Fundamentals of Materials for Energy and Environmental Sustainability

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The global energy landscape and energy security

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2.1 Focus

The global energy landscape encompasses the distribution of energy resources, as well as the related aspects of energy production, storage, transmission, use, and efficiency. In addition, energy use has been correlated with economic development. Together, these attributes define the context within which countries strive to satisfy their energy demands, in terms of both economic productivity and quality of life. With the current rapid increase in demand for energy, the question of how countries will provide their populations with access to a clean and affordable energy supply in an environmentally sustainable manner has emerged as a grand challenge for today's society.

2.2 Synopsis

This chapter summarizes the global energy resources and their availability, economic viability, and environmental consequences. Although these topics are discussed with respect to individual fuels and technologies in greater detail in other chapters of this book, they are examined here in a broader sense relating to the overall global energy landscape.

Despite the dramatically increasing worldwide demand for energy, there exist sufficient resources to ensure that the world will not 'run out of energy' in the near future. However, in addition to the theoretical availability of a resource, several practical considerations determine whether and to what extent that resource is employed. In particular, various resources differ in energy content, price, ease of resources, conversion efficiency, waste, and CO_2 emissions. Moreover, some important sources of energy – such as oil, gas, and uranium – are concentrated in just a few countries, making them more susceptible to price and supply volatility. Increasing concerns over environmental impacts of energy use have led to a global emphasis on generating and using energy efficiently, as well as developing more environmentally benign resources. All of these factors combine to influence countries' decisions on energy policy and practices and, in turn, affect the further evolution of the global energy landscape.

The interplay between energy and politics, specifically in terms of energy security, can be illustrated through two sources: biofuels and nuclear power. Because of the perceived depletion of fossil energy resources and fears of supply denials by energy-rich countries, many nations of the world have prioritized energy security in order to ensure an adequate energy supply for their citizens. Governments have intervened on the basis that new innovations in renewable energy technologies continue to be expensive and require subsidies before they can become cost-competitive with existing energy sources.

The goal of energy security is also being pursued through the transformation of the electrical grid into a "smart grid." This transformation will become important not only for the technical reasons highlighted in Chapter 42, such as robustness and efficiency, but also because of the interrelated policy issues of pricing and control. These are challenges facing many renewable sources of energy: cost ($/watt) and the ability to integrate variable (and unpredictable) sources of power.

2.3 Historical perspective

A country's energy consumption is directly related to both its economic output and the individual well-being of its citizens. Both population growth and the desire to maintain growth while raising standards of living result in increased energy consumption as a society develops. For example, in 1800, before the full-scale onset of the Industrial Revolution, the world's population was about 1 billion, with a total annual energy consumption of 0.6 TW·year. (By analogy with kilowatt-hours, a terawatt-year is a unit of energy equal to 1 TW of power expended for one year of time. In terms of other energy units, $1 \text{ TW·year} = 8.76 \times 10^{12} \text{ kW·h} = 3.15 \times 10^{19} \text{ J} = 31.5 \text{ EJ} = 30$ Quads.) By the turn of the millennium, the global population had increased by a factor of 6, whereas the annual primary energy consumption had increased by a factor of more than 20, reaching about 14 TW·year today. The reason why growth in energy is not in step with the population are those changes that transformed the daily lives of many individuals. For example, agricultural improvements allowed larger amounts of food to be grown with less human effort, thus shifting increasing numbers of people away from employment in farming. Increased manufacturing made a greater variety of goods available, and more extensive transportation networks delivered those goods more widely and efficiently to the public. Labor-saving devices such as washing machines and power lawn mowers led to increased leisure time, which, in turn, increased demand for leisure goods, such as televisions. More recently, computers, cell phones, and video-conferencing equipment have become symbols of far-reaching transformations. Despite improvements in energy efficiency, both the manufacture and the use of such lifestyle-enhancing devices entail increased energy consumption.

However, the increased energy consumption, enhanced prosperity, and improved standard of living have not been shared equitably among all countries, nor are they shared equally among all individuals of a country or all sectors of an economy. For example, Figure 2.1 presents the trends in energy consumption of a variety of countries between 1980 and 2006. The values are given on a per capita basis because this allows an easier comparison among individuals living in the different countries. Bear in mind, however, that each country's total energy consumption is a product of the per capita value and the total population. Thus, the total energy consumption of China, with a population of 1.3 billion, far exceeds that of the Netherlands (population 16.5 million), even though the per capita consumption of the latter is over four times higher.

Table 2.1. The 2010 gross domestic product (GDP) per capita for selected countries [2]

Country	GDP per capita (USD)
USA	47,132
Netherlands	40,477
Russia	15,806
Brazil	11,289
China	7,517
India	3,290
Zimbabwe	395
Somalia	300[a]

[a] Estimated.

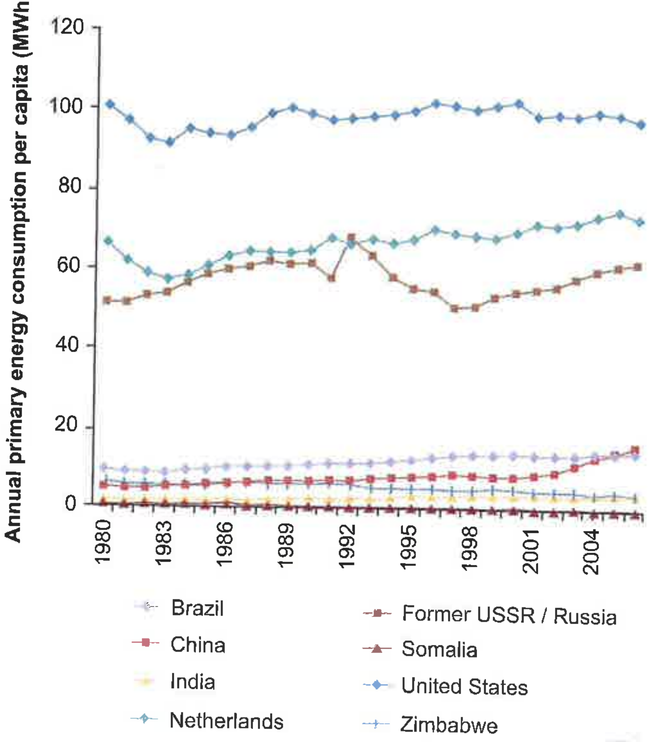

Figure 2.1. Annual primary energy consumption per capita of selected countries (1980–2006) [1].

For comparison, the 2010 **gross domestic products (GDPs)** per capita of the same countries are presented in Table 2.1. The GDP is a measure of the total market value of all goods and services produced in a country in a given year and is considered an approximate measure of a country's prosperity. As can be seen, per capita energy usage and per capita GDP generally follow the same trends. Thus, the disparities in energy use are reflected in similar disparities in economic growth and, in turn, in individual well-being. It is only natural, then, that countries strive to satisfy their energy demands, to foster both economic development and improved quality of life. As the global energy landscape evolves over time, they must adapt the strategies they use to do so.

2.4 The global energy landscape and its implications

2.4.1 Energy resources and their availability

Energy is harnessed from a mix of sources, from the burning of fossil fuels to the fission of uranium atoms in a nuclear reactor. Various issues determine the fuel choice, such as the availability, cost, and efficiency of energy generation (and conversion). Additional factors are concerns about the environment and the reliability of supply.

In theory, there is no dearth of global energy resources (Table 2.2). The existing fossil energy and uranium reserves together are projected to be able to sustain the global energy demand for several centuries. In fact, the limits imposed by the depletion of uranium ore could be more than compensated for by reprocessing spent fuel to recover plutonium and using thorium after conversion to ^{233}U. However, such advanced fuel cycles would have associated cost and proliferation concerns, which are discussed in more detail in Chapters 13 and 14.

Although the theoretical availability of energy resources is not an issue, several considerations have shifted the global fuel mix over the years. Figure 2.2 reflects this trend between 1973 and 2008 [4]. Oil still dominates as the single largest source of energy, although its preeminence is somewhat subdued. Globally, it still remains the transportation fuel of choice because of its energy content, easy transportability, and reasonable availability. In fact, almost 55% of oil used worldwide is for transportation, and the recent growth of the automobile sector in developing countries is making further demands on this fuel. It is estimated that, at the present rate of consumption, the world's current conventional oil reserves would last for a little more than four decades [5]. In addition, although they are generally more difficult to access, costlier to develop, and more controversial, untapped resources such as deepwater reservoirs could be harnessed. Moreover, substitute resources for extracting oil, such as tar sands and oil shale, could also be developed (see Chapter 11).

Table 2.2. Global availability of energy resources (present world primary energy consumption is about 14 TW · year) [3]. The energy resource availability of nuclear breeder reactors has been assessed by the authors

Resource	Energy potential (TW · year)
Coal	5,000
Gas and oil (conventional)	1,000
Gas and oil (unconventional)	2,000
Methane clathrates	20,000
Oil shale	30,000
Nuclear fission (conventional)	370
Nuclear fission (breeders)	7,400
Nuclear fusion	unlimited
Sunlight (on land)	30,000 per year
Wind	2,000 per year

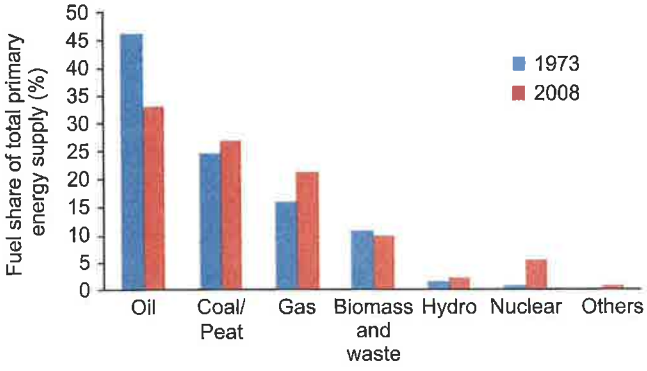

Figure 2.2. Fuel share of world total primary energy supply (1973 and 2008) [4]. Total world primary energy supply was 0.8 terawatt year equivalent in 1973 and 1.6 terawatt year in 2008.

Although the shifts in shares of various fuels appear modest, it is important to remember the enormous increase in total production for every type of energy source. The uses have also changed, with a much greater emphasis on the generation of electricity because of its cleanliness (from the consumer's perspective) and convenience (ability to perform multiple tasks such as lighting, heating, cooling, and even transportation). Essentially all nuclear power is used for electricity (naval propulsion being a negligible use), and most of the growth in coal has been for electric power production. Use of natural gas has also grown for electricity generation, where it has replaced oil in many cases because it is more efficient and more environmentally friendly. For example, natural gas combustion emits about 0.5 kg of

CO_2 per kW·h of electricity as compared with 0.85 kg per kW·h for oil and more than 1 kg per kW·h for coal. In addition, from a power-generation perspective, it is much faster to build plants for natural gas (often requiring less than half the time) than for coal. Over land, natural gas is transported under pressure through pipelines with diameters of several feet. For transport across water, natural gas is liquefied relatively easily at a reasonable cost and carried in giant tankers. As a result, several countries have established in-port facilities for liquefaction and regasification of natural gas. Further details on natural gas, as well as oil, are provided in Chapter 9.

As shown in Figure 2.2, nuclear power has grown tremendously since 1970. During this period, for example, France, Japan, and the USSR/Russia all built dozens of reactors, and India and China also embarked on major nuclear power programs. Despite this expansion, there are continuing concerns about the safety of nuclear reactors, the storage and disposal of nuclear wastes, and the proliferation of nuclear materials for use in weapons (see Chapters 13–15). Although strict international controls are in place regarding supply and use of nuclear materials, efforts to improve the safety and security of nuclear operations through both technology and policy continue. In a recent case, described later in this chapter, India was considered an exception to the non-proliferation regime because of its urgent needs for energy and also its impeccable record in non-proliferation.

Despite the emergence of natural gas and nuclear power, coal continues to hold its prominence both in developing and in developed countries. The global coal reserves are extensive and expected to last for centuries (see Table 2.2). Other attractive qualities of coal include its widespread availability, low cost of energy generation, and mature conversion technologies. However, as already mentioned, use of coal has significant environmental drawbacks, including high CO_2 emissions, as well as emissions of other pollutants such as SO_2, NO_x, mercury, and particulates. At present, there are no renewable energy technologies that could replace coal on a large scale. Thus, continuing research efforts are focusing on improving the efficiency and reducing the environmental impact of power generation from coal. These issues are discussed in detail in Chapter 10.

In terms of renewable resources, the share of hydroelectric power has remained constant (see Figure 2.2), as concerns have grown about its social and environmental consequences. In particular, hydroelectric plants generally require large land areas for their reservoirs. It is estimated, for example, that the massive Three Gorges System in China (~18,200 MW upon completion in 2009, with the scope for some expansion) displaced some 1.5 million people from the regions submerged for its upper reservoir. Nevertheless, hydroelectric power can still be an important resource under appropriate conditions. For example, in Norway, which has a low population density, hydroelectric dams contribute more than 90% of the power generation. Further details on hydroelectricity can be found in Chapter 45.

Wind energy has matured considerably over the past few decades. In 2010, the installed capacity was 0.2 terawatts [6], and it is projected to increase to 1.5 terawatts by 2020. Moreover, its cost of generation is now almost comparable to that of conventional power-generation technologies. However, wind power entails several difficulties, including that it is intermittent and location-specific. Lack of capacity for transmitting power from wind installations to load centers has hampered wind power in many parts of the world. In addition, aesthetic concerns about the location of wind generators and noise are stunting its expansion in the USA. See Chapter 30 for a detailed discussion of the current status of wind energy and the challenges it faces.

Biofuels have achieved increasing prominence because of the perceived scarcity (and distributional concentration in selected areas) of petroleum resources and the volatility in their price and supply. Biofuels are at present produced from feedstock such as sugarcane, molasses, corn, palm oil, and other oil-bearing crops. In addition, cellulosic materials can be converted into ethanol by enzymatic or thermochemical processes. These processes are discussed in detail in Chapters 25 and 26. There are increasing concerns about deforestation of tropical forests to plant palm-oil plantations, as well as diversion of food-producing lands to energy crops. Some of these issues are examined in the next section as an example of the challenges encountered in developing alternatives to the fossil-fuel-dominated energy landscape of today.

In theory, solar irradiation provides limitless potential for meeting global energy needs. One hour of sunshine falling on the Earth's surface could potentially meet the entire world's energy needs for an entire year (around 14 TW·year). Nevertheless, solar energy currently provides less than 0.1% of the world's energy supply. Unfortunately, the flux of solar radiation is low (less than 1,000 $W\,m^{-2}$ at the noon peak) and intermittent, and conversion technologies currently are not at grid parity with conventional fossil fuels. However, considerable research development and deployment is ongoing worldwide in a range of solar technologies and some are demonstrating a learning curve that will make them competitive, as discussed in detail in Chapters 17–22.

2.4.2 The quest for energy security: some examples

All nations of the world are concerned about providing an uninterrupted supply of energy at affordable prices and in the form required. Because energy resources are not equitably distributed, this can be a major challenge. In January 2009, for example, a dispute between Russia and Ukraine led to disruptions in the supply of natural gas not just in Ukraine but in several countries of the European Union as well. Similarly, a late-2010 ban by China on the export of rare-earth minerals (critical components of advanced batteries and many catalysts) illustrated the deep vulnerability of developed economies to supply disruptions. Countries have undertaken many initiatives to overcome such disruptions, including stockpiling fuel and resorting to unconventional and often environmentally contentious technologies. Another option is for governments to subsidize and support newer technologies that are not at present cost-competitive.

In this section, we discuss three responses to challenges in **energy security**. The first is the development of ethanol and biodiesel as substitutes for oil. The second concerns the implementation of a political agreement that enabled India to pursue domestic nuclear power while still addressing international concerns about proliferation. The third addresses the technical–economic and even social challenges involved in designing and implementing smart grids superimposed on the existing electricity distribution and transmission grids. These three scenarios were chosen to highlight different aspects of the challenges presented by the current global energy landscape, beyond the obvious issue of cost-effectiveness. With biofuels, the challenge is one of scale and impacts; with nuclear power, it is one of policy and global regimes; and with smart grids, it is one of managing a fundamental transformation of the existing energy infrastructure.

Biofuels

In the past few decades, biofuels have received a great deal of attention. As oil prices reached record highs in recent years, several countries announced programs in biofuels. For example, the USA has an ambitious target of producing 36 billion gal (1.4×10^{11} l $= 1.4 \times 10^{8}$ m^3) of biofuels per year by 2020 [7]. Such responses follow a trend similar to that of the oil shocks of the 1970s, which exposed the vulnerability of the world economy to the volatile geopolitics in oil-producing countries. Then, as now, several countries came forward to invest in biofuels, as such an investment promises to provide some amount of energy security through reduced reliance on imported fossil fuels. In addition, biofuels are embraced because of their expected environmental benefits compared with fossil fuels.

In the 1970s, Brazil initiated a program for the large-scale production of ethanol from sugarcane. Large tracts of land were converted for growing sugarcane, and a sizable fraction of the harvest was diverted for producing ethanol. Cars were designed to handle any blend of ethanol, even up to 100%, and fueling stations supplying/pumping such blends became ubiquitous. The cost of producing ethanol from sugarcane is reasonable, and the Brazilian government provides no subsidies. Currently, Brazil produces 25 billion liters annually. Nevertheless, the USA is actually the world's largest ethanol producer, using mainly starch-containing crops, primarily corn. In the USA, corn is grown on an area of 10 million hectares (ha), and the yield is about 1,060 gal ha^{-1} (4,000 l ha^{-1}), for a total of 10.6 billion gal (40 billion l) in 2009. Ethanol from corn is about 30% more expensive than that from sugarcane because the corn starch must first be converted into sugar before it can be distilled into alcohol. The US government thus provides a federal tax credit of \$0.51 gal^{-1} (\$1.93 l^{-1}) and imposes a tariff of \$0.54 gal^{-1} (\$2.04 l^{-1}) on ethanol imports from Brazil, to protect its domestic ethanol industry.

Given the intended purposes of national biofuels policies, namely to increase energy security and decrease environmental impact, it is natural to ask whether they are fulfilling their promise. In fact, the life-cycle energy assessment of ethanol has been a subject of much debate. (See Chapter 41 for more information on life-cycle assessments.) Initial calculations suggested that it takes more energy, generally derived from fossil fuels, to make corn-based ethanol (as in the USA) than can be obtained from it, leading to an energy output-to-input ratio of less than 1 [8] [9]. These calculations were subsequently refuted, and now it is generally accepted that this ratio is around 1.3 [10]. In contrast, the energy balance for ethanol from sugarcane is estimated to be 8.3–10.2 [11].

The marginal energy and environmental benefits of corn ethanol notwithstanding, the implementation of the US federal incentives motivated farmers in corn-growing states to increase the area under corn cultivation and devote significant amounts of corn to making ethanol. This coincided with a period of increased global food grain prices. A World Bank study reported that large-scale production of biofuels and the related consequences of low grain stocks, speculative activity, and export bans accounted for almost 75% of the total price rise [12]. The report mentioned that the large increase in biofuel production in the USA and Europe was the main reason for the steep price rise, whereas Brazil's sugarcane-based ethanol did not have an appreciable impact on food prices. It also argued that the presence of subsidies and tariffs on imports added to the price rise and that, without such policies, the price increase would have been much lower. The World Bank study recommended that the USA and European Union remove their tariffs on ethanol imports to support efficient ethanol production in countries such as Brazil. Another study determined that the current biofuel support policies in the European Union and USA would reduce greenhouse gas emissions from transport fuel by no more than 0.8% by 2015, but that Brazilian ethanol from sugarcane would reduce greenhouse gas emissions by at least 80% compared with fossil fuels [13]. It thus called for more open markets in biofuels to improve efficiency and lower costs.

Another unanticipated impact of biofuels policy is illustrated by the experience of Europe. In 2008, the European Union announced a target for 10% of transportation fuels to come from renewable energy sources, mostly biofuels, by 2020. However, a March 2010 study reported that a biofuels level of more than 5.6% could actually harm the environment, mostly as a result of "**indirect land-use change**." Specifically, the initial EU announcement led to the large-scale clearing of forest and peat lands in Indonesia and Malaysia to support the cultivation of biofuel crops. The process of land clearing results in such a large initial release of CO_2 to the atmosphere that it could take a few decades for the CO_2 to be recovered by the annual biofuel cycle [8] [14]. In fact, deforestation significantly increased Indonesia's CO_2 emissions and made the country among the world's leading emitters (Figure 2.3). In terms of land-use change, the area under development for palm-oil plantations in Indonesia increased from less than 2,000 km^2 to more than 30,000 km^2. There was widespread deforestation (and illegal logging) during this period, and palm-oil plantations were identified as the greatest threat to forests and wildlife in southeast Asia. Of course, the decisions to cut down forests had local support because doing so contributed to job creation and economic growth. In response, the international community implemented the Reducing Emissions from Deforestation and Forest Degradation (REDD) program to help developing countries reduce emissions from forested lands and invest in low-carbon paths to sustainable development, with financial support from developed economies. For example, in May 2010, Norway pledged $1 billion to help Indonesia reduce further deforestation.

Biofuels, particularly corn ethanol, provide one instance where politics has taken precedence over sound science and economics in decision making. The production of biofuels is now largely from food crops such as sugarcane, corn, and beets. However, other plants that are not in the food chain and grow wildly in tropical and subtropical climes could be used instead. **Jatropha** is one such hardy plant and has attracted considerable attention because of its oil content and widespread growth from Africa to South America and south Asia.

Jatropha can be grown in wastelands and has minimal nutrient and care requirements. The fruits and seeds of the plant are poisonous and contain about 35% oil that has properties suitable for making biodiesel [15]. In 2008, jatropha was planted on an estimated 900,000 ha, mainly in Indonesia. By 2015, according to some forecasts, the area should increase to 12.8 million ha.

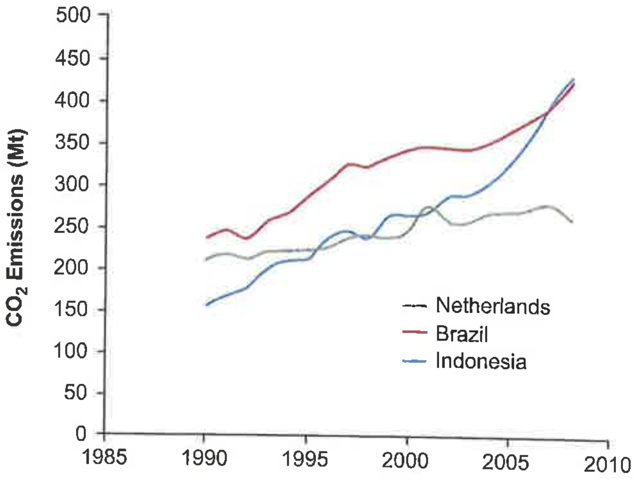

Figure 2.3. The steep rise in CO_2 emissions in Indonesia over the past two decades. Over the same period, emissions from the Netherlands started at a higher level but grew at a much lower rate. Even though emissions from Brazil started at a much higher level and grew at a substantial rate, they are now slightly surpassed by those from Indonesia.

The yield from this plant can vary significantly from 1 to 3 tonnes per hectare, and the plant starts yielding fruits even from the second year of planting [16]. A recent study concluded that jatropha cultivation in lower-quality wastelands would help small and marginal farmers, creating rural employment and making biodiesel available for rural areas [15] [17]. This study also underlined the potential of jatropha for sustainable development that helps eliminate poverty.

Despite these initiatives, it is unlikely that biofuels alone can meet even a modest fraction of global transportation requirements, which account for 30% of total primary energy use. Even for a relatively high-yield crop such as jatropha, the acreage required for a country to achieve even a modest (10%–20%) biofuel blend would make it one of the largest crops planted in the country. However, if targeted properly, biofuels can help meet a fraction of the transportation fuel needs of some countries, especially in the tropics, and also enable the alleviation of rural poverty, unemployment, and lack of energy sources.

Nuclear power

In the 1950s, nuclear power was considered the answer for the energy needs of all countries, because it is efficient, compact, and even cost-effective. In fact, the Second Geneva Conference on Peaceful Uses of Atomic Energy of 1958 recommended nuclear fission as the preferred technology until nuclear fusion became mature by the end of the twentieth century.

However, three concerns shattered this hope. First, three major nuclear reactor accidents [Windscale (1957) in the UK, Three Mile Island (1979) in the USA, and Chernobyl (1986) in the USSR] demonstrated the devastating and long-lasting damage from such events. The second concern is the possible proliferation of nuclear materials that could result in rogue states and non-state actors obtaining the material and the know-how for making nuclear weapons. Chapter 14 details the technology and policy countermeasures employed by the international community as safeguards against nuclear proliferation. The third concern, addressed in Chapter 15, regards the safe disposal of nuclear wastes from the spent fuel and other radioactive wastes. These concerns grew so intense that some countries, such as Italy, abandoned their nuclear power programs altogether. Even in the USA, no new nuclear reactors have been commissioned for over two decades.

The case of India

One country that has continued to pursue nuclear power options is India, through a program that began soon after the country gained independence (1947). However, its refusal to sign the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) in 1970 and its 1974 and 1998 nuclear weapons tests resulted in India being shunned by the global nuclear community. During the subsequent decades of isolation, India was unable to obtain commercial nuclear fuel, nuclear power plant components, and services from the international market, meaning that it had to rely on its own scientists and resources for the development of its nuclear industry.

Because of limited domestic uranium resources, the Indian political and scientific leadership decided to pursue a fast breeder reactor program (see Chapter 13), in which the spent fuel of thermal nuclear reactors can be reprocessed to recover plutonium, which can then be used as a fuel for fast reactors. It was felt that plutonium is too precious a resource to be buried as nuclear waste and that it should be used for generating additional power instead. Because of the extensive availability of thorium, India went a step further to use fast breeder reactors to convert thorium, which is not fissionable, into additional ^{233}U fuel.

It is only in the past few years that there have been some landmark changes in relations between the Indian nuclear power sector and the global community. This series of steps started with the US–India Civil Nuclear Cooperation Initiative (July 2005), under which India agreed to separate its civil and military nuclear facilities and place several of its civil nuclear facilities under International Atomic Energy Agency (IAEA) safeguards in return for civil nuclear assistance from the USA. In addition, a waiver was obtained from the Nuclear Suppliers Group (NSG), the export-control organization established in response to India's 1974 nuclear test to ensure that nuclear technology is not diverted from peaceful use to weapons programs. This 2008 waiver allows India to participate in nuclear trade and commerce, even though it has nuclear weapons and has not signed the NPT. According to the Indian nuclear establishment, these arrangements will allow a significant growth in nuclear power generation in India and also enable plutonium and thorium to be harnessed successfully [18] [19]. However, it was preceded by intense national and international negotiations, which almost brought India's coalition government to the brink of collapse. The threat of proliferation and waste disposal were among the two main concerns. In any event, this example illustrates one country's efforts to ensure a reliable and efficient energy supply for its citizens.

The upcoming transformation of the power system

The power grid of today looks essentially the same as that built a century ago, unlike, say, the telecommunications network, which has benefited from rapid advances in materials and technologies, especially digital technologies. The "**smart grid**," aims to use digital communications and control technologies to make the electricity supply system more robust, efficient, cost-effective, and amenable to renewables. A detailed discussion of smart grids appears in Chapter 42.

In today's "dumb" grid, power is treated as a commodity (all kilowatt-hours are mostly treated as equal) and flows like water across the path of least resistance, with limited measurements (except for broad operations and billing) and few controls. In the envisioned smart system, one would know exactly what power was going where and when, and be able to act in response to conditions, either through direct control mechanisms or through economic signaling (changing the price). For example, today's retail consumers have mostly enjoyed flat-rate tariffs for electricity, even though power at 5 pm is typically more expensive to supply than that at 5 am. With a smart grid (including smart meters that record the time as well as the amount of usage), the billing could be done accordingly.

Under the proposed transition, something as mundane as an electricity meter has enormous policy and political implications. At base, it would mean that consumers would be paying for the electricity they use, ideally at prices that directly reflect costs. It is just such microeconomic efficiency that has proponents excited. Conversely, fears have been raised about the complexity

Table 2.3. Metering and underlying functionalities over time [20]

	Phase I, options define service, 1800s to early 1900s	**Phase II, option consolidation, 1920s to 1960s**	**Phase III, separate options, 1970s to 2000**	**Phase IV, integrated options, after 2000**
Pricing	End-use rates	Usage-based rates	TOU-based rates	Real-time pricing
Metering	None	Total kilowatt-hour usage	Time-period loads	Hourly loads
Load-shape objectives	Load growth	Load growth, valley filling	Peak shaving, shifting, conservation	Preserve electric reliability, customer cost management
Customer involvement	Active, fuel switching	Passive, few options	Utility command and control	Interactive participation
Demand response	Contracts for service	Water-heater time clocks	Curtailable, interruptible, direct control	Demand bidding, risk management
	⇩	⇩	⇩	⇩
	Increased choice, service tailored to customer needs	Reduced choice, increasing value to customers, declining cost	Reduced choice, increasing costs, loss of control, declining value to customers	Increasing choice, cost volatility, value of information

TOU, time of use.

of such a system, about the undue financial burden it could place on those least prepared to respond to dynamic prices (e.g., senior citizens), and about the potential it could pose for invasion of privacy and risk to consumer data.

Table 2.3 shows how metering technology has changed over time with different policy, political, and business needs.

At this point, the structure of the smart grid has many unknowns that will need to be resolved by regulators, policy makers, and consumers as technologies evolve. Beyond monitoring, pricing, and control, smart technologies could change the power grid in more fundamental ways. For example, a smart grid could more easily integrate distributed generation resources, including intermittent sources such as solar or wind plants or new storage technologies such as electric cars.

Beyond unknowns regarding what the future grid will look like, there are also challenges relating to how to get there. The benefits of smart grids will take time to be realized, but there will be a need for very large investments up front (estimated at $100–300 per consumer). It is unclear who will pay for this and what the effect on costs for consumers will be.

Nevertheless, the potential for smart grids is very large. Beyond a return on investment for utilities, compelling societal benefits could be realized, including allowing for far greater implementation of "green" power. Indeed, without a smart(er) grid, the variability of some renewables can impose unmanageable operating burdens on utilities. Most importantly, today's grid (which is considered strained in some developed countries such as the USA or fledgling in growing economies) simply cannot provide the reliability, quality, and environmental sustainability needed for the twenty-first century.

2.5 Summary

According to current projections, the available energy resources could sustain the world's energy requirements for centuries. However, merely having energy resources alone or the technologies to harness them is not adequate. These options must be cost-effective, environment – friendly, and socially and politically acceptable, in terms of both accessibility and security. It is within this context that each country must satisfy its energy needs. The examples of biofuels, nuclear power, and a smart electricity distribution grid illustrate the many factors that must be considered in addressing these challenges.

2.6 Questions for discussion

1. What are the global and country-specific trends in energy intensity? Is the global energy intensity likely to converge in the long run?
2. The longevity of world energy reserves has been a subject of considerable debate and speculation and there has been varied experience with different resources such as oil, natural gas, coal, and uranium. It is generally believed that the world will soon run out of oil and gas reserves whereas coal and uranium will remain for a much longer time. Given the growing energy demand in developing countries, what are the estimates for longevity of coal and uranium reserves? Further, oil and gas prices have shown considerable volatility, whereas coal and uranium prices have been relatively stable. What are the reasons for the differences in price behavior of these sources?
3. How do different biofuels compare in their life-cycle costs and CO_2 emissions? Which biofuels are likely to impact food security?
4. What is the potential of emerging biofuel technology options such as cellulosic ethanol and algae-based ethanol? How does their economics compare with that of conventional biofuels and also oil?
5. The spent fuel of nuclear reactors consists of plutonium, which is a fuel for nuclear power. However, most countries having nuclear power programs follow the once-through cycle and do not reprocess spent fuel. How does the economics of reprocessing compare with that of direct disposal of the spent fuel?
6. The motivation for adoption of smart electricity grids varies. In developed countries, the main drivers are load control and peak shaving, whereas in developing countries, the main driver is loss reduction. How do these differences translate into country-specific technology and business models?

2.7 Further reading

- International Energy Agency (IEA), *Energy Technology Perspectives*, provides an overview of world energy scenarios and the role of emerging technologies (http://www.iea.org/textbase/nppdf/free/2008/etp2008.pdf).
- **D. Victor** and **T.C. Heller** (eds.), 2007, *The Political Economy of Power Sector Reform: The Experiences of Five Major Developing Countries*, Cambridge, Cambridge University Press. This book provides a comparison of the electricity reforms in five developing countries.
- *The Future of Coal: An Interdisciplinary MIT Study*, Massachusetts Institute of Technology, 2007; available at http://web.mit.edu/coal/The_Future_of_Coal.pdf. This report gives an overview of coal's energy-generation potential and the techno-economics of present and future conversion technologies including carbon capture and sequestration.
- *Update of the MIT 2003 Future of Nuclear Power: An Interdisciplinary MIT Study*, Massachusetts Institute of Technology, 2009; available at http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf. This report discusses the potential, technologies, and economics of nuclear power, including the option of recycling of spent fuel.

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