generation costs, these factors may be set as follows for all technologies:

- Payback time (PT) of all plants: 15 years
- Interest rate (z): 6.5%

Different interest rates may be applied in any economical study. The interest rate depends on stakeholder behavior and is a function of a guaranteed political planning horizon of promotion scheme of technology of investor category.

Generation costs are calculated per unit of energy output, so fixed costs must be related to generation. Hence, fixed costs per unit of output are lower if the operation time of the plant—characterized by full-load hours—is high. Deriving generation costs for CHP plants is similar to calculating them for plants that produce electricity only. Both short-term marginal costs (i.e., variable costs) and fixed costs must be considered for new plants. Of course, variable costs differ between CHP and conventional electricity plants because the revenue from heat power must be considered in the former. In general, no taxes are included in the various cost components.

1.6 EUROPEAN TARGETS FOR RENEWABLES

Worldwide, several scenarios share the goal of sustainability in general or in the energy field. Thus, groundbreaking targets toward this goal are important for renewable energy and end-use energy efficiency. Such targets can guide policymakers during decision making and send important signals to investors, entrepreneurs, and the public. Case studies have demonstrated how concrete targets can lead to increased impact in various fields. In the case of renewable energies, policymakers formulate concrete policies and support measures to foster their development. Investors develop related strategies and renewable businesses as targets convince them that their investment will yield the returns projected.

Renewable power is available in many environmental energy flows, harnessed by a range of technologies. The parameters used to quantify and analyze these forms are listed in Table 1.4.

A study by C. Kjaer [7,8] in the EU emphasizes 10 requirements for any community-wide mechanism to create a sound investment climate for renewables:

1. Compatibility with the “polluter pays” principle
2. High investor confidence

3. Simplicity and transparency in design and implementation
4. High effectiveness in deployment of renewables
5. Encouragement of technological diversity
6. Encouragement of innovation, technological development, and lower costs
7. Compatibility with the power market and with other policy instruments
8. Facilitation of a smooth transition (“grandfathering”)
9. Encouragement of local and regional benefits, public acceptance, and site dispersion
10. Transparency and integrity by protecting consumers and avoiding fraud and free riding

1.6.1 Demand-Side Management Options

In the transport sector, biofuels are just beginning to be developed in Europe. However, in some countries, such as Brazil, sugarcane and oily plants already play important roles in the energy matrix. In the transport sector, the integration of renewables requires the adaptation of an infrastructure that has grown over a century of development based exclusively on fossil fuels. Besides the gradual substitution of vehicles in circulation, it is necessary to develop a new supply chain for the production and distribution of biofuels. This will require substantial investment. However, development of the fossil fuel–based transport system also required investment, which was subsidized by the public sector in many countries.

In the heating sector, the full integration of renewable energy requires an adaptation of historical infrastructures. In many parts of Europe, it is already possible to construct buildings completely independent of fossil fuels or electricity for heating needs. This is achieved using state-of-the-art renewable heating and cooling applications linked with energy-efficiency measures and demand-side management (see Appendixes B and C).

A substantial economic restriction to the integration of renewable heating (i.e., solar thermal, biomass, and geothermal) is the long lifetime of buildings. The installation of renewable heating systems is more cost-effective during the construction of a building or when the overall heating system is being refurbished. This means that there is a small window of opportunity for cost-effective integration of renewable heating. If this opportunity is lost, a building will remain dependent on fossil fuels or electricity to cover its heating demand for decades. For this reason, it is essential that all possible measures be taken to ensure that renewable heating sources are installed in all new buildings. It is also necessary to promote the use of renewable heating whenever a conventional heating system is being modernized.

Renewable heating sources can also be used for cooling. An increasing number of successful systems are being installed, based mainly on solar thermal and geothermal energy. The growing demand for cooling is affecting electricity systems in Europe, and several countries are now reaching peak electricity demand in summer instead of winter. These problems can be mitigated by the development and commercialization of renewable cooling technologies.

The existing infrastructure and market dominance of conventional heating and cooling technologies create a substantial barrier to growth for renewable heating. Biomass heating and cooling can be competitive in areas where the fuel supply chain is well developed, but this is not yet the case in many parts of the world. Solar thermal systems can be good economic investments, but in many areas, users are not aware of this. In addition, most heating installers are trained only for conventional heating systems and therefore encourage customers to stick to conventional heating. The integration of distinct energy-intensity profiles can be considered in these cases.

The choices that millions of citizens make for their homes and offices are crucial to the future integration of renewable energies in the heating and cooling sectors. Raising awareness among the public and training the professionals involved (e.g., conditioning and climatization installers, building engineers, architects, and managers of heat-intensive buildings or devices) are therefore very important.

Increasing use of renewable energies must be accompanied by energy efficiency and demand-side management measures at the customer end. Renewable energy development and energy efficiency are strongly interdependent. The European Union has always stressed the need to renew commitment at the community and member-state levels to promote energy efficiency more actively. In light of the Kyoto agreement to reduce carbon dioxide emissions, improved energy efficiency, together with increased use of renewables, will play a key role in meeting the EU Kyoto target economically (see Table 1.1). In addition to a significant positive environmental effect, improved energy efficiency will lead to a more sustainable development and enhanced security of supply as well as many other benefits. An estimated economic potential for energy-efficiency improvement of more than 18% of present energy consumption still exists today in the EU as a result of market barriers, which prevent the satisfactory diffusion of energy-efficient technology and the efficient use of energy. This potential is equivalent to more than 1900 TWh, roughly the total final energy demand of Austria, Belgium, Denmark, Finland, Greece, and the Netherlands combined.

Special emphasis should be placed on urban areas, where a high proportion of energy is consumed. Urban areas are characterized by highly developed infrastructures, which do not always easily allow a rapid increase in renewable energy generation. The fact that electrical network infrastructures are generally overdimensioned in urban areas can, in some cases, allow a high penetration of photovoltaic generators and wind energy without changing the existing cabling, transformer stations, and so on. However, in general, the future energy infrastructure will need to be designed from the beginning to accommodate renewable energy effectively at a high level. The small contributions that every home makes by using energy derived directly from nature (as wind, heat, coolant, light, photovoltaic electricity, and clean air) will make the biggest difference in the end.

1.6.2 Supply-Side Management Options

The European renewable energy industry has already reached an annual turnover of €10 billion and employs 200,000 people. Europe is the global leader of renewable energy technologies, and the use of renewables has a considerable effect on the investments made in the energy sector. Renewable energy replaces imported fuels, with beneficial effects on the balance of payments. Although per unit of installed capacity, renewable energy technology is more capital intensive, when the external costs that have been avoided are taken into account, investing in renewables turns out to be cheaper for society than business-as-usual investments in conventional energy. Renewable energy technologies are often on a smaller scale than fossil fuel and nuclear projects, and they can be brought online more quickly and with lower risks. Finally, deployment of renewables creates more employment than do other energy technologies.

The development of smarter, more efficient energy technology over past decades has been spectacular. Technologies have improved, and costs have fallen dramatically (see Figure 1.2). The examples of wind and solar photovoltaics are striking. Investment costs for wind energy declined by around 3% per annum over the past 15 years. For solar photovoltaic cells, unit costs have fallen by a factor of 10 in the past 15 years (stimulated initially by the space program).

In the European Union, renewables already make up a significant share of total energy production. Germany, for example, has doubled its renewable output in the past five years to 8% of total electricity production. Denmark now gets 18% of its electricity from wind power alone and has created an industry with more jobs than

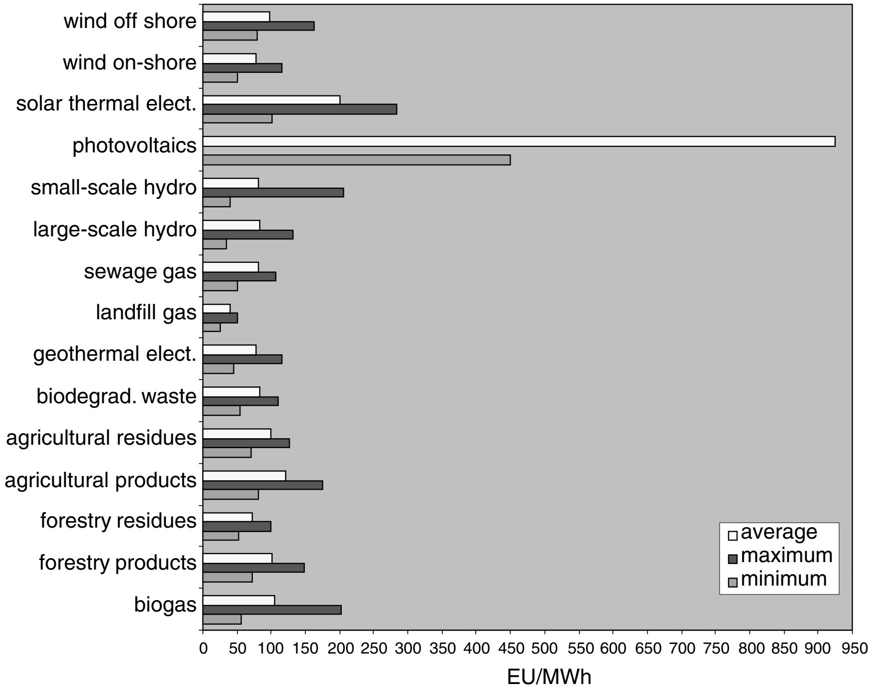

Figure 1.2 Long-run marginal generation costs (€/MWh) for renewable energy technologies in EU-15. (From Ref. [2].)

TABLE 1.5 Technical and Economical Characteristics of Selected Renewable Energy Technologies

	Unit Capacity (kW)	Electrical Efficiency (%)	Thermal Efficiency (%)	Lifetime (yr)	Full-Load Operating Hours	Investment Costs (€/kW)	Generation Costs (€ cents/ kWh)
Gas diesel engines	3–10,000	30–45	45–50	15	5000	450–1400	2.5–4.0
Microturbines	25–250	15–35	50–60	15	5000	1000–1700	3–4
Stirling engines	10–150	15–35	60–80	15	5000	1400–2200	4–5
Steam engines	0.5–10,000	15–35	40–70	15	5000	1500–3000	3–4
Wind power	0.1–5000	40–50	—	20	2500	900–1100	4–5
Fuel cells	0.5–2000	38–55	40–70	15	5000	2800–4400	5–8

Source: Vartiainen, E. et al., 2002; Gaya Group Oy, 2004; Obernberger, I., 2004).

in the electricity sector. Spain has leapt from using virtually no renewables a few years ago to become the second-biggest wind power country in Europe, with 6000 MW of capacity. Countries such as Finland, Sweden, and Austria have supported the development of very successful biomass power and heating industries through fiscal policies, sustained R&D support, and synergistic forestry and industrial policies. In addition to saving significant carbon dioxide emissions, equipment from all three countries is exported worldwide. Table 1.5 presents some technical and economical characteristics of selected renewable energy technologies, and Table 1.6 presents the EU-25 electricity production mix of 2002.

Going further, in 1991, the European Union and the United States launched ExternE, a joint project to assess the economic costs of externalities from the production and use of energy, and estimated that these costs amount to 1 to 2% of the EU's gross domestic product [8]. In July 2001, the European Commission issued a

TABLE 1.6 EU-25 Electricity Production Mix, 2002

Primary Source	Production (%)
Coal	30.4
Oil	6.1
Nuclear	31.5
Gas	17.0
Wind power	2.1
Large hydro	10.0
Other renewable energy	1.7
Other	1.2

Source: Ref. [7].

press release on the study's findings [9] which concluded that the "cost of producing electricity from coal or oil would double and the cost of electricity production from gas would increase by 30% if external costs such as damage to the environment and to health were taken into account."

1.7 INTEGRATION OF RENEWABLE ENERGY SOURCES

Integration of renewable energy sources involves integrating in a system any energy resource that naturally regenerates over a short period of time. This time scale is derived directly from the sun (such as for thermal, photochemical, and photoelectric energy), indirectly from the sun (such as for wind, hydropower, and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as for geothermal and tidal energy). In the long term, renewable energies will necessarily dominate the world's energy supply system for the simple reason that there is no alternative. Humankind cannot survive indefinitely off the consumption of finite energy resources, concentrate supplies on some points on Earth, or carelessly spread its population over the world.

Today, the world's energy supply is based largely on fossil fuels and nuclear power. These sources of energy will not last forever and have proved to be a major cause of environmental problems. Environmental effects of energy use are not new, but it is increasingly well known that they range from deforestation to local and global pollution. In less than three centuries since the industrial revolution, humankind has burned away roughly half of the fossil fuels accumulated under Earth's surface during hundreds of millions of years. Nuclear power is also based on limited resources such as uranium, and the use of nuclear power creates such incalculable risks that nuclear power plants cannot be insured.

Renewable sources of energy are in line with an overall strategy of sustainable development. They help reduce dependence on energy imports and do not create a dependence on energy imports, thereby ensuring a sustainable security of supply. Furthermore, renewable energy sources can improve the competitiveness of industries, at least in the long run, and have a positive effect on regional development and employment. Renewable energy technologies are suitable for off-grid services; they can serve remote areas of the world without expensive and complicated grid infrastructure.

The ability to integrate electricity generated from renewables into grid supplies is governed by several factors, including:

- The variation with time of power generated
- The extent of the variation (availability)
- The predictability of the variation
- The capacity of each generator
- The dispersal of individual generators
- The reliability of plants

- The experience of operators
- The technology for integration
- The regulations and customs for embedded generation

Despite these difficulties, the experience of the past 25 years has shown that ever-increasing amounts of electricity from renewables can be integrated into grid supplies without significant financial penalty. The standard response of grid operators that are accustomed to large-scale centralized generation is that intermittent and dispersed renewable energy generation cannot be so integrated. However, given the requirement to accept specific renewable energy generation, the technology and methods have followed successfully. Examples include:

- Electrical safety equipment and grid-fault disconnectors
- Grid-linked inverters for photovoltaics, solar cells, and power from buildings
- Doubly-fed induction generators for variable-speed wind turbines
- Voltage reinforcement on rural power lines
- Cofiring of steam boilers with biomass
- Gas turbines for the output of gasifiers

The outstanding example of ever-increasing integration of renewable energy generation into the grid is Jutland, western Denmark. In the early 1980s, the limit for wind power exported to the grid was considered to be 20% of total supply. However by 2003, about 40% of annual electricity supply was from wind, and at times, significant areas were supplied totally by wind power. The reason for the change was the willing application of new technologies and practices.

Nevertheless, there are fundamental limitations for any renewable energy generation technology and plant; for instance, the sun never shines at night. Also, in the middle of large towns and cities, the surface roughness for wind move is not acceptable for small towers. So it is essential to integrate renewable energy generation options with control and storage such that they complement each other.

1.7.1 Integration of Renewable Energy in the United States

The United States currently relies heavily on coal, oil, and natural gas for its energy. Fossil fuels are nonrenewable: They draw on finite resources that will eventually dwindle and become too expensive or too environmentally damaging to retrieve. In contrast, renewable energy resources such as hydropower, wind energy, and solar energy are replenished constantly and will never run out.

As in any other place, most renewable energy in United States comes directly or indirectly from the sun. Sunlight, or solar energy, can be used directly for heating and lighting, to generate electricity, and for cooling as well as for a variety of commercial and industrial uses. The sun's heat also drives winds (whose energy is captured with wind turbines) and evaporates waters, turning them into rain or snow, which then flows into rivers or streams and whose energy may be captured in water dams.

Other renewable sources include geothermal energy, which is tapped from Earth's internal heat for electric power production and heating and cooling buildings, and the oceans' tides, which come from the gravitational pull of the moon and sun. In fact, ocean energy comes from a number of sources. In addition to tidal energy, there is the energy of the oceans' waves, which are driven by tides and winds. The sun also warms the surface of oceans more than it warms ocean depths, which creates a temperature difference that can be used as an energy source. All these forms of ocean energy can be used to produce electricity.

In contrast to fossil energy, renewable energy is an attractive source for several reasons: clean environment, long-lasting life, increased jobs, increased comfort, and industry and energy self-sufficiency through decreased dependence on other nations. An economy that uses less energy also produces less pollution, and an energy-efficient economy can grow without using more energy. Energy efficiency means using less energy to accomplish the same task. More efficient energy use results in less money spent on energy by homeowners, schools, government agencies, businesses, and industries. The money that would have been spent on energy can instead be spent on consumer goods, education, services, and products. From 1970 to 2000, U.S. energy consumption grew only 45% although the U.S. gross domestic product increased 160%. In other words, the energy used per dollar of gross domestic product decreased 44% from 1970 to 2000. By 1999, greenhouse gas emissions from energy use had risen 13% above 1990 levels. During that period, energy use increased 14.9%.

1.7.2 Energy Recovery Time

The cost of electricity depends entirely, or largely, on the size of power stations. Between 1960 and 1980, the ideal size of a station rose from 400 MW to 1000 MW. These days, 5 MW is regarded as ideal because small-scale power generation permits a flexible response to energy demand and return of capital. Small-scale units such as wind turbines, photovoltaic cells, fuel cells, and biogasification plants represent the future.

Regardless of the type of primary source, it takes energy to convert energy from one type into another. The lower the specific energy content, the more energy intensive is the conversion process. When the specific energy content is low, the energy process chain uses more energy than it generates in electricity. Most of the primary energy extracted today has a profitable content that makes conversion cost-effective.

However, if any energy were to gain momentum, a point would come when the specific energy conversion would no longer be cost-effective. The amount of time a power plant needs to operate before all the energy consumed in the chain has been earned back (and the power plant begins to produce net energy), the *energy recovery time*, is highly dependent on the specific energy content of the primary source. It is difficult to compare this figure with the energy recovery time for fossil fuel–powered power stations. A fossil fuel power station has to recover only the electricity used for construction and other constituent processes in the chain. In such a case, the recovery

TABLE 1.7 Recovery Time of Selected Sources of Energy

Alternative Source	Recovery Time (years)
Wind	0.62–0.90
Gas and oil	1
Photovoltaic system	1.5–3
Nuclear power station	10–18

Source: Ref. [3].

time for power stations fired by gas and oil is 0.09 of a full-load year (approximately 0.13 of a calendar year); for coal-fired power stations, it is 0.15 of a full-load year (approximately 0.21 of a calendar year) [8]. But unlike modern gas-fired power stations that generate and supply commercial heat, alternative sources of energy such as nuclear power plants, wind turbines, and photovoltaic systems can generate only electricity. All the energy used in the chain is recovered in the form of electricity, which increases recovery time considerably. As a frame of reference, assume that fossil fuel–fired power stations must recover the energy used in their construction only in the form of electricity. This results in a recovery time of 0.7 full-load year for gas- or oil-fired power stations, which is approximately one calendar year. Coal-fired power stations have a longer recovery time. Table 1.7 lists the recovery time of selected sources of energy.

Improvements in conversion yields and production methods will help reduce the recovery time for photovoltaic systems in the future. Photovoltaic technology is at a peak of development and at the moment is in the sharply rising section of the learning curve, which means that prices will fall significantly as more capacity is commercialized. It is conceivable that the recovery time for photovoltaics will drop to less than one year as technical progress continues. Nuclear energy, on the other hand, is a mature technology; the price of nuclear power will not decrease as more nuclear power stations are built. In the past, there were even cost hikes of approximately 14% a year until the mid-1980s. Since 1979, no new nuclear power stations were ordered in Organization of Economic Cooperation and Development countries, which ended the competitive time in which further price rises could occur. Clearly, the recovery time for nuclear power stations is much longer than that of other power stations and will never decrease. In contrast, the recovery time for photovoltaic systems, in particular, is certain to decrease if new technologies and materials are used.

Environmental issues such as the greenhouse effect have focused attention on fossil-fuel combustion and electricity generation around the world. In Australia, 47% of the annual emissions of greenhouse carbon dioxide come from fossil fuel–fired power plants [3–9]. As coal-based plants are retired, due to age and greenhouse concerns, there is an opportunity for renewable energy generation sources to grab a larger share of the global electric energy market.

Wind systems, solar systems, storage components, and complete energy systems are now commercially available from many suppliers [5] to fill niche markets.

Fundamental research (especially in the production of thin-film solar photovoltaic devices, hydrogen from sun-mirrored heat, and new forms of batteries) is occurring in many countries, and these activities are steadily reducing the cost of renewable energy systems. However, there are still issues to resolve before such systems gain a bigger portion of the electric energy marketplace. Such systems must lower the overall cost of delivered energy, gain acceptance by a conservative industry, and convince the industry's customers that renewable energy systems are safe, reliable alternatives to conventional grid-supplied power.

Another issue is that although the primary energy supply may be free, the cost of using wind and solar energy is not. This is because structures and energy collectors must be built and energy storage must be provided. Any initiative that increases the energy collected or stored will lead to a reduction in the price of energy delivered from a complete system [5,8]. *Balanced* and *optimized* are terms frequently used to indicate that a system is designed to size the renewable, storage, and fuel-based components to deliver minimal all-of-life costs in a specific site and for a specific customer loading pattern. Such a system operates to maximize renewable energy capture and to minimize all-of-life costs of components.

1.7.3 Sustainability

The Fifth Environmental Action Programme of 2000 established EU legislation and defined sustainable development as "that which meets the needs of the present without compromising the ability of future generations to meet their own needs" [10]. The policy objectives underlying this definition were to ensure compatibility between economic growth and efficient and secure energy supplies together with a clean environment.

Environmentally polluting by-products are produced by conventional energy generation, which also depends on finite energy sources that are gradually being depleted. However, energy is essential for socioeconomic progress in developing and industrialized countries, and the demand for energy will increase with global population.

Targets established in the EC white paper of 1997 foresee a 12% share of renewables in Europe's total energy consumption by 2010 (double the 1997 share). Individual targets for each renewable energy technology are also set. Annual growth rates between 1995 and 2001 show that one sector (wind) is far beyond the target and that others (i.e., hydro, geothermal, and photovoltaics) are in line with expectations. To reach the overall and sector targets (which is feasible), specific support actions have to be taken soon for technologies that lag behind, such as biomass and solar thermal. The deployment status of energy consumption by energy source in the United States is illustrated in Table 1.8.

Given the present state of market progress and political support, the expectation is that if strong additional support measures are adopted, the overall contribution of renewable energy to energy consumption in 2020 will be 20%. These estimates are based on a conservative annual growth scenario for the technologies. To reach the target, strong energy-efficiency measures have to be taken to stabilize

TABLE 1.8 U.S. Energy Consumption by Energy Source, 2003

Source	Production (%)
Coal	22.773
Natural gas	22.490
Petroleum	39.074
Nuclear	7.795
Hydroelectric	2.779
Biomass	2.865
Solar	0.063
Wind	0.108
Geothermal	0.314

Source: Renewable DOE-EIA Energy Annual, 2003.

energy consumption between 2010 and 2020. These novelties in the energy market have opened discussions about what would be necessary socially, politically, and economically for a country to adapt to new environmental surroundings. In particular, when the director of the National Aeronautics and Space Administration's Goddard Institute for Space Studies enlightened the U.S. Congress to the fact that human-induced global warming was detectable in the climate record, some skeptical members of Congress argued that the data were unclear and inconclusive. According to the Goddard Institute, the consequences predicted for global warming include worldwide floods, droughts, rising sea levels, category 5 hurricanes, and typhoons. These effects, though, were widely debated. Agreement was barely reached that deep reductions in carbon emissions cannot be made economically without the use of energy-efficiency and renewable energy technologies.

Since then, standards have become necessary to regulate new power interconnections with distribution systems. The Institute of Electrical and Electronics Engineers (IEEE) 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems is the first in the 1547 series of planned interconnection standards [11]. There are major obstacles to an orderly transition to the use and integration of distributed power resources with electric power systems, as discussed in Chapter 15. Examples include the lack of uniform national interconnection standards and tests for interconnection operation and certification and the lack of uniform national building, electrical, and safety codes. Resolving this requires time to develop and promulgate consensus. The 1547 standard is a milestone for the IEEE standard-setting process and demonstrates a model for ongoing success for further national standards and for moving forward in modernizing the national electric power system.

Figure 1.3 depicts the 1999 U.S. energy flow in the net primary consumption given in quads and exajoules. A quad is 1 quadrillion (1015) Btu, and an exajoule is 1018 joules.

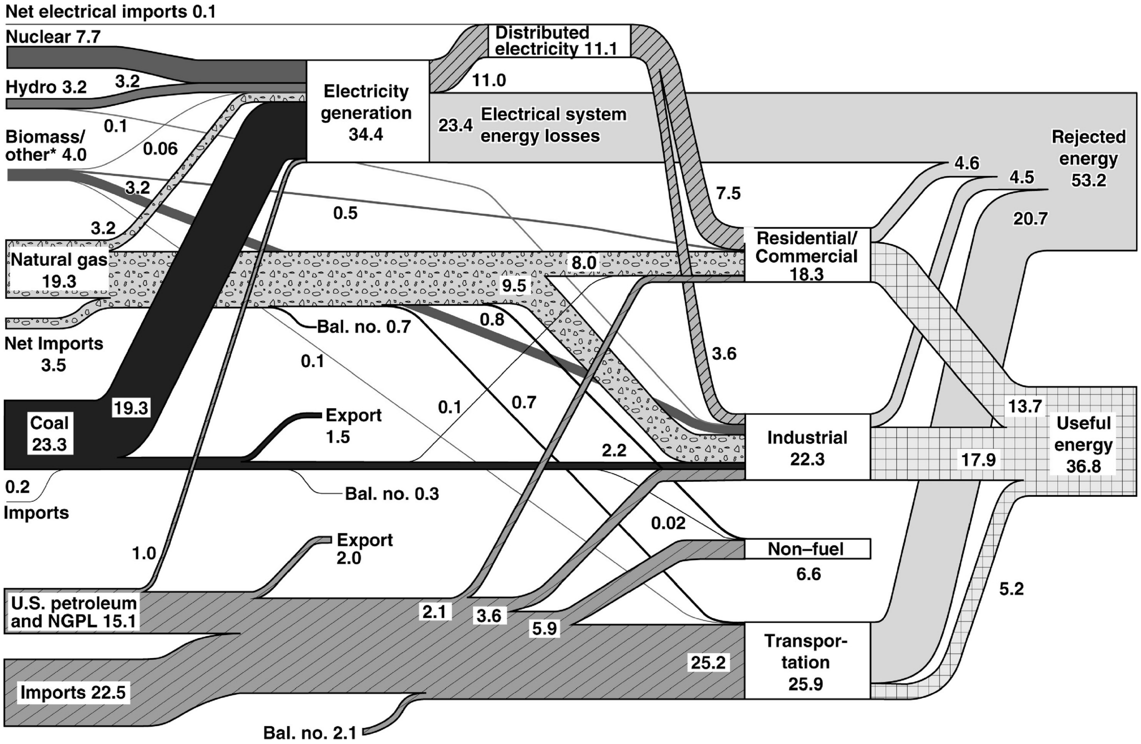

Figure 1.3 U.S. energy flow, 1999. Net primary resource consumption = 97 quads. (From Ref. [12].)

1.8 MODERN ELECTRONIC CONTROLS OF POWER SYSTEMS

Renewable and alternative energy sources must eventually be integrated with existing electric systems. Power electronics are a crucial enabling technology toward this end. Power electronics is a part of electronic application systems that encompasses the entire field of power engineering, from generation to transmission and distribution to transportation, storage systems, and domestic services. The progress of power electronics has generally followed microelectronic device evolution and influenced the current technological status of renewable energy conversion.

The power produced by renewable energy devices such as photovoltaic cells and wind turbines varies on hourly, daily, and seasonal bases because of variation in the availability of the sun, wind, and other renewable resources. This variation means that power is sometimes not available when it is required and that on other occasions there is excess power. The variable output from renewable energy devices also means that power conditioning and control equipment is required to transform this output into a form (i.e., voltage, current, and frequency) that can be used by electrical appliances. Therefore, energy must be stored and power electronics used to convert this energy.

Power-processing technology can be classified according to the energy, time, and transient response required for its operation. As the cost of power electronics falls, system performance improves. Applications are proliferating, and it is expected that this trend will continue with high momentum in this century. Modern industrial processes, transportation, and energy systems benefit tremendously in productivity and quality enhancement with the help of power electronics. The environmentally clean sources of power—such as wind, photovoltaics, and fuel cells—will be highly emphasized in the future because efficient-energy conversion from renewable sources depends heavily on power electronics.

In this book we are concerned with how alternative and renewable energy can be integrated electrically. Power electronics technology plays a major role in the injection of electrical power to the utility grid, as discussed in Chapter 12. If only photovoltaic and fuel cell systems are used, a dc-link bus could be used to aggregate them, and ac-power could be integrated through dc–ac conversion systems (inverters). If only hydro or wind power is used, variable-frequency ac voltage control can be aggregated into an ac link through ac–ac conversion systems. Ac–ac conversion systems can be created through several approaches discussed in this book.

Of course, alternative energy sources such as diesel and gas can also be integrated with renewables. They have a consistent and constant fuel supply, and the decision to operate them is based more on straightforward economics. Gas microturbines and diesel generators are commercially available with synchronous generators that supply 60 Hz, and a direct interconnection with the grid is typically easier to implement. When integrating and mixing these sources, a microgrid can be based on a dc- or ac-link structure. The design of such a microgrid must incorporate energy storage with seamless control integration of source, storage, and demand.

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