Water, Energy, and Environment

A Primer

ALLAN R. HOFFMAN

A highly-readable 'primer' for those entering the water and energy fields

IWA PUBLISHING

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Preface

This book springs from my strong conviction that clean water and clean energy are the critical elements of long-term global sustainable development. I also believe that we are experiencing the beginning of an energy revolution in these early years of the 21st century. Providing clean water requires energy, and providing clean energy is essential to reducing the environmental impacts of energy production and use. Thus, I see a nexus – a connection, a causal link – among water, energy, and environment. In recent years we have adopted the terminology of the water-energy nexus for the intimate relationship between water and energy, and similarly we can apply the term nexus to the close connections among water, energy, and environment. This use of the term nexus can be, and has been, extended to include the related issues of food production and health. Dealing with, and writing about, a two-element nexus is difficult enough. In this book, I will limit my analysis and discussion to the three-element water-energy-environment nexus and leave the discussion of other possible nexus elements to those more qualified to comment.

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This book also springs from my observation that while there are many existing books of a more-or-less technical nature on the three elements of this nexus, a book addressing each of them and their interdependencies in a college-level primer for a broad global and multidisciplinary audience would be valuable. Consideration of these and related issues, and options for addressing them, will be priorities for all levels of government. They will also be priorities for many levels of the private sector in the decades ahead, both in developing and developed nations. A handbook-style primer that provides an easily read and informative introduction to, and overview of, these issues will contribute broadly to public education. It will assist governments and firms in carrying out their responsibilities to provide needed services and goods in a sustainable manner, and help to encourage young people to enter these fields. It will serve as an excellent mechanism for exposure of experts in other fields to the issues associated with the water-energy-environment nexus. Further, in addition to the audiences mentioned above, target audiences include economists and others in the finance communities who will analyze and provide the needed investment funds, and those in the development community responsible for planning and delivering services to underserved populations.

The book is organized as follows: the first chapter will be devoted to the concept of nexus and how the three elements, water, energy, and environment, are inextricably linked. This recognition leads to the conclusion that if society is to optimize their contributions to human and planetary welfare they must be addressed jointly. No longer must policy for each of these elements be considered in its own silo. Chapters 2 and 3 will be devoted to spelling out global contexts for water and energy issues, respectively. Chapter 4, on related environmental issues, will address the issues of water contamination, oil spills, fracking, radioactive waste storage, and global warming/climate change. Chapter 5 will be a discussion of energy efficiency – i.e., the wise use of energy – and its role in limiting energy demand and its associated benefits. Chapter 6 will focus on the basics of fossil fuels – coal, oil, natural gas – which today dominate global energy demand. Chapter 7 will discuss nuclear-fission-powered electricity production, which today accounts for 10% of global electricity. It will also discuss the prospects for controlled nuclear fusion. Chapter 8 will discuss the broad range of renewable energy technologies – wind, solar, hydropower, biomass, geothermal, ocean energy – which are the basis of the now rapidly emerging energy revolution. Chapter 9 will discuss the closely related issue of energy storage. Finally, Chapter 10 will address policy issues associated with water, energy, and environment, discuss policy history and options, and provide recommendations.

Allan R. Hoffman

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With love and appreciation, I acknowledge the constant support of my wife, Yvonne, throughout our many years together as I pursued the issues discussed in this book, and the many hours I have spent in transferring whatever I have learned to print. These efforts would have been impossible without her love, patience, and encouragement.

It is also important for me to acknowledge the individual most responsible for my involvement in energy and environmental issues, and eventually in related water issues, Dr. David Inglis. David had been a distinguished theoretical physicist before joining the Manhattan Project and participating in the effort to end World War II. He subsequently served as a senior physicist at Argonne National Laboratory. In 1969 he retired from Argonne and joined the Physics and Astronomy Department at the University of Massachusetts/Amherst, where this young professor formed a deep friendship with a much older colleague. David had devoted his post-war years to efforts to control nuclear weapons, and when I met him he was writing a book on energy and arms control. Through our friendship I was exposed to nuclear power issues, and, as I learned more and one thing led to another, I changed my professional focus from low-temperature physics to energy. I can truthfully say that my friendship with David shaped my subsequent career. Looking back, I can only say, “Thank you David”.

Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
ac	alternating current
ASPO	Association for the Study of Peak Oil and Gas
BP	British Petroleum
Btus	British thermal units
BWRs	boiling water reactors
CAFE	corporate average fuel economy
CAGR	cumulative average growth rate
cc	cubic centimetre
CFLs	compact fluorescent lamps
CH_4	methane
CLASP	international organization promoting appliance efficiency policies (formerly the Collaborative Labeling and Appliance Standards Program)
CO	carbon monoxide
CO_2	carbon dioxide
CPV	concentrating photovoltaics
CSTP	concentrating solar thermal power

D (^2H)	deuterium
dc	direct current
DOD	Department of Defense
DOE	Department of Energy
DVD	digital optical disc storage device
EC	electrochromic
ED	electrodialysis
EDR	electrodialysis reversal
EGS	enhanced geothermal system
EIA	Energy Information Administration
EISA	Energy Independence and Security Act (2007)
EPA	Environmental Protection Agency
EPCA	Energy Policy and Conservation Act
EU	European Union
EVs	electric vehicles
GDP	gross domestic product
GHP	ground source heat pump
g	gram
GPS	global positioning system
GW	gigawatts
H (^1H)	hydrogen
H_2O	water
HCPV	high-concentration photovoltaics
He	helium
Hg	mercury
HTF	heat transfer fluid
HTGR	high-temperature gas reactor
IAC	InterAction Council
IDA	International Desalination Association
IEA	International Energy Agency
IPCC	International Panel on Climate Change
ITER	International Thermonuclear Experimental Reactor
LCOE	levelized cost of energy

LEDs	light-emitting diodes
Li	lithium
LNG	liquefied natural gas
MED	multi-effect distillation
MENA	Middle East and North Africa
MeV	million electron volts
mph	miles per hour
MSF	multi-stage flash
Mtoe	millions of tons oil equivalent
MW	megawatts
Ni-cad	nickel–cadmium
nm	nanometres
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NREL	National Renewable Energy Laboratory
OECD	Organization for Economic Co-operation and Development
OLEDs	organic LEDs
OPEC	Organization of Petroleum Exporting Countries
OSW	offshore wind
OTEC	ocean thermal energy conversion
Pb	lead
PM	particulate matter
ppm	parts per million
psi	pounds per square inch
PWRs	pressurized water reactors
R&D	research and development
RANN	Research Applied to National Needs
RO	reverse osmosis
RPS	renewable energy portfolio standard
RSF	Research Support Facility
SEGS	solar energy generating system
SO_2	sulfur dioxide
T (^3H)	tritium
Tcf	trillions of cubic feet

TPES	total primary energy supply
TV	television
TW	terrawatts
UK	United Kingdom
UNICEF	United Nations Children's Fund
US	United States of America
USD	US dollars
UV	ultraviolet
VCD	vapor compression distillation
WEC	wave energy conversion
WHO	World Health Organization
WW	World War
ZEB	zero energy building
ZEH	zero energy home

“The future depends on what we do in the present.”

Mohandas Karamchand Gandhi

Chapter 1

Water and its global context

Water – a tasteless, odorless, simple chemical compound (H_2O) – is the most important commodity on Earth. It is 'key to life as we know it' (1) and has always been a focus of human attention. In fact the pre-Socratic Greek philosopher Thales of Miletus put forward his 'cosmological thesis' that 'the originating principle of nature and the nature of matter was a single material substance: water.' (2) In modern times water has also been the focus of our search for life on other planetary bodies.

1.1 EARTH'S WATER RESOURCES

The Earth is a water-rich planet. The estimated total volume of water is more than 300 million cubic miles, each cubic mile contains more than 1 trillion gallons (10^{12} gallons, approximately 3.78 teralitres), and water covers 71% of the Earth's surface. Along with energy, water is one of the two

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essential ingredients of sustainable economic development. However, there is one critical difference between the two: while energy can be derived from a variety of resources, there is no substitute for water. The Arab saying ‘water is life’ is a truism – without water you die.

Given the large amount of water on Earth, which has been constant for at least hundreds of millions of years, why are people concerned about water supply? The biggest problem is that most of that water, approximately 97%, is found in the oceans (seawater), with an average salt concentration of 35,000 parts per million (ppm). People and animals cannot drink that water for any length of time without dehydrating internally – the body extracts water from its cells to dilute the ingested salt – and eventually dying from organ failure. Salty (saline) water, such as that found in the oceans, must be desalted (desalinated) to a level at or below 1000 ppm for human and animal consumption. Saline water can also impose limits on agricultural production.

Of the remaining 3–4% of water on the Earth that is fresh, most is not easily available for our use. Over two-thirds is tied up in glaciers, polar ice caps, and permanent snow cover in mountainous regions, and the rest as groundwater in lakes and rivers, and as water vapor in the atmosphere – and even much of the groundwater is at unreachable locations and depths. The net result is that we make productive use of less than 1% of our global water resources.

1.2 SALINE WATER AND DESALINATION PROCESSES

Saline water is characterized into three broad categories:

- Highly saline water: more than 10,000 ppm
- Brackish water: 1000–10,000 ppm
- Freshwater: less than 1000 ppm

How does one remove salt from highly saline or brackish water to produce drinkable (potable) water? Quite a few technologies exist to do this separation, the oldest being sun-heated water that evaporates and is then condensed on a cold surface, leaving the salt behind. (*Note*: this also describes the first stage of the Earth's hydrologic cycle, in which sun-heated water evaporates from the oceans and other bodies of water into the atmosphere.) References to this process of evaporation and condensation, known as distillation, can be found in historical records going back centuries. Variations are widely used at sea today and, in the past, helped keep many early explorers and traders alive during long ocean trips. A modern-day example is a United States nuclear-powered aircraft carrier that uses waste heat from its nuclear reactor to desalinate 400,000 gallons of seawater per day.

The technologies used to perform this separation can be categorized broadly as either thermal or membrane technologies. The most popular today is reverse osmosis (RO) in which a pressurized stream of saline water is forced through a membrane which allows the small water molecules to pass through, but not the various salts found in brackish water or sea water. Several stages of such separation can lead to freshwater at or below the 1000 ppm level of salt. Other major desalination technologies are listed in Table 1.1.

Table 1.1 Desalination technologies.

Thermal Technology
- multi-stage flash distillation (MSF)
- multi-effect distillation (MED)
- vapor compression distillation (VCD)

Membrane Technology
- reverse osmosis (RO)
- electrodialysis (ED)
- electrodialysis reversal (EDR)

Multi-stage flash (MSF) distillation occurs in several successive stages, each at a progressively lower pressure. The feed water is first heated at high pressure, and the lower pressures in successive stages result in a sequence of sudden evaporation and condensation. In multi-effect distillation (MED), which uses the same principle of evaporation and distillation at progressively lower pressures, the water vapor of each vessel ('effect') serves as the heat source for the next vessel. Another variation is vapor compression distillation (VCD), where mechanical compression is used to generate the heat for evaporation.

In addition to RO, other membrane technologies are electrodialysis (ED) and electrodialysis reversal (EDR), both of which predate RO. Both are voltage-driven processes which utilize the fact that salts dissolved in water are electrically charged ions (either positive or negative). For example, in a saline solution containing dissolved sodium chloride, the sodium ion has a positive charge (cation) and the chloride ion a negative charge (anion). Applying a voltage across the ED membrane allows either a cation or an anion to pass through the membrane, leaving diluted water behind. In EDR the polarity of the driving voltage is reversed several times an hour. Once the desired water quality is achieved and the desalinated water is removed, the concentrate channels are flushed and clean water production resumed.

The RO process is a variation on osmosis, the phenomenon in which water with a low-salt concentration passes naturally through a semi-permeable membrane into a region of higher salt concentration. By applying pressure to the solution with a higher salt concentration, the water is forced to flow in a reverse direction through the membrane, leaving the salt behind. The required pressures range from about 150 pounds per square inch (psi), roughly equivalent to 1035 kPa, for low-salinity brackish water up to 800–1000 psi (5515–6895 kPa) for high-salinity seawater.

1.3 ENERGY REQUIREMENTS AND COSTS OF DESALINATION

How much does it cost to desalinate salty water? Figure 1.1 shows a typical breakdown of costs for seawater desalination showing that energy is one of the largest cost factors:

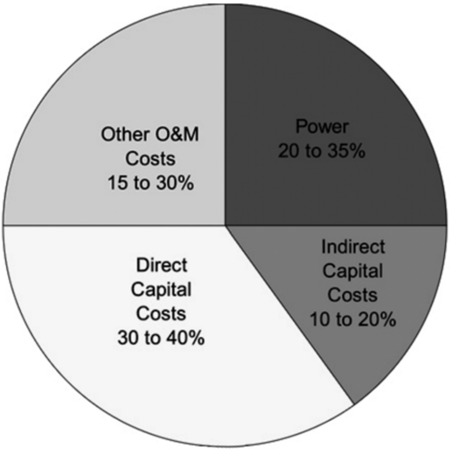

Figure 1.1 Breakdown of costs for seawater desalination (3).

Energy requirements (electrical + thermal) for a range of saline waters are shown in Table 1.2 for various desalination technologies (these figures do not include the energy required for pre-treatment, brine disposal and movement of water).

Table 1.2 Energy consumption for desalination technologies (4).

Technology	Total Equivalent Electrical Energy (kWh/m^3)
MSF	13.5–25.5
MED	6.5–11
VCD	7–12
RO	3–5.5

In recent years much effort has gone into reducing the costs of desalination, as its global importance has grown. Even though currently it only provides about 1% of the word's drinking water, this fraction is growing steadily, and desalination is increasingly recognized as a reliable, drought-proof source of potable water for coastal communities worldwide. Energy costs have been reduced by approximately 80% over the past two decades, and are projected to decrease by up to a further 60% in the next 20 years. These costs today range from 40 to 100 US cents per cubic metre (1000 litres) of freshwater. Nevertheless, while 'Today, the energy needed to produce freshwater from seawater for one household per year is less than that used by the household's refrigerator' (5), that cost is still higher, on average, than the cost of deriving freshwater from groundwater, water recycling or water conservation.

The International Desalination Association (IDA) reports that worldwide at the end of 2015 there were more than 18,000 desalination plants in 150 countries, producing about 87 million cubic metres of freshwater every day. About 44% of this capacity is located in the Middle East and North Africa (MENA). It is estimated that more than 300 million people currently rely on desalinated water for some or all of their daily needs.

1.4 DEMAND FOR FRESHWATER

Two important questions are: how is global demand for freshwater changing, and what are the implications when freshwater supplies are limited? Some people have identified access to freshwater as the 21st century's analog to the burning issue of access to petroleum supplies in the previous century.

During the 20th century, global population tripled while the human demand for freshwater increased by a factor of six. That demand tripled in the past 50 years alone. Providing that much water has significant environmental impacts, which will be discussed in Chapter 4. Today, on average, a little over two-thirds of global water withdrawals (70%) are for agriculture, while 20% are for industrial use and 10% for municipal use. In developing countries the percentage of water used for agriculture is even higher.

Figure 1.2 shows historic and projected world water demand from 1980 to 2030. It shows that current annual withdrawals are of the order of 5000 km^3, or about 30% of the estimated 14,000 km^3 of easily accessible freshwater.

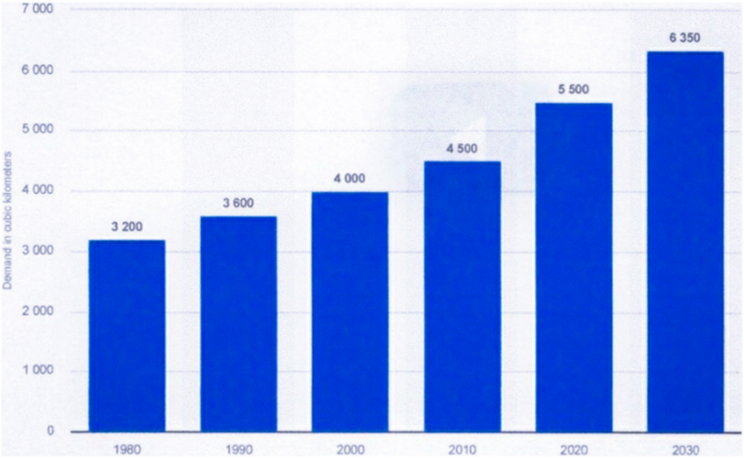

Figure 1.2 Historic and projected water demand (cubic kilometres) (6).

Thus, in theory there is enough freshwater to meet not only the current demand, based on a population of just over 7 billion, but also an increasing demand from a future population that may reach 9–10 billion by 2050. A related consideration is that ‘the world’s middle class is expected to grow from less than 2 billion in 2014 to nearly 4.9 billion by 2030, with even more growth by 2050. As this more affluent population increases, demand for water will surge – not least owing to a greater appetite for meat and other goods that are more water-intensive to produce. In developing countries, where the vast majority of both population growth and rising incomes can be found, a 50% increase in water withdrawals is expected by 2025, while developed countries will increase by 18%. As a result, as UN-Water highlights, water use continues to expand at more than twice the rate of population growth (7).'

An additional consideration, with major implications for global tensions, is that freshwater resources are not distributed uniformly around the globe, either in time or geography. Some locations have large resources of freshwater, and some have little or none. Even where resources exist, water scarcity can exist during specific times of the year – for example, when snow melt at one time cannot be captured for use at another time. It does not then come as a surprise that the struggle to control water resources has shaped human economic and political history. Globally, the 215 international rivers and 300 groundwater basins that are shared by two or more countries have often generated tensions. For example, in the volatile Middle East, water is a source of conflict not only between the Israelis and Palestinians, but also between Egypt and Sudan, and among Turkey, Syria and Iraq. Such tensions also exist between several states in the US, and elsewhere as well.

It is also important to recognize that the precipitation (rainfall) patterns that bring much of the world's freshwater will change as a result of global warming and climate change, often with adverse consequences. A more comprehensive discussion of this topic can be found in Chapters 4 and 10. Over-pumping and depletion of underground aquifers, as well as contamination of freshwater sources, are also serious concerns. It is estimated that withdrawals by farmers in India, China, the US, and elsewhere already exceed natural replenishment by 4%, and that gap is growing. Industrial, municipal, and agricultural runoff are contaminating existing freshwater sources, requiring water treatment before reuse.

1.5 IMPLICATIONS OF LIMITED ACCESS TO FRESHWATER

The implications of limited or no access to freshwater are significant, not only for food production but also for public health. Unfortunately, reliable data on clean water access and sanitation practices for parts of the developing world are still hard to come by. The 2017 report of the WHO/UNICEF Joint Monitoring Program on Drinking Water, Sanitation and Hygiene (8) estimates that in 2015 '844 million people still lacked even a basic drinking water service … 159 million people still collected (potentially contaminated) water directly from surface water sources/58% lived in sub-Saharan Africa … 2.3 billion people still lacked even a basic sanitation service' … 892 million people still practiced open defecation.'

An additional challenge is posed by increasing urbanization, the population shift from rural to urban areas. Seen as an inevitable consequence of the industrial revolution, it has major implications for delivery of water services. Currently more than half of the world's population lives in urban areas, and this fraction is expected to increase to 70% by 2050. In 1970 Tokyo and New York were the only cities with a population greater than 10 million people, so-called megacities. Today, there are 13 megacities in Asia, four in Latin America, and two each in Africa, North America, and Europe. Many of these cities are already experiencing severe water stress and their situations will only worsen. Water stress (sometimes referred to as water scarcity) can be defined as the inability to meet human and ecological demand for freshwater. The minimum quantity of water deemed necessary to satisfy basic human needs ranges from 20 to 50 litres (7.3–18.3 m^3) per person per day, depending on what is included in 'basic needs'. Many countries already fall below that level – water shortages currently plague almost every every country in MENA – and experts project that, under 'business as usual', close to 2 billion people in

39 countries will still face serious freshwater shortages in mid-century.

In the developing world it is estimated that waterborne diseases account for almost 80% of infections, causing more than 3 million premature deaths. Approximately 5000 children die from diarrhea every day (one every 17 seconds) and many more are stunted in their development as a result of recurrent diarrheal episodes. In addition, several hundred million people are infected with the parasitic disease schistosomiasis (snail fever disease), an estimated 880 million children are in need of treatment for intestinal worms, and an estimated 1.9 million people are blind from trachoma (caused by infection with the bacteria *Chlamydia trachomatis*) with an at-risk population in 41 countries of 190 million (9).

1.6 ACTIONS TO INCREASE ACCESS TO FRESHWATER

Many voices have tried to sound the alarm on growing water issues, especially in recent years. World Water Forums, hosted by the World Water Council, have been held every three years since 1997. The UN Millennium Summit in New York in 2000 identified water availability as a critical global issue, as did the 2002 World Summit on Sustainable Development in Johannesburg. The UN declared 2003 the International Year of Freshwater, and designated the period 2005–2015 the UN Decade of Water.

At its 2000 Summit the UN adopted a series of Millennium Development Goals (MDGs), two of which dealt with water issues: ‘to reduce by half, by 2015, the proportion of people without access to (a) safe drinking water and (b) basic sanitation.’ Assuming a world population in 2015 of 7.2 billion implied that, by 2015, 1.6 billion more people would need to be supplied with access to safe drinking water and an additional 2.2 billion to basic sanitation. Even if achieved, these goals still would have left 600 million people without access to safe drinking water and 1.5 billion without access to basic sanitation. The safe drinking water goal was met in 2010, but the basic sanitation goal is yet to be achieved in more than 70 countries.

In 2011 the InterAction Council (IAC), a high-level group of former national leaders that has met annually since 1963, warned of an impending ‘water crisis’ and established a panel to address what they saw as a worldwide leadership gap on the issue. In 2012 the panel released a report, ‘The Global Water Crisis: Addressing an Urgent Security Issue’ (10).

In the foreward to the report, Gro Harlem Brundtland, the former Prime Minister of Norway and IAC Chair, underlined the danger in many regions where critical shortages already exist – sub-Saharan Africa, West Asia, and North Africa: ‘As some of these nations are already politically unstable, such crises may have regional repercussions that extend well beyond their political boundaries. But even in politically stable regions, the status might very well be disturbed first and most dramatically by the loss of stability in hydrological patterns.’ IAC co-Chair Jean Chretien, former Canadian Prime Minister, added, when the report was released, that ‘The future political impact of water scarcity may be devastating. Using water the way we have in the past will not sustain humanity in the future. The IAC is calling on the United Nations Security Council to recognize water as one of the top security concerns facing the global community. Starting to manage water resources more effectively and efficiently now will enable humanity to better respond to today’s problems and to the surprises and troubles we can expect in a warming world.’

1.7 GENDER EQUITY ISSUES

To complete this overview of water issues I turn to the important issue of gender equity. In the context of this chapter ‘gender’ is a social and not a biological concept: for our purposes it refers to a set of relations which define social function and power on the basis of gender identity. This implies that gender-based relations can be changed. While these relations are not inherently oppressive, all too often they have been oppressive of women. Where gender equity is missing – that is, where women and men do not have equal opportunity to realize their full human rights and potential – there are serious negative consequences for development and for addressing issues related to water scarcity.

Women head one-third of the world's families (and more than half of the families in Latin America) and frequently are the principal water providers and income producers for their families. They are responsible for half of the world's food production, and produce a majority of the food in most developing nations. To produce this food and have adequate sanitation for their families they must first 'produce' water. They do this in many cases by spending several hours a day hauling water, time that could be better spent on education, cottage industries, and community development. If safe and reliable water sources do not exist within reach, they are forced to rely on often contaminated local water supplies or pay exorbitant prices to local water vendors. This has major implications for hygiene and the spread of diseases among poor women and their families. Finally, poor women's access to water in many communities is less than that of men because decisions are most likely made by men, and the needs of women are often ignored or undervalued. This has led to a situation where women are the poorest of the poor in many parts of the world, creating what has come to be called the 'feminization of poverty'.

Chapter 2

Energy and its global context

Any discussion of energy must begin with the recognition that energy is valued not for itself but rather for the beneficial services that its use makes possible. These ‘energy services’ include lighting, heating, cooling, communications, transportation (movement of people, water, and goods), and a broad range of commercial and industrial activities. In fact, there is some discussion that what should be marketed to consumers is not energy, as has historically been done, but the services that energy makes possible.

2.1 ENERGY’S ROLE IN SOCIETY

An often heard statement is that ‘energy is the lifeblood of modern societies’. While water may want to compete for that title, what is indisputably true is that energy in its various forms has been crucial to human activities over the centuries. Initially this was in the form of human and animal power and of fire. What is also true is that modern societies provide a wide and

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growing range of energy-dependent services to consumers that go well beyond what was possible before.

It follows that most governments will undertake policies to make it possible to provide these services using the least amount of energy feasible, to minimize economic costs and environmental and national security impacts (see Chapter 10 for a discussion of water and energy policies). For many years, in tandem with the industrial revolution, this energy was provided mostly by the combustion of fossil fuels – coal, oil, and natural gas (see Chapter 6). This is still true today (globally, we have about 80% dependency on fossil fuels) as we approach the third decade of the 21st century, and will probably continue to be true for at least several more decades. Nevertheless, change in the energy sector is well underway as renewable energy in its various forms enters the energy mainstream. A comprehensive discussion of these technologies can be found in Chapter 8.

2.2 ENERGY REALITIES

This change reflects several realities: fossil fuel reserves, while large, are finite and non-renewable on any timescale relevant to human history. Their combustion releases carbon dioxide into the atmosphere, which, unless captured and sequestered, has serious global warming consequences. The infrastructure for extracting and delivering fossil fuels is highly vulnerable to natural disasters, terrorist attacks, and other breakdowns. Their market prices are volatile, and energy imports constitute a major drain on the importing country's finances.

It is also important to recognize that, on a global basis, energy is not in short supply. Our Sun pours 6 million quads of radiation annually into the Earth's atmosphere, where one quad is a quadrillion (10^9) Btu. To put this number in context, the world currently consumes about 600 quads of energy annually as measured by commercial sales. This number is 10,000 times less than what we receive from the Sun, and is only 4 parts in

10 billion of what the Sun radiates in all directions into space. While some of this intercepted solar radiation (insolation) bounces off the Earth's clouds back into space, approximately 70% enters the atmosphere and becomes part of the Earth's energy balance with the Sun, which determines the Earth's average temperature (a more detailed discussion of this energy balance and global warming can be found in Chapter 4). In addition, there is considerable geothermal energy under our feet in the form of hot water and hot rock (see Chapter 8). Thus, the reality is that large quantities of energy are available on our planet. What is in short supply is inexpensive energy that people can afford to buy.

2.3 WHAT IS ENERGY?

Where does the word 'energy' come from, and how is it defined? It derives from the Greek word 'energeia' (as translated) which means activity or operation. When first used, probably by Aristotle in the 4th century BC, it was 'a qualitative philosophical concept, broad enough to include ideas such as happiness and pleasure (11).' Leibniz, in the late 1600s, defined something he called 'vis viva' (living force) as the product of an object's mass and its velocity squared, mv^2. Today, $\frac{1}{2}mv^2$ is referred to as an object's kinetic energy, as first articulated by Coriolis in 1829. The concept of potential energy was introduced in 1853 by Rankine.

Energy is often defined as 'the capacity or power to do work'. In physical/scientific terms it is 'the quantitative property that must be transferred to an object in order to perform work on, or to heat, the object' (12). It comes in several broad categories: kinetic energy – energy of motion; potential energy – energy due to an object's position in a gravitational or electromagnetic field; chemical energy – energy released when a fuel burns; radiation energy – energy carried by electromagnetic waves; elastic energy – energy stored by stretching solid objects; and thermal energy associated with an object's temperature. Energy is also a conserved quantity, as first discussed by Lord Kelvin in his development of thermodynamics. The law of energy conservation states that energy can be converted in form, but not created or destroyed. In addition, mass and energy are closely related, as expressed by the famous Einstein equation $e = mc^2$. The importance of this mass–energy equivalence will be discussed in our discussion of nuclear energy (Chapter 7).

2.4 ENERGY TRENDS

Historic trends in energy supply and demand – reflecting population growth in the 20th century (from 1.8 billion in 1900 to more than 6 billion in 2000), increased average income and associated welfare, and increasing urbanization (from 13% in 1900 to 48% in 2000) – led to a rapid rise in electrification and a dramatic increase in global energy demand, from 44 quads in 1900 to 406 quads in 2000. Transportation was the fastest-growing end-use sector, with petroleum supplying over 90% of its energy needs. These trends are continuing in the 21st century.

Projections by the International Energy Agency (IEA), the Energy Information Administration (EIA) of the US Department of Energy, and other major international energy organizations, all point to the same general conclusions: over the next few decades consumption of energy will increase, mostly in developing countries; fossil fuels will account for most of the increase and remain the dominant energy source; natural gas use will grow the fastest; nuclear power will grow, but slowly; and use of renewable energy will grow rapidly but will not displace fossil fuels as the principal energy source.

To be specific, the EIA, in its 'International Energy Outlook 2017' report (13), projects that under its 'business as usual' Reference case (which 'considers current policies 'as reflected in current laws, regulations' and stated targets that are judged to reflect an actual policy commitment') there will be an increase in global energy consumption from 575 quads in 2015 to 663 quads by 2030 and to 736 quads by 2040, with most of the increase in energy demand coming from countries that are not members of the OECD – the Organisation for Economic Co-operation and Development (see Figure 2.1).

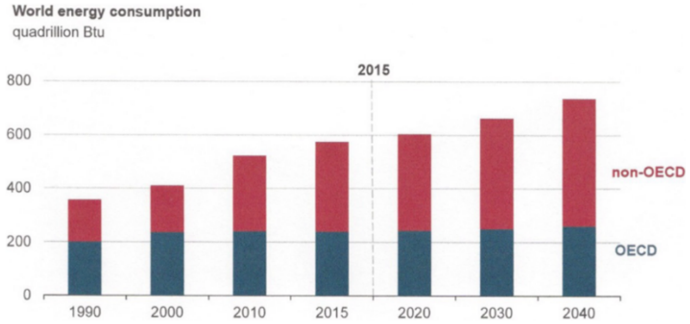

Figure 2.1 World energy consumption (*Source:* US Energy Information Administration).

It should be noted that the EIA recognizes the uncertainties inherent in creating these projections, and addresses this by creating High and Low Oil Price cases. In the Reference case the price of crude oil reaches $109 per barrel in 2040, whereas it reaches $226 in the High Oil Price case and $43 per barrel in the Low Oil Price case. These assumptions are reflected in Figure 2.2.

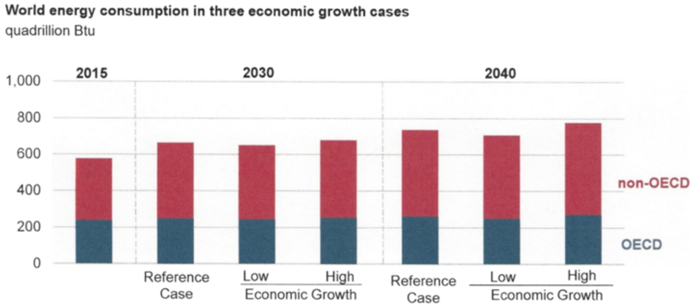

Figure 2.2 Energy consumption in three scenarios (*Source:* US Energy Information Administration).

2.4.1 Important questions

These projections mask several important questions. How urgent is it to reduce growth in global energy demand and related emissions of carbon dioxide and other greenhouse gases? When will conventional oil production reach peak supply, with attendant impacts on oil price and international competition for resources? What can the mining of oil-rich tar sands and the fracking of shale deposits rich in oil and natural gas mean for future oil and natural gas supplies? How vulnerable to disruption is our energy infrastructure, on which we depend so heavily? How quickly can renewable and advanced nuclear energy technologies be brought on line to replace fossil fuels? The answers to these questions will largely determine our energy future in the 21st century.

2.4.2 How is energy used?

We also need to ask: how is energy being used today and how is it likely to be used in the decades ahead? The industrial sector, which includes agriculture, mining, manufacturing, and construction, is responsible for most global energy consumption today, and will continue to be the largest end-user (more than 50%) through the EIA's projection period. The transportation sector sits in second place and the buildings sector comes in third (see Figure 2.3).

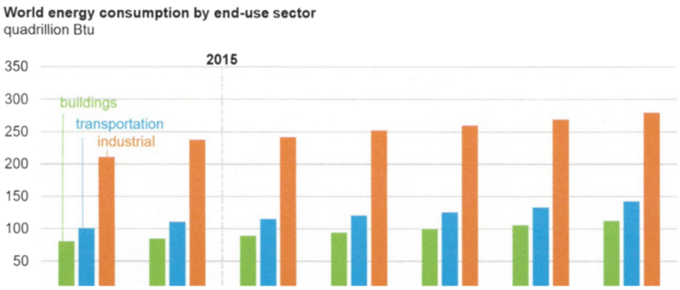

Figure 2.3 Energy consumption by end-use sector (*Source:* US Energy Information Administration).

Throughout the EIA’s projection period the use of all fuels grows, except for coal, where worldwide use stays flat. It is increasingly replaced by natural gas and renewables, and, in China, by nuclear power. Renewable energy grows the fastest. Petroleum and other liquid hydrocarbons remain the world’s largest energy source, but natural gas is the fastest-growing fossil fuel (see Figure 2.4).

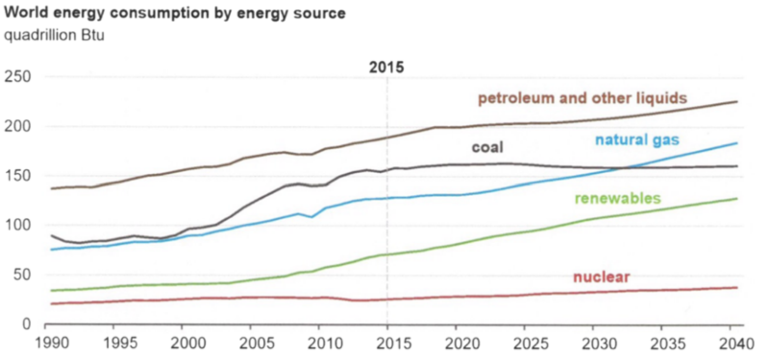

Figure 2.4 Energy consumption projections (*Source:* U.S. Energy Information Administration).

World oil production (including all liquid hydrocarbons), 93.7 billion barrels per day in 2016 (14), is currently holding its own due to major new discoveries of conventional reserves at great depths beneath the ocean floor. There is also considerable new non-conventional production from tar sands and fracking, both of which will be discussed in Chapter 6. In fact, according to Dr Fatih Birol, head of the IEA, ‘Fracking will make the United States the largest supplier of oil and gas in the world by 2023 (15).’ Further discoveries of conventional oil are also anticipated in Arctic and Antarctic regions as they become less ice-covered due to global warming.

Nevertheless, many, if not most, analysts expect oil production to reach its peak (‘peak out’) within the first half of the 21st century. It is important to note that 'peaking out' still leaves lots of liquid hydrocarbons to be extracted. The US currently ranks as the world's top oil producer, followed by Saudi Arabia, Russia, Canada and China (see Figure 2.5).

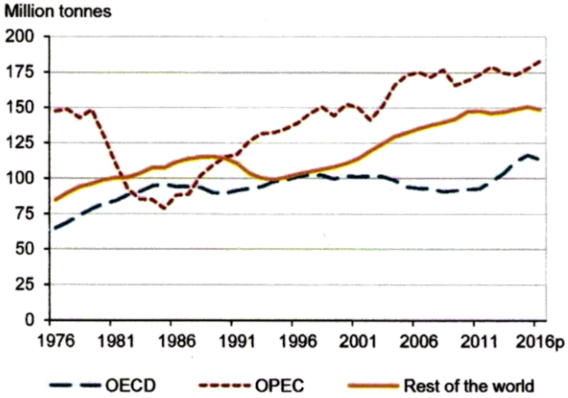

Figure 2.5 World oil production by region (*Source:* International Energy Agency).

Demand for liquid fuels today is driven largely by their use in transportation and is growing as automobile, truck, and aviation use grows in many countries. Eventually, this demand will begin to decrease as more fuel-efficient cars, alternative fuels, and electric drive propulsion systems enter the transportation market. According to the IEA, between 1971 and 2016 oil's share of total primary energy supply (TPES) fell from 44% to 32% (16).

This is just one of several changes that have occurred in the global energy picture over this period. TPES increased by a factor of 2.3 (from 6101 Mtoe to 13,647 Mtoe); coal increased its share to 29% in 2011, when it peaked, and has been declining since (27% in 2016); nuclear's share rose from 1% to 5%; and the natural gas share grew from 16% to 22% (see Figure 2.6).

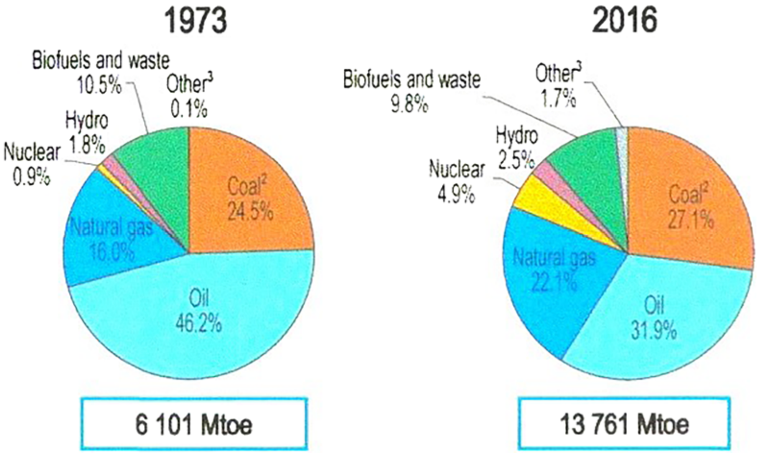

Figure 2.6 Total primary energy supply by fuel (*Source:* International Energy Agency).

2.4.3 Electrification

As mentioned previously, increasing electrification was a defining characteristic of energy supply in the 20th century and continues to define the 21st. In fact, it is the electrification made possible by use of distributed renewable electric technologies, such as solar, wind and hydropower, that is enabling the delivery of energy services to remote parts of the world. Combined with increasing sensitivity to the negative impacts of fossil fuel combustion, this increasing use of renewable energy technologies (and, to some extent, nuclear) in place of fossil fuels constitutes an energy supply revolution. This transition took its first tentative steps in the latter part of the 20th century and is now developing rapidly. It has the potential to improve the welfare of hundreds of millions if not billions of people as our new century progresses.

In 2017 fossil fuels were used to generate 65% of world electricity, with coal accounting for 38%, natural gas 23%, and oil 4%. The corresponding figures for other supply sources were nuclear power at 10% and renewable sources (hydropower, geothermal, wind, solar, tidal) at 25%. See Figure 2.7 (17).

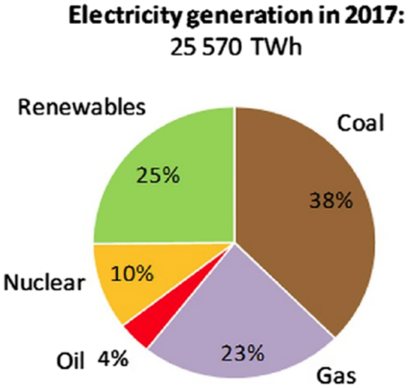

Figure 2.7 World electricity supply by source-2017 (*Source:* International Energy Agency).

This pie chart will look quite different in coming decades as coal's share of electricity production decreases, natural gas's share increases, nuclear's share stays flat or decreases, and renewable energy's share increases significantly.

Chapter 3

Exploring the linkage between water and energy

What seems obvious upon reflection, but has been little discussed until fairly recently, is that there is an inextricable linkage between water and energy. This linkage has been given a name, the water–energy nexus. It recognizes explicitly that making water available to consumers requires the use of energy to extract water from underground aquifers and move it through pipes and canals, to desalinate brackish water or seawater, to treat used water so that it can be recycled, and to disinfect contaminated water.

At the same time it also recognizes that many forms of energy production and use depend on the availability of water, for example, hydropower sites where the kinetic energy of falling water is converted to rotary motion and electricity in a turbine generator. It includes the use of water to cool the thermal exhausts of steam-driven turbine generators, as in fossil fuel, nuclear, geothermal, and concentrating solar power plants. Water plays an important role in fossil fuel extraction via

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injection into conventional oil wells to increase production; in production of oil from tar sands; in the extraction of oil and natural gas from fracking of underground shales; and in the conversion of petroleum into products such as gasoline, diesel fuel, and plastics. In addition, water is essential to the growth of biomass, increasingly seen as a source of alternative liquid and gaseous fuels. Finally, if in the future we move toward greater use of hydrogen as an energy carrier and energy storage medium, large quantities of water will be required to provide the needed hydrogen via electrolysis.

3.1 INDIRECT LINKAGES

Other, indirect, linkages exist as well. The production and use of energy creates emissions and waste products that can pollute surface and underground water supplies. Energy production is also recognized as a major contributor to global warming and climate change (see Chapters 4 and 10), which can disrupt the hydrological cycle and affect global water resources long before other impacts are felt. A US National Assessment in 1998 stated that 'In many cases and in many locations, there is compelling evidence that climate changes will produce serious challenges to our water systems'. The 2008 Intergovernmental Panel on Climate Change (IPCC) 'Technical Paper on Climate Change and Water' stated that 'Observational records and climate change projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change.' By altering the timing of winter snows, snowmelt, and spring rains, climate change could overload reservoirs earlier in the year than usual, forcing unanticipated releases of water that leave areas like the Himalayas and California dry later in the year. Coastal areas and island nations also face a serious threat from global warming: elevated sea levels, which destroy property, flood low-lying areas, and cause infusions of seawater into freshwater supplies, putting the drinking water of millions of people at risk.

Another concern is that competition for water resources is already limiting electricity production: operating licenses for some thermal power plants have been denied or issued with water use restrictions. An additional concern is that a significant fraction of goods are moved by freight on inland waterways. If competing demands for water limit the depth of such waterways, more energy will be required to move these goods by less efficient rail and truck.

3.2 THE POLICY LINKAGE

A further linkage exists in the recognition that energy and water policy can be expressed in exactly the same terms. Energy security requires that we use the least amount of energy to provide energy services, and that we have access to technologies that provide a diverse supply of reliable, affordable and environmentally benign energy. This implies that the first priority of an energy policy must be the wise, efficient use of whatever energy supplies are available (whether fossil fuel, nuclear or renewable). The next focus must then be on finding new energy supplies that meet sustainability and environmental requirements. The same words, with water replacing energy, can be used to describe water policy.

3.3 THE CONUNDRUM

It is clear that the energy security of a nation is closely linked to the state of its water resources. No longer can water resources be taken for granted if energy security is to be achieved or maintained. At the same time, water security cannot be guaranteed without careful attention to the energy issues involved in provision of water services. Built into this relationship is a conundrum: policy goals associated with providing adequate supplies of energy and clean water are often in conflict. As we move further into the 21st century, when demand for one increases so does demand for the other. Given their linkage, can we satisfy increasing demands for both as global population and human welfare increase? Are trade-offs necessary between the two? This was not a problem at the beginning of the 20th century, when the world's resources supported fewer than 2 billion people, but today's population of more than 7 billion, and heading higher, presents a vastly different situation.

3.4 ADDRESSING THE CONUNDRUM

When one looks at how to address the conundrum, one must start with the understanding that water and energy are in abundant but not necessarily inexpensive supply. The world will not run out of water nor of energy, but we may – and most likely will – have to pay more for one or both. Complicating this situation is that government officials are too often resistant to telling people the hard truth if that truth involves higher consumer costs and risks negative political reactions. Generally, people want more clean water and more energy, but are reluctant to pay for it. This tells us that the issue is not technological, but economic and political.

An interesting example of how we might deal with the conundrum is associated with desalination. In the early days of large-scale desalination, thermal distillation was the norm. The needed thermal energy was provided by the waste heat from the combustion of fossil fuels for electricity generation: for example, via the combustion of oil in Saudi Arabia and of natural gas in Qatar. The irony is that the CO_2 released into the atmosphere by this combustion increases global warming and results in changed rainfall patterns that often reduce freshwater supplies. Addressing this conflict requires breaking the link between the use of fossil fuels and supplies of clean water.

Breaking this link can be achieved in two ways: replacing electricity powered by fossil fuels with nuclear power, and facilitating the inevitable transition to a global energy system that, over time, will rely less on fossil fuels and more on renewable energy sources. These latter technologies – solar, wind, hydropower, geothermal, biomass, ocean power – offer a large energy resource, reduced water requirements, the possibility of reduced energy costs (and their long-term stabilization), reduced market uncertainties, reduced international competition for energy resources, reduced greenhouse gases, enhanced job creation, and the ability to reduce energy imports and keep an increasing share of the payments for energy supplies in one's country for domestic investment.

Nuclear fission power offers some of these advantages (it is a large, non-CO_2 emitting energy source), but faces several serious problems – safety, cost, radioactive waste storage, weapons proliferation – that must be addressed if it is to play an important role in our future energy system. The long-term hope for nuclear power is nuclear fusion, which involves the fusion of two hydrogen isotopes (deuterium and tritium) into the heavier element helium, with a mass loss that is converted to energy. The world's oceans contain enough deuterated water (D_2O) – roughly 1 part in 6000 – to supply endless amounts of energy. In addition, the radioactive waste problems associated with nuclear fusion are much less than those with nuclear fission. Both technologies are discussed in Chapter 7.

3.5 THE NEED FOR PARTNERSHIP

Let me close this discussion with one further word on the emerging understanding of the close relationship between water and energy. Until fairly recently most people in the energy community thought about water in limited ways – hydropower and cooling of power plant exhausts – while many people in the water community rarely thought about the energy needed to provide water services. This may have worked well enough in the 20th century but will not work in the 21st as populations and demands for both water and energy continue to grow. If we are to optimize our use of these essential resources we cannot treat water and energy issues as separate entities. Rather, we must create effective partnerships between those in government who have responsibility for water and energy security. This new understanding also suggests a related research agenda that requires government and private sector support:

- Reducing the energy requirements of desalination
- Developing improved technologies for water treatment and reuse
- Reducing the water requirements of agriculture
- Reducing the water requirements of thermal power plants
- Understanding the impact of global warming and climate change on spatial and temporal variability of water resources
- R&D to understand the water requirements of emerging energy technologies (to be discussed in succeeding chapters:
    - biofuels from biomass
    - oil and natural gas from fracking of shale deposits
    - oil extracted from tar sands
    - carbon capture and sequestration
    - concentrating solar power
    - the hydrogen economy.

The conundrum presents serious challenges, but many promising options to address these challenges exist.

Chapter 4

Energy production and its consequences for water and the environment

4.1 IMPACTS

Environmental issues arise from harmful effects of human activity on the biosphere, the part of the world in which life can exist. A significant number of these impacts are associated with energy production and they come in many forms.

Global warming and climate change: the result of introducing large quantities of CO_2, CH_4, and other greenhouse gases into the atmosphere. Adverse impacts of climate change are already being felt, for example, changes in rainfall patterns, droughts, intense storms, rising sea levels, ocean acidification, and migration of disease carriers. Many scientists and others believe that addressing climate change on a coordinated global basis is the most critical challenge currently facing the world. The basics of global warming will be discussed in this chapter; its potential impacts and related policy issues will be discussed in Chapter 10.

Air, water, and soil pollution: arising from the combustion of fossil fuels, heavy use of nitrogen-rich fertilizers, and

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agricultural runoff. Fossil fuels, a major source of thermal energy for electricity generation, create a large number of toxic emissions when combusted: carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), heavy metals such as mercury (Hg), and low levels of radioactivity released when coal is burned. Combustion products contaminate the air we breathe and can contaminate water sources unless carefully controlled. Nitrogen-rich fertilizers, now widely used in agriculture, release nitrogen dioxide (NO_2) into the atmosphere; NO_2 is a powerful greenhouse gas, much more so than CO_2. CH_4 is widely used as a fuel in power generation, and is also a powerful greenhouse gas that can leak into the atmosphere if not carefully contained. In addition, the transport of fossil fuels – as in the movement of petroleum products through pipelines and by rail – has occasionally involved accidents that have spilled large amounts of petroleum, threatened water supplies, and in some cases led to damaging fires.

Deforestation and land degradation: trees are a major sink for CO_2, which is required for biomass growth. When they are chopped down for energy use or other uses and not replaced systematically, the land is degraded in terms of its water-holding ability and its aesthetic appearance. With less vegetation, less CO_2 is removed from the atmosphere, and combined with the contemporaneous release of CO_2 into the atmosphere from the combustion of fossil fuels the atmosphere's average concentration of CO_2 increases. This enhances the global warming effect. Also, power plants can have large footprints that prevent other uses of surface areas as well as changing the covered ground's reflective properties (albedo), which can also contribute to global warming.

Habitat destruction and loss of biodiversity: the destruction of forests has another impact, the removal of traditional homes/habitats for many species of animals. If these animals cannot move and adapt to new habitats, their numbers will decline and, in some cases, they may become extinct. One example of such habitat destruction is the cutting down of forests in the Amazon to create new agricultural land for growing crops that can be converted into liquid fuels (e.g., alcohols).

Water requirements: thermal power plants – fossil fuel, nuclear, geothermal, concentrating solar – require large amounts of water for cooling turbine generator exhausts; fracking requires large amounts of water per well to release trapped oil and natural gas; hydropower generators require high water flow rates. These requirements often conflict with other demands for community and agricultural water, creating potential shortages and tensions.

Issues associated with nuclear fission power: while nuclear power offers a large, CO_2-free thermal energy source, its use presents five serious areas of concern:

(a) safety: nuclear fission creates large amounts of short- and long-lived radioactive waste products that, if released accidentally, can cause serious health effects and long-term abandonment of public areas. The meltdown of the Chernobyl nuclear power plant in Ukraine in 1986 has put a large area around the plant off limits for human occupation for about a century. A similar situation exists around the site of the Fukushima Daichi reactor meltdowns in Japan in 2011.

(b) the capital requirements and running costs of nuclear-generated electricity;

(c) the safety of transport of radioactive wastes through communities on the way to temporary or permanent storage;

(d) the ability to store safely, for long periods of time, highly radioactive wastes with long half-lives; and

(e) protecting nuclear materials from diversion to use as weapons.

Several of these impacts will be discussed in more detail in succeeding chapters on specific energy technologies.

4.2 MORE ON CLIMATE CHANGE

As mentioned above, climate change has been identified by some as the most important challenge facing mankind. I would pair it with the threat posed by potential use of nuclear weapons in warfare as our most challenging issues. Nevertheless, climate change is worthy of our most careful attention.

What causes global warming and the resulting climate change? It is not hard to understand using only basic physics: it is the same physical process that occurs in a car on a hot day that we all experience. Every warm body radiates energy. The visible light rays from the sun, distributed in a frequency spectrum determined by the Sun's surface temperature (about 5500° C/10,000°F), easily pass through the car's glass windows and are absorbed by the car's interior, which gets warm and often hot to the touch. These warm or hot surfaces then reradiate in a spectrum different from the sun's radiation because of their vastly different surface temperatures. The basic physics is the same – Planck's Law, first proposed in 1900, specifies the spectral distribution and intensities of the radiation emitted by a black (perfectly emissive) body at temperature T. In a car the energy reradiated from the interior surfaces is mostly in the infrared region, which doesn't pass easily through the glass. This trapping of the reradiated heat causes the car's interior temperature to rise until, owing to the interior's now higher temperature, enough reradiated infrared radiation gets through the glass to provide a balance between the energy of the incoming and outgoing radiation streams.

This is exactly what happens in the Earth's atmosphere, with gases and water vapor in the atmosphere playing the role of the glass windshield and determining the atmosphere's transmission characteristics. Important global warming (greenhouse) gases are CO_2 (much arising from combustion of fossil fuels), methane (CH_4), and a few others such as NO_2 and certain hydrofluorocarbons. The Earth's current temperature, hospitable to life as we know it, reflects an energy balance between the Sun and the Earth. Venus is an example of a planet where the equilibrium temperature reached by the planet to achieve an energy balance with the Sun is much higher.

4.3 ENVIRONMENT AND RELIGION

An interesting aspect of dealing with environmental issues is the emergence in recent years of academic disciplines studying the relationship between the environment and religion. This emergence reflects a growing understanding that 'the environmental crisis is fundamentally a crisis of 'values'' (18) and that values derive largely from religious teachings. Some scholars trace Western Society's concern for the environment to the fundamental concept of Judaism and the Judeo-Christian tradition that God created the universe and that only God has absolute ownership over Creation. This is the theocentric worldview, as opposed to the anthropocentric viewpoint that emphasizes, as stated in Genesis I, that humans exercise 'dominion' over the Earth. Others point to the Deuteronomic commandment 'bal tashchit' in the Old Testament that is an injunction against unnecessary destruction.

4.3.1 The theocentric worldview

In the theocentric, God-focused, worldview, the environmental implications are that humans must realize that they do not have unrestricted freedom to misuse Creation as it does not belong to them. Everything we own, everything we use, even ourselves, ultimately belongs to God. We are to be stewards of the Earth and the role of mankind is to enhance the world as 'co-partners of God in the work of Creation.' This implies that we must always consider our use of Creation with a view to the larger good in both time (i.e., responsibility to future generations) and space (i.e., responsibility to others on this world). It also implies that we must think beyond our own species to that of all Creation. There is a Jewish midrash, a rabbinic teaching that fills in perceived 'gaps' in the Old Testament, that builds on this concept of co-partnership:

> 'In the hour when the Holy one, blessed be He, created the first man,
> He took him and let him pass before all the trees of the Garden of Eden
> And said to him: 'See my works, how fine and excellent they are!
> Now all that I have created, for you have I created.
> Think upon this and do not corrupt and desolate My World,
> For if you corrupt it, there is no one to set it right after you.'

4.3.2 The anthropocentric worldview

The anthropocentric worldview, the 'dominance' view, focuses on how mankind uses the fruits of Creation to meet its own needs. In a 1966 lecture to the American Academy of Arts and Sciences, subsequently published in 1967 in the journal *Science* (19), the historian Lynn White argued that that the Judeo–Christian heritage arising from the 'dominion' commandment is responsible for the current ecological crisis. One response has been a Jewish and Christian environmental movement that was in many ways motivated by the revival of back-to-the-land values in the 1960s and 70s'.

4.3.3 Other worldviews

By the 1990s the debate on environmentalism had expanded to analysis of how nature is valued in other religions. Critical events were the series of ten conferences on Religion and Ecology organized between 1996 and 1998 by two professors at Yale University, Mary Ellen Tucker and John Grim. Papers from the conferences, attended in total by about 2000 people, were then published in a series of ten books, one for each major world religion (20). What becomes clear is that all major religions preach mankind's harmony with nature. What is all too real is that there is often a large gap between what is preached and what is practiced.

How is this harmony described in other than Judaism and Christianity? Buddhism emphasizes the interconnectedness of nature and life – damage done to our environment is also done to us. Concern for nature in Hinduism reflects the social thoughts of Mahatma Gandhi, sometimes referred to as the 'father of Indian environmentalism'. He argued that 'environmental sustainability and social inequalities should be managed in similar fashions' (21). Islam treats the environment as sacred and argues that people, as trustees of God, are responsible for protecting the world and its variety of life. Similar messages can be found in the teachings of Taoism, Jainism, and Animism.

Has this common ethic of harmony with nature impacted our use of energy? Firewood has long been a source of energy for individuals and communities, requiring the cutting of trees. In old Muslim cemeteries in Pakistan ancient trees can still be found because they are not allowed to be cut. Similar prohibitions have protected an ancient Maronite forest in Lebanon. Monasteries in Thailand have been built by Monks in endangered forests to make them sacred and safe from logging. The Sikh community in India is reducing its use of fossil fuels in their temples. The Church of Germany has installed solar panels on 300 churches and helped other organizations switch to solar. And as we advance further into the 21st century, protection of the environment has become a powerful political force, as reflected by the energy revolution that is currently underway.

Chapter 5

Energy options

The world is presented with quite a few options for the energy it needs, with most of them derivative of the largest energy source of all, our Sun.

5.1 FOSSIL FUELS

The energy resources known as fossil fuels were formed from organic matter that, under high pressures and temperatures deep in the Earth, was converted over millions of years into solid, liquid or gaseous fuels. Organic matter refers to the huge quantities of carbon-based compounds that originally were the remains of plants and animals. This matter, over time, has been physically and chemically altered to become a different set of compounds that we now know as coal, petroleum (oil), and natural gas. Each will be discussed in more detail in Chapter 6. While such fuels are still being formed in various deep underground locations, they are considered non-renewable on

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any timescale relevant to human activities. Their production takes millions of years, while their depletion through use occurs on a much, much shorter timescale.

5.2 NUCLEAR ENERGY

Nuclear energy, the energy that is released when matter is converted to energy, can be tapped via nuclear fission, the splitting of heavy nuclei into lighter ones, or via nuclear fusion, the fusing of two low atomic weight nuclei to create one of greater atomic weight. In both cases mass is lost in the nuclear process and this lost mass provides large amounts of energy in accord with Einstein's $e = mc^2$ equation. These nuclear processes are described in Chapter 7.

5.3 GEOTHERMAL ENERGY

Another large energy resource is the heat energy stored in the Earth that derives from radioactive decay at the Earth's core. This geothermal energy is available everywhere on Earth if one drills deep enough and is discussed in Chapter 8.

5.4 THE SUN

Our largest energy resource, the Sun, is a modest-sized star located, on average, 93 million miles (150 million kilometres) from the Earth. Its energy, as does that of other stars, derives from long-lasting fusion reactions in the Sun's interior. Chapter 7 provides a detailed discussion of the Sun's primary fusion reaction, the fusing of hydrogen isotopes into helium. The energy created in the Sun is transmitted to the Earth as radiation that enters the Earth's atmosphere. Through a variety of mechanisms, this radiative energy becomes available for our use as solar, wind, biomass, hydropower, and ocean energy. These, and another form of energy (tidal energy, driven by the gravitational tug between Earth and Moon) constitute, together with geothermal energy, the emerging category of renewable energy. They are described more fully in Chapter 8.

5.5 ENERGY EFFICIENCY

It is useful to begin an in-depth discussion of energy options with a discussion of energy efficiency, the wise use of energy that enables reduced energy demand. It can also be described as the low-hanging fruit in the pursuit of providing safe, reliable, and sustainable energy services. Energy efficiency is the one 'energy resource' that every country possesses and for which there remains vast untapped potential. It has even been suggested that, rather than treating energy efficiency as solely a demand-side approach, it be treated as an energy supply resource to be 'mined'. In the opinion of many, including me, it should be the cornerstone – that is, the essential starting point and pillar – of a nation's energy policy.

We begin this discussion by differentiating between two terms that are sometimes confused: energy conservation and energy efficiency. Energy efficiency means using less energy to perform a task, for example, providing a specified amount of light by expending fewer kilowatt-hours. Energy conservation is a broader term in that it includes actions, such as changes in behavior, to decrease energy consumption. An example of conservation without efficiency improvements would be driving your car less to reduce fuel consumption, or drying your clothes on an outdoor clothesline to avoid using a clothes dryer. US President Jimmy Carter brought the term 'conservation' forcefully to public attention during his 5 April 1979 'Energy Address to the Nation' (22), at a time when energy issues were a prime focus of attention. He stated that 'In addition to producing more energy, we must conserve more energy. Conservation is our cheapest and cleanest energy source. It helps to control inflation, and every barrel of oil we save is a barrel we don't have to import.' He also stated that 'In addition, I ask each of you to take an important action on behalf of our nation. I ask you to drive 15 miles a week fewer than you do now. One way to do this is not to drive your own car to work every day. At least once a week take the bus, go by carpool or, if you work close to home, walk.' Unfortunately, this speech came to be regarded as a request 'to do without' and conservation, for some, took on a negative connotation. In the following years, costs of imported oil dropped dramatically, until in the mid-1980s the price of an imported barrel of oil went below $10 a barrel. It would be several more years before energy issues again began to capture public attention.

5.5.1 Energy demand

An important starting point is: how is energy consumed by end-use sectors? Categories for this consumption vary among analysts, but a common categorization is buildings (residential and commercial), industry (manufacturing, mining, construction, power), and transportation (road, air, water, rail). Another categorization, utilized by BP in its 'BP Energy Outlook – 2018 edition' (23), uses the terms transport, buildings, industry, and non-combusted, where 'industry' excludes non-combusted use of fuel, usually as a feedstock in production of petrochemicals (see Figure 5.1, and note that the data is presented as billions of tons oil equivalent (btoe), where one btoe equals 39.7 quads).

The figure shows that, today, industry (if one includes non-combusted) accounts for just over half of total global consumption, buildings account for just under 30%, and transportation accounts for about 21%. The Executive Summary of this BP report also includes the following statements:

- In the Evolving Transition scenario [one of several scenarios examined by BP and the one selected for discussion 'for ease of explanation'], world GDP more than doubles by 2040, driven by increasing prosperity in fast-growing emerging economies, as more than 2.5 billion people are lifted from low incomes.

- This rising prosperity drives an increase in global energy demand, although the extent of this growth is offset by accelerating gains in energy efficiency; energy demand increases by only around one-third over the next 25 years.
- The world continues to electrify, with almost 70% of the increase in primary energy going to the power sector.
- All the growth in energy consumption is in fast-growing developing economies: China and India account for half of the growth in global energy demand.
- Renewable energy is the fastest-growing energy source, accounting for 40% of the increase in primary energy. The energy mix by 2040 is the most diversified the world has ever seen.

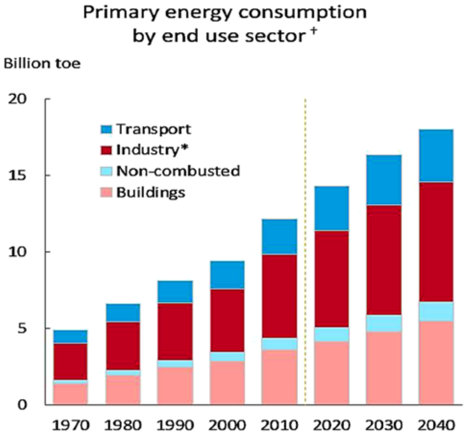


Figure 5.1 Global energy consumption (*Source:* 2018 BP Energy Outlook).

5.5.2 Implementation

Energy efficiency improvements can be implemented in a variety of ways in every end-use sector of the economy, and many new approaches to delivering energy efficiency are being developed and tested. While there is some debate about how to ensure and document actual energy savings, energy efficiency has demonstrated in many cases that it is a cost-effective strategy for economic growth without increasing energy consumption. A prime example is the state of California, which in the 1970s, under the guidance of visionaries such as Art Rosenfeld, began implementing building code and appliance standards with strict efficiency requirements. As a result, California's per capita energy consumption has remained flat for decades while the corresponding number for the entire nation has doubled. California also ranked energy efficiency as its first priority for new energy resources, ahead of renewable electricity supplies (#2) and new fossil fuel plants (#3). Other US states and other countries have followed suit.

5.5.3 Saving energy

How much energy can be saved through energy efficiency? We know that large amounts of energy are wasted through losses in transmission lines, thermal power generation, lighting and heating systems, internal combustion engines, and other industrial and commercial technologies. The Rocky Mountain Institute, headed by Amory Lovins, estimates that 'there are abundant opportunities to save 70% to 90% of the energy and cost for lighting, fan, and pump systems; 50% for electric motors; and 60% in areas such as heating, cooling, office equipment, and appliances.' (24) The US Department of Energy (DOE) has similarly identified potential for large energy savings. Many other studies confirm these estimates and present many reasons to improve energy efficiency: reduced energy consumption reduces energy costs, reduces emissions of CO_2 and other toxic combustion products, reduces water demands, reduces energy imports, and keeps money not spent on imports available for local investment.

5.5.4 Accelerating implementation

Given all the positive attributes of improved energy efficiency, how does one accelerate its implementation? In the aftermath of the 1973–74 OPEC Oil Embargo, which brought energy supply and demand issues to the fore in the US and other nations, the US Congress in 1975 passed the Energy Policy and Conservation Act (EPCA), which was later amended and updated by the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007. This legislation, together with the National Appliance Energy Conservation Act of 1987, established a regulatory framework that sets minimum efficiency standards for a wide range of appliances and equipment used in residential and commercial buildings. The EPCA also set corporate average fuel economy (CAFE) standards for new automobile and light-duty van fleets, and introduced energy efficiency labels to assist consumers in their purchasing decisions.

Currently, DOE efficiency standards are in place, or in active development, for approximately sixty categories of product, as shown in Figure 5.2. DOE is required to set the standards at ‘levels that achieve the maximum improvement in energy efficiency that is technologically feasible and economically justified.’ (25)

Through the regulations issued by DOE, they have proven to be one of the most impactful energy-saving policies to date. They help ensure that all regulated products meet minimum performance standards and keep low-quality, inefficient products out of the marketplace. Several US States have adopted their own appliance and equipment standards for products that are not already covered by a federal standard. These state standards may be enforced up until the federal standards take effect. States that have not set product standards are subject to the applicable federal standards immediately. Promotion of energy efficiency standards is also the core mission of CLASP (26), which began

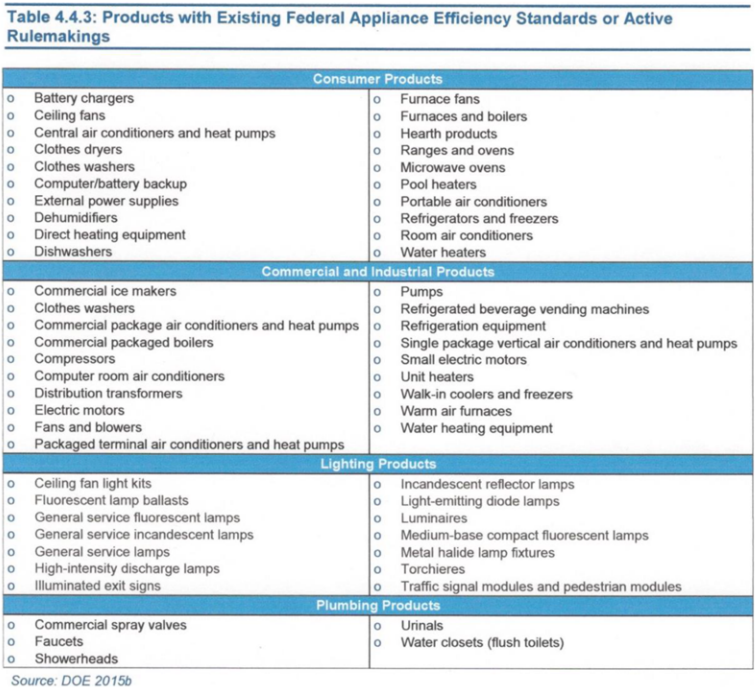


Table 4.4.3: Products with Existing Federal Appliance Efficiency Standards or Active Rulemakings

Consumer Products

- Battery chargers
- Ceiling fans
- Central air conditioners and heat pumps
- Clothes dryers
- Clothes washers
- Computer/battery backup
- External power supplies
- Dehumidifiers
- Direct heating equipment
- Dishwashers
- Furnace fans
- Furnaces and boilers
- Hearth products
- Ranges and ovens
- Microwave ovens
- Pool heaters
- Portable air conditioners
- Refrigerators and freezers
- Room air conditioners
- Water heaters

Commercial and Industrial Products

- Commercial ice makers
- Clothes washers
- Commercial package air conditioners and heat pumps
- Commercial packaged boilers
- Compressors
- Computer room air conditioners
- Distribution transformers
- Electric motors
- Fans and blowers
- Packaged terminal air conditioners and heat pumps
- Pumps
- Refrigerated beverage vending machines
- Refrigeration equipment
- Single package vertical air conditioners and heat pumps
- Small electric motors
- Unit heaters
- Walk-in coolers and freezers
- Warm air furnaces
- Water heating equipment

Lighting Products

- Ceiling fan light kits
- Fluorescent lamp ballasts
- General service fluorescent lamps
- General service incandescent lamps
- General service lamps
- High-intensity discharge lamps
- Illuminated exit signs
- Incandescent reflector lamps
- Light-emitting diode lamps
- Luminaires
- Medium-base compact fluorescent lamps
- Metal halide lamp fixtures
- Torchieres
- Traffic signal modules and pedestrian modules

Plumbing Products

- Commercial spray valves
- Faucets
- Showerheads
- Urinals
- Water closets (flush toilets)

Source: DOE 2015b

Figure 5.2 Appliances with federal efficiency standards (*Source:* U.S. Department of Energy, 2015).

as a US-focused organization but has now extended its activities to many other countries.

5.5.5 Energy star

A US federal program that extends the impact of energy efficiency standards is Energy Star, a voluntary program started by the EPA in 1992. It is now managed jointly with DOE and provides information that consumers and businesses can use to make well informed purchasing decisions. It also promotes the Energy Star label (see Figure 5.3) that is awarded to certified energy-efficient products, homes, commercial buildings, and

Figure 5.3 Energy Star labels (*Source:* U.S. Department of Energy).

industrial plants. The program now serves not only the US but also the European Union, Canada, Iceland, Japan, Liechtenstein, Norway, Switzerland and Taiwan.

5.5.6 The lighting revolution

An important example of improving energy efficiency is the revolutionary change in lighting technology that is currently underway. This involves the replacement of traditional incandescent light bulbs with much more energy-efficient and longer-lasting light-emitting diodes (LEDs). It is a significant revolution because lighting accounts for about 20% of electricity consumption in the US and 19% on a global basis. It is estimated that LED use could cut the US number in half by 2030.

The revolution actually began with the introduction of CFLs (compact fluorescent lamps) which had been gaining market share for several years until they were displaced in turn by LEDs. The reason for this displacement is explained below.

Let us start with a few words about lighting technology. An incandescent light bulb, the most common type today in households and the least expensive to buy, produces visible light from a glowing filament wire (made of tungsten) heated to a high temperature (several thousand degrees) by an electric current passing through it. It was not invented by Thomas Edison (many earlier inventors had experimented with hot filament lamps), but he did invent the first commercially practical incandescent bulb. It was introduced into residential use more than 125 years ago. Its principal shortcoming is that more than 90% of the energy used by the traditional incandescent bulb escapes as heat and less than 10% goes into producing light. Filaments also burn out and are fragile, and a typical bulb lifetime is about 1000 hours.

Halogen lamps, also in common use today, are incandescent lamps with a little halogen gas (iodine or bromine) added to the bulb. The chemical reaction between the halogen and the tungsten wire allows the filament to operate at a higher temperature and increases the bulb's lifetime and light-producing efficiency (also referred to as efficacy).

A fluorescent lamp or fluorescent tube is a low-pressure mercury-vapor gas-discharge lamp that uses UV-stimulated fluorescence of a deposited phosphor to produce visible light. It is more energy efficient than an incandescent lamp, but does require an electrical ballast to regulate the current through the lamp, increasing its initial cost.

CFLs fold a fluorescent lamp tube into the space of an incandescent bulb with a ballast in the base. They use 3–5 times less energy than incandescent bulbs of the same light output and have much longer lifetimes. They do contain a small amount of mercury, creating a disposal problem.

Light-emitting diodes (LEDs) are solid-state semiconductor, monochromatic, point light sources. First appearing as practical electronic components in 1962, early LEDs emitted low-intensity red light, but modern versions are available at visible, ultraviolet, and infrared wavelengths with very high brightness. (*Note*: when different visible colors are mixed, white light can be produced). Today they are used in applications as diverse as aviation lighting, automotive lighting, advertising, general lighting, and traffic signals. They are also used in the infrared remote control units of many commercial products including televisions, DVD players and other domestic appliances. Their high switching rates are useful in advanced communications technology.

LEDs have many advantages over incandescent light sources including significantly lower energy consumption, much longer lifetimes, improved physical robustness, smaller size, and faster switching rates. While LED costs have come down rapidly, they do require more precise current and heat management than compact fluorescent lamp sources of comparable light output. Their advantages over CFLs are greater efficacy (i.e., more light output measured in lumens per watt), longer lifetimes, smaller size, directionality of the light produced, and, importantly, they contain no mercury which has to be disposed of. Deficiencies in these aspects severely limited CFLs' market appeal.

While LEDs are based on inorganic (non-carbon-based) materials, OLEDs are organic (carbon-based) solid-state light emitters which are made in sheets that provide a diffuse-area light source. They are still in an early stage of development and several years away from broad commercial application. Interesting potential applications include TV screens, computer and cell phone screens, wall coverings that allow changes in color, and automobile skins that allow you to change the color of your car.

A simple calculation will help to demonstrate the cost effectiveness of the new lighting sources. They may be more expensive to buy than incandescent bulbs, but they save energy and money over extended lifetimes. It is also important to note that replacing bulbs less often also saves money by reducing labor costs. I will use LEDs as my example.

I compare a 100 W soft-white dimmable incandescent bulb with an equivalent light source, a soft-white dimmable 11 W LED bulb, both selected from an online catalogue. The incandescent bulb is available at a cost of $1.08, while the LED bulb sells for $9.99; to simplify the calculations I will use $1 and $10 as their respective costs. To be conservative, we will assume a 2000 hour lifetime for the incandescent bulb and a 10,000 hour lifetime for the LED, which means that you replace the incandescent bulb five times more often than the LED. We will also assume the cost of electricity to be \$0.10 per kWh.

Thus, after 10,000 (10^4) hours the cost of operating with incandescent bulbs, including the purchase costs for 5 bulbs, would be: $\$5 + (0.1\text{ kW}) \times (10^4\text{ h}) \times (\$0.10/\text{kWh}) = \$105$. The cost of operating the LED would be $\$10 + (0.011\text{ kW}) \times (10^4\text{ h}) \times (\$0.10/\text{kWh}) = \$11$. This comparison, even without considering labor costs, shows why the switch from incandescent bulbs to LEDs is inevitable and now taking place rapidly. Utilities also benefit because they will need fewer power plants to meet lighting electricity requirements, as well as reducing environmental impacts of power generation. Given that lighting consumes a significant fraction of global electricity, the benefits of this lighting revolution in combating global warming and climate change are obvious.

5.5.7 Energy efficiency in buildings

Buildings account for approximately 40% of the energy (electrical and thermal) consumed in the US and Europe, and about 30% on a global basis. Most of this energy today is fossil-fuel based. As a result, this energy consumption accounts for a significant share of global emissions of carbon dioxide. This makes it imperative that buildings be a primary target for reducing energy and fossil fuel demand.

5.5.7.1 Zero energy buildings

One approach that is gaining visibility is the introduction of net zero energy buildings (ZEBs) and the retrofit of existing buildings to approach net zero energy operation. A ZEB is most often defined as a building that, over the course of a year, uses as much energy as is produced by renewable energy sources on the building site. This is the definition that will be considered in this discussion. Other ZEB definitions take into account any source energy losses in generation and transmission, emissions (zero carbon buildings), total cost (cost of purchased energy is offset by income from sales of electricity generated on-site to the grid), and off-site ZEBs where the offsetting renewable energy is delivered to the building from off-site generating facilities. Details on these definitions can be found in the National Renewable Energy Laboratory (NREL) report CP-550-39833 entitled 'Zero Energy Buildings: A Critical Look at the Definition' (27).

The keys to achieving net zero energy buildings are straight forward in principle: first focus on reducing the building's energy demand through energy efficiency, and then focus on meeting this reduced energy demand, on an annual basis, with onsite renewable energy – for example, use of localized solar power generation. This allows for a wide range of approaches due to the many options now available for improved energy efficiency in buildings, and the rapidly growing use of increasingly less expensive solar photovoltaics (PV) on building roofs, covered parking areas, and nearby open areas. Most ZEBs use the electrical grid for energy storage/backup, but some are grid-independent and use on-site battery or other forms of energy storage (e.g., heated or cooled materials).

A prime example of what can be done to achieve ZEB status is NREL's operational Research Support Facility (RSF) at its campus in Golden, Colorado. It incorporates demand reduction features that are widely applicable to other large new buildings, and some that also make sense for smaller residential buildings and retrofits (cost issues are discussed below). These include:

- optimal building orientation and office layout, to maximize heat capture from the sun in winter, solar PV generation throughout the year, and use of natural daylight when available

- high performance electrical lighting
- continuous insulation precast wall panels with thermal mass
- windows that can be opened for natural ventilation
- radiant heating and cooling
- outdoor air preheating, using waste heat recovery, transpired solar collectors, and crawl space thermal storage
- aggressive control of plug (‘vampire’) loads from appliances and other building equipment
- advanced data center efficiency measures
- roof top and parking lot PV array.

US ZEB research is supported by DOE’s Building America Program, a joint effort with NREL, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, and several industry-based consortia such as the National Institute of Building Sciences and the American Institute of Architects. Many other countries are exploring ZEB’s as well, including jointly with the US through the International Energy Agency’s ‘Towards Net Zero Energy Solar Buildings’ Implementing Agreement (Solar Heating and Cooling Program/Task 40). This IEA program has now documented and analyzed several hundred net zero energy and energy-plus buildings worldwide (an energy-plus building generates more energy in a year than it consumes).

An interesting example of ZEB technology applied to a residential home is NREL’s Habitat for Humanity zero energy home (ZEH), a 1280 square foot, 3-bedroom home in the Denver area built for low-income occupants. NREL report TP-550-431888 (‘The NREL/Habitat for Humanity Zero Energy Home: a Cold Climate Case Study for Affordable Zero Energy Homes’) details the design of the home and includes performance data from its first two years of operation. The home exceeded its goal of zero net source energy and was a net energy producer for these two years (24% more in year one and 12% more in year two). The report concluded that ‘Efficient, affordable ZEHs can be built with standard construction techniques and off-the-shelf equipment.'

A word about cost: today ZEBs cost more to build than traditional office buildings and homes, but not much more – perhaps 5 to 10% for new construction – but this gap is closing rapidly. Part of this extra cost is recovered via reduced energy bills. In the future, the zero energy building goal will become more practical as energy efficiency is emphasized, the costs of renewable energy technologies decrease (in the way that solar PV costs have decreased significantly in recent years) and the costs of traditional fossil fuels increase. The recent surge in availability of relatively low-cost shale gas thanks to fracking will slow this evolution, but it will eventually occur.

In addition, in the US, DOE has established two goals for residential and commercial buildings: create energy systems integration solutions that will enable marketable ZEHs by the year 2020 and commercial ZEBs at low incremental cost (relative to traditional buildings) by the year 2025. These objectives align with the Energy Independence and Security Act of 2007 (EISA), which calls for a 100% reduction in fossil-fuel energy use (relative to 2003 levels) for new Federal buildings and major renovations by 2030.

Some additional points about ZEBs/ZEHs: while an individual building or home may use an average of net zero energy over the course of a year, it may demand energy from the grid at other times when peak grid demand occurs. In such a case, the grid must still provide electricity to all loads, and a ZEB may not necessarily reduce the required power plant peak capacity. In addition, current definitions of ZEBs/ZEHs do not mandate a minimum performance level for heating and cooling the building shell, thus allowing oversized solar PV systems to fill the energy gap.

A further consideration is that the energy consumption in an office building or home is not strictly a function of technology – it also reflects the behavior of the occupants. In one illuminating example two families on Martha’s Vineyard in Massachusetts lived in identical zero-energy-designed homes and one family used half as much electricity in a year as the other. In the latter case, electricity for lighting and plug loads accounted for about half of total energy use. As one energy consultant noted: ‘There are no zero-energy houses, only zero-energy families.’

5.5.7.2 Electrochromic windows

A third example of an emerging energy efficiency technology is electrochromic (EC) windows. They have fascinated me since I first saw one demonstrated many years ago. It is part of the family of smart glass technologies that control the amount of light and heat that the glass transmits. This control can be activated by temperature (thermochromic), by light (photochromic), or voltage (electrochromic). This chapter will focus on the latter, which offers significant potential for reducing the energy consumed in buildings. They have other useful applications as well.

How do they work? When a voltage is applied between the transparent electrical conductors (usually less than 5 volts) an electric field is set up in the window material. This field moves ions reversibly through the ion storage film through the electrolyte and into the electrochromic film. Different ions (typically lithium or hydrogen) produce different colorations, and the window can be switched between a clear, highly transparent state and a transparent blue-gray tinted state with no degradation in view (similar to that achieved in photochromic sunglasses) by reversing voltage polarities.

Critical aspects of designing and using electrochromic windows include materials and manufacturing costs, installation costs, electricity costs, durability, as well as functional features such as degree of transparency, possibilities for dimming, and speed of transmission control (complete switching can take several minutes). Many different electrochromic window options at different price points for buildings are now available, and active R&D efforts are underway. One recent advance is the development of reflective, rather than absorptive, windows which switch between transparent and mirror-like.

Electrochromic windows are an attractive energy efficiency measure because (a) they can block heat (infrared radiation) in the summer, reducing air conditioning loads, and (b) allow infrared radiation to pass into buildings in the winter and reduce heating loads (windows account for about 30% of building energy load). This also reduces utility peak load demands. Tunable electrochromic windows also serve to reduce lighting loads when adequate natural light is available, reduce glare, provide privacy without the need for blinds and curtains, and reduce fabric and art fading by blocking ultraviolet radiation.

Other important applications include use in automobile windows, sunroofs and rear view mirrors, in aircraft (e.g., the Boeing 787 Dreamliner uses electrochromic windows in place of pull down window shades), and as internal partitions in buildings with the ability to switch screens and doors from clear to private.

Given that EC windows have been under development for many years, their obvious ability to block or transmit wavelengths of light as needed, and their many applications, why hasn't greater use of such windows become a standard part of building construction? The simple answer is cost. NREL looked at this issue in its December 2009 report entitled 'Preliminary Assessment of the Energy-Saving Potential of Electrochromic Windows in Residential Buildings' and compared the cost of low-e argon-filled windows with that of EC windows and concluded that '…EC windows would have to reach a price point of approximately $20/square foot before they would be competitive…' At that time EC windows were in the range of \$50–100/square foot, with commercial buildings on the lower end of that range and residential applications on the higher end. Another approach being taken by a few EC window companies is to add an EC film to existing windows, which is also capable of reducing energy costs.

How much energy can EC windows save? The NREL study, using a model to evaluate the performance of EC windows in a single-family traditional new home in Atlanta, predicted that whole-house energy demand could be reduced by 9.1% and whole-house electricity demand by 13.5%.

Note: some thought has been given to combining electrochromic windows and solar PV cells so that instead of uselessly reflecting away sunlight, darkened smart windows could soak up that energy and store it for use at another time. It's easy to imagine windows that capture some of the solar energy falling on them during the day and storing generated electricity in batteries that can power lights inside your home at night. However, a window can't be 100 percent transparent and work as an efficient solar panel at the same time. The incoming energy is either transmitted through the glass or absorbed and stored, but not both. A window that doubles as a solar panel would of necessity involve a compromise: a darker window even when clear and less efficient at capturing energy than a good solar panel. Nevertheless, R&D on this concept is underway, and we can probably look forward to dual-purpose windows in the future.

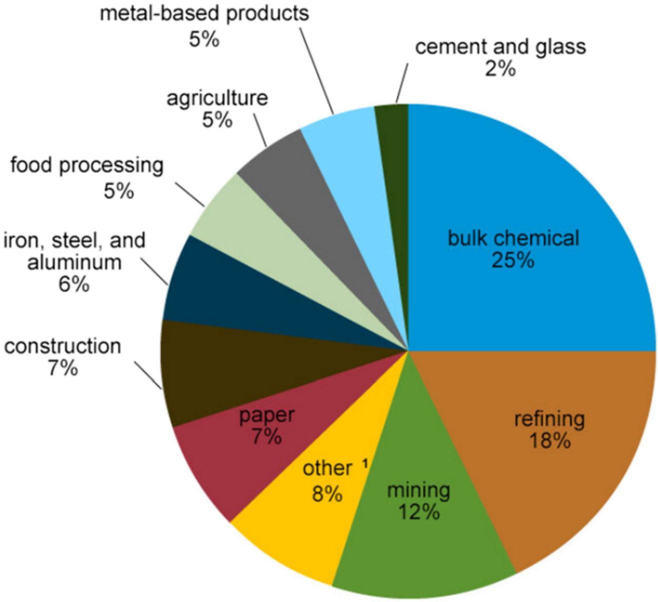
5.6 ENERGY EFFICIENCY IN INDUSTRY

Currently, the industrial sector consumes just over half of all global energy and feedstock fuels. Sector demand is expected to grow over the next few decades, with the most rapid growth occurring in the use of feedstocks for petrochemicals. It will account for about half of the projected growth in energy demand through 2040 and will remain dominant, although energy demand in transportation will grow more rapidly.

Multiple opportunities exist for the industrial sector to improve its energy efficiency, through performance standards for industrial equipment and improved process design and operating procedures. Such steps have already contributed to a 20% reduction in industrial energy intensity (energy consumed per unit of GDP) between 2000 and 2016. Energy productivity is the inverse of energy intensity and is measured in units of GDP per unit of energy consumed.

The EIA defines the industrial sector to include manufacturing (transformation of raw materials into products), agriculture, mining, and construction. For energy purposes it can also be categorized into three different types: energy-intensive manufacturing, non-energy-intensive manufacturing, and non-manufacturing. Figure 5.4 shows a breakdown of US industrial energy consumption in 2016 for subsets of these categories.

Given that industry's appetite for energy continues to be the main driver of overall energy demand, it is not surprising that there have been many studies on how to reduce this demand. Two examples are the Indian report 'Tips for energy conservation for Industries' (29) and the 2015 US DOE report to Congress 'Barriers to Industrial Energy Efficiency (30). The DOE report identified barriers in three broad categories: economic and financial, regulatory, and informational. It also identified energy efficiency opportunities and provided specific examples of success. The report concluded that while 'the industrial sector has shown steady progress in improving energy efficiency over the past few decades, and energy efficiency improvements are expected to continue … . There is potential to accelerate the rate of adopting energy efficient technologies and practices that could reduce energy consumption in the industrial sector by an additional 15 to 32% by 2025.' It is also important to note that improved industrial energy efficiency remains the



Note: Includes electricity purchases and energy sources used as feedsctocks for making products. [1]*Other* includes wood products (1%), plastics products (1%), and all others (6%).
Source: U.S. Energy Information Administration, *Annual Energy Outlook* 2017, Tables 25-35, January 2017

Figure 5.4 US industrial energy consumption in 2016.

most cost-effective option for reducing greenhouse gases for the next few decades.

5.7 ENERGY EFFICIENCY IN TRANSPORTATION

Transportation, the movement of people and goods from one place to another, today accounts for about one-quarter of global energy consumption and one quarter of energy-related greenhouse gas emissions. These numbers are expected to increase in the future. The sector includes personal vehicles, light and heavy-duty trucks, public transportation (buses, trains, aircraft), freight trains, barges, ships, and pipelines.

Transportation also plays a critical role in development: without adequate access to transportation '… poor countries cannot provide for their own basic needs, much less contribute their share of world production; and they cannot help prepare for the additional two billion people coming before 2025 (31).' The reality is, that on a planet where nations have become increasingly interdependent, only a few are affluent and highly mobile, while the majority lack adequate resources and mobility. As stated in 2016 by Ban Ki-moon, then UN Secretary-General, to the first ever Global Sustainable Transport Conference: '… the transport sector has a human side and we should all be concerned about people who do not have the access they deserve (32).'

Some interesting facts about global transportation:

- Currently there are about 1.3 billion light-duty vehicles on the road. The US, with less than 5% of the world's population, accounts for about 20% of these vehicles.
- OECD countries consume just over half of the world's total transportation energy, and non-OECD countries, where 80% of the world's population lives, should catch up by 2020 (see Figure 5.5) (33).
- Petroleum and other liquid fuels provide over 90% of transportation energy today, with non-OECD demand exceeding that of OECD countries. Motor gasoline remains the largest transportation fuel throughout this projection period.
- Passenger or personal vehicles today account for about 60% of transportation energy consumption, with light-duty vehicles accounting for 44%, followed by aircraft at 11%. Freight accounts for the remaining 39% (see Figure 5.6) (34).
- About 4 billion passengers are carried annually by airlines, which release approximately 2% of human-induced CO_2 emissions. Road transport releases much more.

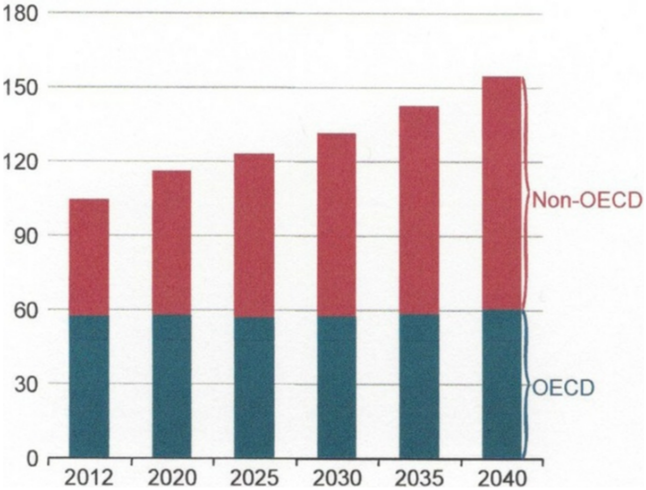


Figure 5.5 Global transportation energy consumption (quads) (*Source:* International Energy Agency).

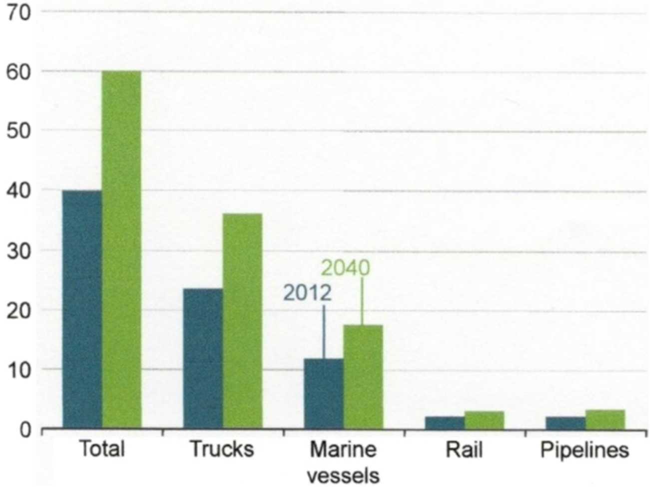


Figure 5.6 Transportation energy consumption by passenger mode (quads) (*Source:* International Energy Agency).

Demand for transportation energy and associated CO_2 emissions can be reduced in a number of ways. These include improving the fuel efficiency of all modes of passenger and freight transportation, fuel substitutions, improving urban environments, designing transport-conserving communities, and using telecommunications to reduce the need for commuter trips. For example, jet aircraft in service today are well over 80% more fuel efficient than the first jets in the 1960s; DOE's Heavy Duty Vehicle Efficiency Program has developed an improved version of a Class 8 truck, called a 'super truck', that is 50% more efficient than Class 8 trucks currently on the road. These heavy duty trucks use approximately 20% of US transportation fuel; in response to the OPEC oil embargo of 1973–74 the US Congress (35) established federal Corporate Average Fuel Economy (CAFE) standards for cars and other light- duty vehicles in 1975. In 2007 the *New York Times* called the CAFE standards 'The most effective energy efficiency policy ever adopted by the federal government …' and the US National Academies of Sciences has called the CAFE standards 'One of the most impressive efficiency successes in modern memory …'. Other countries have since adopted similar standards, and standards are under consideration for medium and heavy-duty vehicles.

Other possibilities for reducing fuel consumption in transportation include the use of lighter, stronger, and more durable structural materials; the use of alternative liquid (alcohols, biofuels) and gaseous (compressed natural gas) fuels; hybrid vehicles (powered by both internal combustion engines and electric motors); and pure electric vehicles (EVs) powered by electricity stored in batteries or electricity generated by fuel cells powered by hydrogen. EVs offer significant advantages over traditional vehicles because electric motors are much more efficient than internal combustion engines, and the efficiency of fuel cells, which utilize a non-thermal energy conversion process, is not limited by Carnot thermodynamic efficiencies.

Energy storage capability is an important consideration for EVs because mobility range is directly connected to total electric energy stored. If the source of battery-charging electricity is renewable, and not fossil fuel, harmful emissions can be reduced significantly. It should also be noted that more than 90% of all household trips in the US and many other countries are under 100 miles, well within the range of currently available EVs, and longer-range vehicles are on the near horizon.

Chapter 6

Fossil fuels

Fossil fuels, in the form of coal, oil, and natural gas, have been the principal energy sources powering US and global economic development over the past century. Today they supply more than 80% of all the energy consumed in industrially developed nations. They are hydrocarbons, compounds containing only carbon and hydrogen, and range from volatile materials such as natural gas (largely methane, CH_4) with low carbon to hydrogen ratios, to almost pure carbon materials such as anthracite coal. When a fossil fuel is burned (oxidized to CO_2 and H_2O) large amounts of energy are released, which can be used for heating and to produce electricity. When petroleum is refined (i.e., processed into gasoline or diesel fuel) it can be used as a liquid fuel for transportation. Natural gas, when compressed, can also be used as a transportation fuel. Over the past few decades the burning of fossil fuels was responsible for more than 70% of human-caused greenhouse gas emissions.

The idea that fossil fuels were formed from the fossilized remains of dead organisms and plants, via exposure to high

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temperatures and pressure deep in the Earth over millions of years, was first mentioned in the 16th century. Today, it is understood that petroleum and natural gas are the products of anaerobic (low oxygen) decomposition of dead organisms such as aquatic phytoplankton and zooplankton. Coal and natural gas are understood to be decomposition products of terrestrial plants. While these processes are still underway, fossil fuels are considered to be non-renewable resources because they take tens to hundreds of millions of years to form, while they are being consumed at high rates today.

6.1 COAL

Coal is used primarily to heat water to produce steam to generate electricity. China is the world's leading coal producer (45%), followed by the US at 11%. Just over one third of global electricity is currently generated by burning coal. While the world has large reserves of coal, its downside is that coal combustion produces a wide range of air pollutants that are harmful to human health and the environment. These include sulphur dioxide (SO_2) which is responsible for acid rain; nitrogen oxides (NO_x), a family of oxides that contribute to the formation of smog, acid rain, and ozone; mercury (Hg), a cumulative poison when taken into the body; and radioactivity from elements like uranium and thorium that are often found in coal deposits. As discussed in Chapter 4, coal combustion is also a major source of the greenhouse gas CO_2.

The term 'clean coal' was introduced in 2008 by coal industry groups at a time when the US Congress was considering legislation to limit CO_2 emissions. While deliberately vague, it is usually interpreted to mean coal-fired power plants that capture and sequester the CO_2 emitted from smokestacks. This process has been given the name Carbon Capture and Sequestration (CCS). It is a complex and contentious approach to reducing CO_2 emissions from industries such as power generation and cement production, which is discussed in more detail below.

6.1.1 Carbon capture and sequestration

Wikipedia defines CCS as ‘the process of capturing waste carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, transporting it to a storage site, and depositing it where it will not enter the atmosphere, normally an underground geological formation.’

Considerable literature exists on CCS, exhibiting a wide range of opinion on its viability as a technology to reduce CO_2 emissions. The principal argument for CCS is that the world today is fueled largely by coal, oil and natural gas and that this situation is not likely to change any time soon. In fact, as many developing nations industrialize and they emerge from poverty, the demand for energy increases steadily and it is argued that only fossil fuels can meet that demand in coming decades. It is also argued that, while solar, wind and other renewable energy technologies can eventually replace electricity from coal and natural gas power plants, this will not occur quickly and people will need fossil energy during the long transition. In addition, some industries like steel and cement are not so easily ‘fixed’ and will continue to use fossil fuels in increasing amounts as global industrialization grows.

These points raised in support of CCS are countered by the following arguments:

- CCS is expensive, whether added to an existing power plant or industrial carbon dioxide source, or included in newly constructed facilities. The energy penalty for operating CCS is also high, requiring a fair amount of parasitic energy that reduces efficiency and revenues.
- When operating, CCS systems require large amounts of water.

- Captured CO_2 must be liquified and stored for indefinite periods of time in such a way as to avoid leakage and sudden large releases ('burps') that can be toxic. This requires identification and development of storage sites (depleted oil and gas wells, coal mines, underground aquifers) and infrastructure to transport liquid CO_2, which adds additional costs and raises questions of liability if something goes wrong and stored CO_2 is accidentally released.
- The time required for development, demonstration and large-scale deployment of CCS technology that can have a meaningful impact on global warming is too long compared with other options.

Proponents of CCS (see http://www.globalccsinstitute.com) argue that CCS costs can be brought down significantly with a sufficient number of demonstration projects and the economies of scale associated with large-scale deployment. Nevertheless, at the 2013 Doha Clean Energy Forum even one of its supporters admitted that to make an impact a global CCS system will cost an estimated $3.6 trillion. One immediate reaction at the meeting was that for $3.6 trillion we can deliver an awful lot of non-CO_2 emitting renewable energy that will replace coal, oil, and natural gas used in power generation and transportation. Nevertheless, there is the argument that the CO_2 emissions from some industries will still be there in large and growing amounts even with large-scale deployment of renewables and CCS may be the only way to limit these emissions.

These are strong arguments for some attention to CCS R&D and demonstration. Nevertheless, CCS demonstrations are expensive, and the money for them would have to come from somewhere. Government funding is at best problematic in current budget situations. Other funding possibilities are the fossil fuel industries themselves. Countries with large reserves of fossil fuels will also see value in CCS allowing extended use of secure domestic energy reserves.

In a world committed to reducing carbon emissions CCS offers a helping hand but not a definitive one. It may offer a partial answer for the rest of the 21st century, but governments are unlikely to provide the needed funds for large-scale deployment. A major question is whether the private fossil fuel sector is willing to step up to protect its vested interests.

6.1.2 A conundrum

The mining and use of coal presents a difficult-to-resolve conundrum, especially for countries like China, Australia, and the US with large amounts of this fossil fuel. Coal reserves provide a relatively low-cost energy resource, but its combustion produces large amounts of $CO_{2,}$ a greenhouse gas. The conundrum is a clear example of a conflict of values – the need to provide energy services to people around the world, in particular people in developing countries whose per capita consumption of electricity is well below that of developed countries, and the need to address climate change with its many adverse consequences. No easy answer exists to satisfy those on both sides of this conflict.

Joby Warick, in a well researched piece in the 16 October 2015 edition of *The New York Times* examined this question from the US perspective. Several statements caught my attention: ‘Just a dozen nearby mines, scattered across a valley known as the Powder River Basin (Wyoming), contain enough coal to meet the country’s electricity needs for decades. But burning all of it would release more than 450 billion tons of carbon dioxide into the atmosphere – more than all greenhouse-gas emissions from all sources since 2000.’ and ‘The Obama Administration is seeking to curb the United States’ appetite for the basin’s coal, which scientists say must remain mostly in the ground to prevent a disastrous warming of the planet. Yet each year, nearly half a billion tons of this US-owned fuel are hauled from the region's vast strip mines and millions of tons are shipped overseas for other countries to burn.'

Given the legitimate needs on both sides of this conflict I can see only one path to follow to bring the benefits of electricity to as many people as possible while minimizing the risks associated with burning coal. This is to promote the use of energy efficiency technologies wherever feasible, to reduce the demand for coal-based electricity, and to expedite the development and deployment of renewable electric technologies such as solar and wind, and perhaps nuclear, as substitutes for coal. This is already happening to some extent as the world slowly begins to come to grips with the climate change problem, but the pace needs to and can be accelerated.

The ability of renewables to meet most of the world's electricity needs has been documented in several recent studies, for example, the June 2012 NREL report entitled 'Renewable Electricity Futures Study'. What is now needed is a commitment on the part of national governments and international institutions to make it happen as quickly as possible. It is a matter not of technology but of political will and financial resources. Admittedly, such a switch from coal and other fossil fuels that also produce CO_2 when burned, to a renewables-based energy economy, will take time, planning, and money. However, when the full costs of using fossil fuels are taken into consideration, including not just market costs but also health and climate-change-related costs (such as coastline flooding due to rising seas, changes in precipitation patterns that adversely impact water availability and agricultural production, etc.), and international tensions due to competition for fossil fuel resources, then renewables become a much more attractive and even less expensive long-term option. Renewable resources are also insensitive to cost increases once initial capital investments are made, unlike fossil fuels that rely on a depletable resource that produces uncertain and often volatile costs. Renewable energy technologies are discussed in Chapter 8.

Note: Nuclear power advocates will make some of the same arguments since the process of releasing energy via nuclear fission does not produce greenhouse gases, but nuclear technology faces four serious problems: high cost, safety, the need for long-term radioactive waste storage, and proliferation of weapons capability. If these problems can be successfully addressed, then nuclear-powered electricity can be a viable option for the future. Nuclear power also offers the tantalizing option of nuclear fusion, a relatively safer and cleaner nuclear technology with enormous resource potential, but the problem of achieving controlled nuclear fusion on Earth – it is the process that powers our Sun – is proving to be the most difficult technological challenge the world has faced to date. It can legitimately be labeled ‘the technology that is always a few years away.’ Discussion of the promise and problems of both nuclear fission and fusion power can be found in Chapter 7.

In addressing the conundrum the choice is ours – we can continue to use our coal resources without limit or we can move more quickly to a clean energy society that provides needed energy services and minimizes global warming and climate change effects. Most people today would vote for the latter.

In addition, it is important to recognize an important reality of our evolving energy system: as renewable energy begins to displace energy from fossil fuels some people will be adversely impacted as this transition unfolds. We must take these impacts into account as we move forward to a clean energy future. Dr Maria Zuber, Chair of the US National Science Board and Vice President for Research at MIT, has written eloquently on this topic (36):

> ‘As a daughter of coal country, I know the suffering of people whose fates are tied to the price of a ton of coal. But as a scientist, I know that we cannot repeal the laws of physics. When coal burns, it emits more carbon dioxide than any other fossil fuel. And if we keep emitting this

> gas into the atmosphere, Earth will continue to heat up, imposing devastating risks on current and future generations. There is no escaping these facts, just as there is no escaping gravity if you step off a ledge.
>
> The move to clean energy is imperative. In the long run, that transition will create more jobs than it destroys. But that is no comfort to families whose livelihoods and communities have collapsed along with the demand for coal. We owe something to the people who do the kind of dangerous and difficult work my grandfathers did so that we can power our modern economy.'

6.2 PETROLEUM

Petroleum (crude oil) is today the world's primary fuel source for transportation (90%), and is likely to remain so for at least a few decades into the future. It is most often extracted from deep geologic reservoirs underground or below the ocean seabed. It can also be found in shale deposits and tar sands, and both of these 'non-conventional' petroleum sources are now being exploited commercially. Once extracted, it is processed in oil refineries into gasoline, diesel fuel, heating oil, liquefied petroleum gas, and other non-fuel products such as pesticides, fertilizers, pharmaceuticals, plastics, and heavy residues for use in asphalt.

6.2.1 Oil spills

Oil use in transportation creates major environmental problems. Its combustion creates CO_2 and NO_x, as well as particulate matter (a complex mixture of extremely small particles and liquid droplets) that can lead to serious respiratory problems when inhaled. A major concern is that because of its wide use in billions of cars, trucks, and other vehicles, each of which acts as an individual point source of pollution, control of this pollution is quite difficult. Oil, either in extracted or refined form, also has to be transported by ship, pipeline, or truck to its final point of use, and spills are an ever-present danger. While there are many oil spills each year, at least two have attracted international attention, the *Exxon Valdez* spill into Alaska's Prince William Sound in 1989 and the *Deepwater Horizon* oil spill into the Gulf of Mexico in 2010.

In the former case 11 million gallons of crude oil were released into Prince William Sound, with dire impacts on hundreds of thousands of birds, other water creatures, and local fishing and other businesses. Some of those impacts remain to this day.

Two decades later the Macondo Well beneath BP's *Deepwater Horizon* drilling rig blew out, causing a massive fire, the loss of 11 lives, and the release into the Gulf of Mexico of 170 million gallons of crude oil. This oil coated beaches for hundreds of miles in several states around the Gulf, did terrible damage to wildlife and water- and tourist-dependent industries; again, oil from the spill continues to wash ashore today. Much research is underway to understand the effects on the food chain of this very large spill, which took months to bring under control.

Despite this history, large and damaging oil spills still remain a serious threat. Frances Beinecke, former president of the Natural Resources Defense Council, who served on the Commission investigating the *Deepwater Horizon* accident, has written (37): 'Many lessons from the *Exxon Valdez* spill had not been applied, and the country was once again struggling with an industry ill-prepared to respond.' There is also great concern that, with global warming leading to less ice cover in arctic regions, drilling for new oil resources may take place in areas much more vulnerable to the lasting effects of large oil spills.

Oil transport by pipeline or rail is also a major concern. The first was illuminated by the battle over approval of the Keystone XL Pipeline that would cross the international border between the US and Canada. Approval was denied by the Obama Administration, then granted by the Trump Administration, but the project is still on hold due to economic considerations. The second concern gained visibility as a result of a massive fire in Quebec, caused by the derailment of a train carrying crude oil from Canada to the US. Both are discussed below.

Quoting from Wikipedia: ‘The Keystone Pipeline System is a pipeline system to transport oil sands bitumen from Canada and the northern United States primarily to refineries on the Gulf Coast of Texas. The products to be shipped include synthetic crude oil (syncrude) and dilbit (diluted bitumen) from the Western Canadian Sedimentary Basin in Alberta, Canada, and Bakken synthetic crude oil and light crude oil produced from the Williston Basin (Bakken) region in Montana and North Dakota. Two phases of the project are in operation; a third, from Oklahoma to the Texas Gulf coast, is under construction, and the fourth is awaiting US government approval as of mid-March 2013. Upon completion, the Keystone Pipeline System would consist of the completed 2151-mile (3462 km) Keystone Pipeline (Phases I and II) and the proposed 1661-mile (2673 km) Keystone Gulf Coast Expansion Project (Phases III and IV). The controversial fourth phase, the Keystone XL Pipeline Project, would begin at the oil distribution hub in Hardisty, Alberta and extend 1179 miles (1897 km), to Steele City, Nebraska.’

Those opposed to the pipeline cite the contribution to CO_2 emissions from the mining of tar sands in Canada, the possibility and consequences of pipeline leaks associated with heated and highly pressurized bitumen, the initial (now modified) proposed path of the pipeline through areas above the Ogallala Aquifer (a major source of freshwater), and the potential delay in investments in renewable energy technologies due to the continued availability of oil resources.

The proponents of the pipeline argue that Canada will mine the tar sands and produce the bitumen and its associated CO_2 emissions regardless of what the US decides (an alternative pipeline path would be to Canada’s west coast for sales to Asia), Canadian tar sands oil is already reaching the US by train and new quantities could be shipped by rail as well, that obtaining oil from Canada is preferable to obtaining oil from the Persian Gulf and other countries and is in the US national security and economic interest, and that pipeline construction today is under better regulation and is safer than ever before.

In his global climate change speech at Georgetown University on 25 June 2013 President Obama, prior to his denial of the Keystone XL Pipeline project, seemed to hint that he would approve the pipeline, arguing that 'Allowing the Keystone pipeline to be built requires a finding that doing so would be in our nation's interest. And our national interest will be served only if this project does not significantly exacerbate the problem of carbon pollution. The net effects of the pipeline's impact on our climate will be absolutely critical to determining whether this project is allowed to go forward.'

The use of the words 'significantly exacerbate' seemed significant in that it will be hard to argue that the carbon emissions from mining the Alberta tar sands will add significantly to current global CO_2 emissions. Add they will, and add to oil availability they will as well, but by themselves and in terms of impact on global climate change, not significantly.

Thus, if one assumed that the pipeline would be carefully regulated (and with strict enforcement of those regulations), that the Canadian tar sands will be mined regardless, that the new pipeline path is less risky for the Ogallala, and that the pipeline will reduce US needs for other oil imports, approval of the pipeline was a safe bet to make. This would recognize that current US need for liquid petroleum fuels to support transportation is significant and will continue for a while.

What changed, and led to the decision in 2015 by the Obama Administration to deny the project's construction permit, was probably several-fold: the market price of oil (which had dropped to approximately half of what it was in 2013), President Obama's apparent decision to make leadership on global climate change issues an important part of his legacy, and the fact that Canada had a new federal government that was more environmentally oriented than the previous Conservative government. To some, this decision was justified on the basis that if the US won't take even small symbolic steps to reduce carbon emissions and global warming, why should other nations striving to improve their economies undertake such efforts. Others continue to believe that 'The Keystone XL fight hardly matters in the grand scheme of the global climate. Perceptions of US climate leadership depend on Environmental Protection Agency rules to reduce emissions from US power plants and cars, not on a domestic political psychodrama (38).'

6.2.2 Peak oil

Another topic that has come up consistently in recent decades is the notion of Peak Oil: is the world running out of its crude oil resources? The reality seems to be that this is not true on any near-term timescale. Fossil fuels are finite and we are using them much faster than nature can replace them, but much remains to be found and utilized if people wish. This is even more true today with the anticipation of new discoveries in ice-free arctic regions.

An important participant in this discussion was M. King Hubbert, who, at a meeting of the American Petroleum Institute in San Antonio, Texas, in 1956 proposed his theory on oil well production and depletion and published the 'Hubbert Curve' (see Figure 6.1).

It depicts a world oil production distribution, showing historical data and future production, with a peak of 12.5 billion barrels per year about the year 2000. It is valid for some assumptions but ignores other realities that make his conclusions invalid for long-term planning. Before discussing this in some detail, it is important to understand what is meant by Peak Oil.

Hubbert's Peak Theory is based on the fact that the utilization of a finite resource must go through an initial start-up, reach a peak level of production, and eventually tail off as the resource

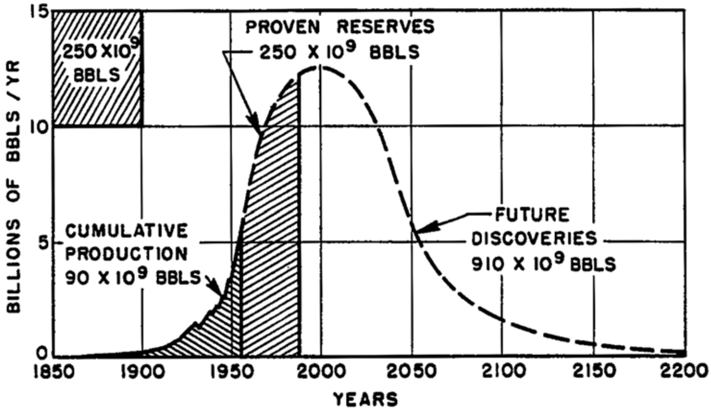

Figure 6.1 The Hubbert Curve (*Source:* 'Nuclear Eenergy and the Fossil Fuels', M.K. Hubbert, March 1956).

is depleted. This is common sense, applicable to all non-renewable resources, and not disputable. What is disputable is the shape of the production/depletion curve and the assumptions that went into identifying the resource to be utilized and eventually depleted. Much of the public discussion that has ensued about the application of Hubbert's Peak Oil theory to petroleum extraction has revolved about these two facets of his theory.

It is important to clarify that Peak Oil is the point in time when oil extraction reaches its maximum rate but is not synonymous with oil depletion. Following a peak in extraction rate about half of the resource is still available for extraction, and the production rate decreases steadily thereafter. Much discussion has focused on the shape of the declining curve after Peak Oil is reached (plateau? sharp decline? slow decline?) and the implications for the US and world economies that are dependent on oil supplies.

Hubbert's theory received great visibility when he correctly predicted, in his 1956 paper, that US domestic oil production would peak between 1965 and 1971. He used the terms 'peak production rate' and 'peak in the rate of discoveries'; the term Peak Oil was introduced in 2002 by Colin Campbell and Kjell Aleklett when they formed ASPO, the Association for the Study of Peak Oil & Gas. ASPO ceased operations in 2017.

Where the application of Hubbert's theory falls short is in the assumptions on which his theory is based. He did not anticipate, nor did others, the rapid emergence of unconventional oil and the substitutions for oil (alternative fuels, electrification of transportation) that have been or are being developed. He did mention these possibilities in the 1956 paper and did his best with the information available at the time.

What has changed is that oil production no longer depends only on 'conventional' oil supplies but increasingly on 'unconventional' resources that are an increasing part of total oil supply. A few definitions, courtesy of Wikipedia, will help:

> 'Conventional oil is oil that is generally easy to recover, in contrast to oil sands, oil shale, heavy crude oil, deep-water oil, polar oil and gas condensate. Conventional oil reserves are extracted using their inherent pressure, pumps, flooding or injection of water or gas. Approximately 95% of all oil production comes from conventional oil reserves.
>
> Unconventional oil is oil that is technically more difficult to extract and more expensive to recover. The term unconventional refers not only to the geological formation and characteristics of the deposits but also to the technical realization of ecologically acceptable and economical usage.'

Given these definitions, it is reasonable to agree that the age of cheap oil, which we enjoyed for a good part of the 20th century, is over. As reported by the former BP geologist Dr Richard Miller in a speech (39) at University College London in 2013: '… official data from the International Energy Agency, the US Energy Information Administration, the International Monetary Fund, and other sources, showed that conventional oil had most likely peaked around 2008.' He further pointed out that ‘peaking is the result of declining production rates, not declining reserves’, that many oil producing countries are already post-peak, and that conventional oil production has been flat since about the middle of the past decade. There has been growth in liquid supply since then, largely due to natural gas liquids and oil derived from oil sands. Reserves have also been growing due to new discoveries, improved oil field extraction technology, and increasing reliance on unconventional resources such as shale oil. In fact, production of shale oil has allowed the US to become the world’s top oil producer.

The debate about Peak Oil has been underway for quite a few decades, and, despite ASPO’s closing, Peak Oil still has its adherents (40). It seems clear that the Peak Oil concept is not valid if you take into account the full liquid fuels situation. In 2009, Dr. Christoph Rühl, chief economist of BP, argued as follows against the Peak Oil hypothesis: ‘Physical Peak Oil, which I have no reason to accept as a valid statement either on theoretical, scientific or ideological grounds, would be insensitive to prices … In fact the whole hypothesis of Peak Oil – which is that there is a certain amount of oil in the ground, consumed at a certain rate, and then it’s finished – does not react to anything … Therefore there will never be a moment when the world runs out of oil because there will always be a price at which the last drop of oil can clear the market. And you can turn anything into oil into if you are willing to pay the financial and environmental price … Global Warming is likely to be more of a natural limit than all these Peak Oil theories combined … Peak Oil has been predicted for 150 years. It has never happened, and it will stay this way.’

According to Rühl, the main limitations for oil availability are ‘above ground’ and are to be found in the availability of staff, expertise, technology, investment security, money, and, last but not least, in global warming. Rühl’s views are shared by Daniel Yergin of Cambridge Energy Research Associates, who added that oil's recent high-price phase might not add to complete exhaustion of resources, but the timely and smooth setup of alternatives.

A further perspective was provided by George Monbiot, writing in *The Guardian* on 2 July 2012: 'We were wrong on Peak Oil. There's enough to fry us all … Some of us made vague predictions, others were more specific. In all cases we were wrong. In 1975 MK Hubbert, a geoscientist working for Shell, who had correctly predicted the decline in US oil production, suggested that global supplies could peak in 1995. In 1997 the petroleum geologist Colin Campbell estimated that it would happen before 2010. In 2003 the geophysicist Kenneth Deffeyes said he was "99% confident" that Peak Oil would occur in 2004. In 2004, the Texas tycoon T Boone Pickens predicted that "never again will we pump more than 82 m barrels" per day of liquid fuels. (Average daily supply in May 2012 was 91 m.) In 2005 the investment banker Matthew Simmons maintained that "Saudi Arabia … cannot materially grow its oil production" (since then its output has risen from 9 M barrels per day to 10 M, and it has another 1.5 M in spare capacity). … Peak oil hasn't happened, and it's unlikely to happen for a very long time.'

6.3 NATURAL GAS

Natural gas (primarily CH_4, but also containing small amounts of other gases, including helium), once burned off as a non-useful byproduct of petroleum production, is an abundant resource in many countries. New discoveries and extraction methods have led to a dramatic increase in its production from shale deposits by fracking, especially in the US, making the US the world's leading producer of natural gas. Considerable research is also going into extraction of natural gas from methane hydrates (both fracking and methane hydrates are discussed below). CH_4 is also released by the decomposition of animal wastes from livestock production and municipal waste in landfills.

Natural gas burns more cleanly than coal or oil – less NO_x and particulate emissions, and minimal SO_2 emissions – and it releases, per unit of energy produced by its combustion, 43% less CO_2 than coal and 30% less CO_2 than oil. As a greenhouse gas in its own right, CH_4 is about 20 times more powerful than CO_2 as a driver of global warming, As a result, leakage of CH_4 from the infrastructure surrounding natural gas production and use is a serious concern. (*Note*: CH_4's half-life in the atmosphere is much less than that of CO_2.)

It is most commonly used to produce electricity and heat for industrial processes and buildings. A small amount of compressed natural gas is used for transportation – for example, in bus fleets. It also serves as a feedstock for the production of fertilizers, paints, and plastics. It is usually transported by pipeline, but increasingly it is being transported internationally in ships as cooled and liquefied natural gas (LNG).

6.3.1 Methane hydrates

For those who follow energy issues closely, a persistent question has been: are methane hydrates a realistically large potential energy resource? The answer is yes.

Several decades ago the information available to answer that question was not available. Today the literature on methane hydrates (also known as methane clathrates, methane ice, and fire ice) is extensive and growing.

What are clathrates and hydrates? Clathrate is a general term that describes solids in which gases are trapped within any kind of chemical cage, while hydrate is the specific term used when that cage is made of water molecules. In methane hydrates the trapped gas is CH_4. CO_2 and other gas hydrates are also possible and are speculated to exist on Mars, other planets and their moons. On our home planet most of the hydrates are filled with CH_4, and they are abundant.

Methane hydrates form as a solid similar to ice under the right conditions of CH_4 and water availability, temperature (low) and pressure (high). They are fragile, easily destabilized (i.e., returned to separated water and CH_4) by pressure and/or temperature changes, and are found most often within, and occasionally on top of, sediments on ocean floors. They are called ‘fire ice’ because they can be lit by a match.

The most common type of methane hydrate (>99%) has a density of 0.9 $g\ cm^{-1}$ or just slightly less than that of water, so it can float. One litre of the fully saturated solid would yield 120 grams of CH_4 or 169 litres of gas at standard temperature and pressure. It forms in the presence of water and methane under conditions found in the oceans, deep lakes, and under ice caps that fall within a gas hydrate stability zone.

The seafloors of most of the world’s oceans fall within the hydrate stability zone. Methane hydrates are also found in Arctic permafrost and continental deposits in sandstone and limestone in Alaska and Siberia. These deposits may cover even larger reservoirs of CH_4 at greater depths.

There are two sources for this methane: thermogenic methane that is formed deep in the earth by the same thermal/high-pressure processes that convert organic matter to coal, oil and gas, and which leaks upward toward the ocean floor where it forms hydrates when it comes in contact with highly pressurized cold (0–2°C) water; and methane generated by microbes degrading organic matter (plankton) in low-oxygen environments in sediments. This latter process is the dominant source of CH_4 for methane hydrates.

Methane hydrates are important because of estimates that such hydrates contain more carbon (and therefore more potential fuel) than all other fossil fuels combined. The EIA reports that these hydrates could hold as much as 10,000–100,000 trillion cubic feet (Tcf) of CH_4. To put these numbers into perspective, total global consumption of natural gas is currently about 130 Tcf. With methane hydrates we are talking about a very large potential energy resource. It is also widely distributed globally, and has the potential to be an indigenous resource for many countries. It is also straightforward to separate the CH_4 from its hydrate cage by heating it up or reducing its pressure. Both techniques have been demonstrated and are currently being explored actively in public and private research programs in many countries. The production problems arise when one tries to convert this resource into a marketable commodity at a reasonable cost.

The presence of most of the hydrates on the deep sea floor and in sediments just beneath it means that extraction must be carried out under extreme conditions of depth, pressure and temperature. The methane concentrations are also geographically dispersed, increasing the harvesting costs, undersea infrastructure costs, and transmission costs of bringing the gas to the surface. The fragility of the hydrates also requires that they be handled carefully, avoiding a sudden release of gas and resultant over-pressurization.

Environmentally, while CH_4 is a powerful greenhouse gas, a saving grace is that CH_4's half-life in the atmosphere is 7.5 years. CO_2 on the other hand has an atmospheric half-life of hundreds of years.

Another problem for CH_4 production from hydrates is the fact that shale gas from fracking is just coming into its own as a major source of competitive natural gas, thus reducing the commercial incentive to develop the hydrates. Unless the cost of producing CH_4 from hydrates can be reduced significantly this will remain an important barrier as long as shale gas is available in quantity.

The US is one of several countries with an active methane hydrate R&D program. Others include Russia, India, South Korea and Japan. Japan has been a leader in this research for many years, given its lack of indigenous energy resources and its heavy dependence on imports. Japan's recent problems with its nuclear power plants has further increased its dependence on imported LNG which is costly in the Asian market (several times higher than in the US market).

The US program was jump-started by the passage of The National Methane Hydrates R&D Act of 2000, which requires 'the development of a national methane hydrate R&D program that utilizes the talents of federal, private, and academic organizations.' The result is a joint public–private effort supported in part by several US government departments and agencies.

6.3.2 Fracking

Hydraulic fracturing is the fracturing of rock by a pressurized liquid. Some hydraulic fractures form naturally. Induced hydraulic fracturing or hydrofracturing, commonly known as fracking, is a technique in which water is mixed with sand and chemicals, and the mixture is injected at high pressure into a wellbore to create small fractures (typically less than 1 mm in length), along which fluids such as previously trapped oil and natural gas may migrate to the well. When hydraulic pressure is removed from the well, small grains of sand or aluminium oxide hold these fractures open once the rock achieves equilibrium. The technique is very common in wells for shale gas, tight gas, tight oil, and coal seam gas and hard rock wells. It is now also being considered for use in revitalizing existing hydrogeothermal wells.

It was first used commercially in 1998 in the Barnett Shale formation in Texas. Today it is being widely used in several shale regions in the US and its use is being explored actively in many other countries. It is also a large fossil fuel resource, and according to the IEA technically recoverable resources are estimated to be 7.3 quadrillion cubic feet for shale gas, 2.7 quadrillion cubic feet for tight gas, and 1.7 quadrillion cubic feet for coalbed methane. Current annual global consumption of natural gas is about 130 trillion cubic feet.

My feelings about shale gas (and oil) fracking are mixed. It represents a large, new fossil fuel resource but may present serious environmental concerns. Here is how I see the issues:

- Wells drilled into gas-rich shale deposits are usually quite deep, well below the underground aquifers supplying freshwater.
- The quantities of water required are large (millions of gallons per well) and create a huge demand on local water supplies.
- Major problems with fracking occur when the injected water is returned to the surface and has to be cleaned up or disposed of. Here is one place where extraction companies may be tempted to take shortcuts to reduce costs.
- The returned water not only has added chemicals that facilitate the fracturing but also heavy metals, uranium, and other contaminants that it releases from the shale along with the trapped CH_4 (and oil). Without these ‘additives’ the water could be returned to reservoirs or reused, but that is not the case. The water with fracking chemicals can be reinjected for reuse in further fracking, but to avoid the build-up of heavy metals and radioactivity these other ‘additives’ have to be removed and disposed of carefully. This costs money. Even returning the drilling water to reservoirs and other non-fracking uses requires water decontamination, again a costly process.
- Here is where I become wary of human behavior. The easiest and least costly thing to do with returned water is dump it in nearby lakes and streams when no one is watching, which I suspect is occasionally done. Water handling and cleanup costs are a major operating expense. Contaminants can disturb ecosystems and eventually get

into drinking water, which is why many people oppose fracking.

- Another problem with fracking is leakage of CH_4 from wellbores that are not fully sealed (again a cost issue), and from other underground cracks induced by the hydrofracturing that released CH_4 away from the wellbore. This kind of leakage has been blamed for the water supplies in homes that seem to be saturated with CH_4 and can be ignited.
- In addition, the use of trucks to haul in fracking water, return to their water sources, and, if necessary, remove the returned water, creates a lot of heavy traffic that is disturbing to communities along the way.

However, fracking is not all bad. There is lots of shale gas (and oil) to be extracted (decades worth), prices for natural gas have come down, natural gas can be substituted for coal in power generation (and release less CO_2 per unit of energy generated), and the prospect of long-term supplies of low-cost natural gas is beginning to attract industries back to the US from overseas locations. CH_4 can also be used in transportation as a compressed fuel or a starter chemical for alternative liquid fuels, reducing our dependence on imported oil.

A detailed review of water issues associated with fracking, *Shale Gas and Hydraulic Fracturing – Framing the Water Issue* by Olsson, Lindstrom, and Hoffman (41), concluded that:

- ‘The emergence of shale gas and shale oil has quickly changed the landscape of opportunities for energy provision and security in different regions of the world.
- ‘Fracking is a water-intensive activity, and, as the (shale) reserves are often found in dry areas, extraction poses additional challenges in what are often already water-stressed environments. The vast water quantities needed over the life span of a shale gas well, where water is used to fracture rock under high pressure, pile further stress on

local freshwater sources which are already needed for many different purposes. At times when water supplies are running short in a specific area it has to be transported to the fracking site from afar.

- 'Water quality is also under threat from fracking as well as the quantity available. Many chemicals used in the fracking fluid (the composition of which is often protected for commercial confidentiality reasons) have increasingly been found to be harmful both to the environment and to human health, yet poor regulations and legislation governing fracking often allow accidents which contaminate surrounding water sources. There is a need for greater responsibility, through developing codes of conduct and regulatory systems governing fracking so as to protect water resources and the environment.'

Given this complex context, where do I come out on fracking? My belief is that commercial mining of shale gas and oil is here to stay for at least the next several decades because of the attractive financial returns, the reduced carbon emissions associated with substituting natural gas for coal in power generation, and the national security benefits associated with an indigenous energy source. Weighing the pros and cons I conclude that what is needed is to create and enforce a strict regulatory regime at federal, state and local levels for fracking. Fracking gas is creating a new 'natural gas era' in the US and elsewhere and we will have to deal with it in as safe a manner as possible. Threats to ecosystems and water supplies are serious threats and require our utmost attention. Given the costs involved in addressing the cons I expect some attempted shortcuts and 'accidents', but that's an inevitable part of supplying energy needs. It is society's job to create disincentives for these shortcuts, educate the public about the threats, and keep the pressure on companies and government officials to adhere to and enforce the regulations.

Chapter 7

Nuclear power

Nuclear power is a relatively recent development in human history and its long-term future is still to be determined. It is an outgrowth of nuclear weapons development during World War II. It comes in two different technology types, nuclear fission and nuclear fusion. Both are discussed in detail below.

7.1 NUCLEAR FISSION

Nuclear fission power is an important energy option for the future, although highly controversial. It now accounts for 11% of the world's electricity. Sixteen countries depend on nuclear power for at least 25% of their electricity supply. See Figure 7.1 (42).

7.1.1 Fission fundamentals

I was first exposed to the basics of nuclear fission as an undergraduate engineering student, and at one point even considered changing my major to nuclear engineering. It is a 'technologically sweet' energy option from the point of view of

The chapter is from the book *Water, Energy, and Environment: A Primer*, Allan R. Hoffman (Author).
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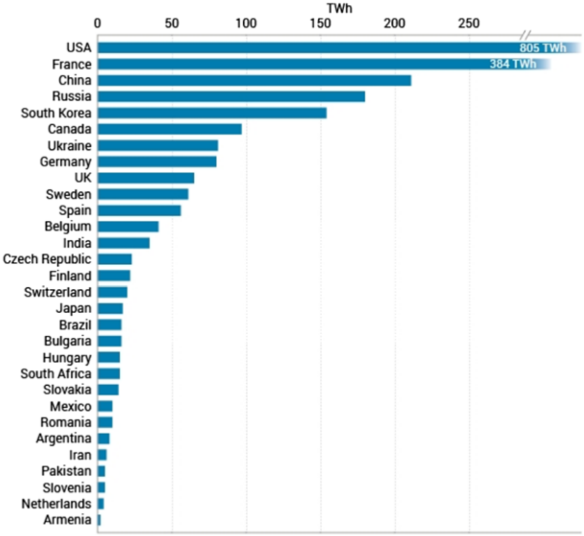

Source: IAEA PRIS Database

Figure 7.1 Nuclear generation by country 2016 (*Source:* International Atomic Energy Agency).

basic physics and offers the prospect of a very large source of electricity that does not release carbon into the atmosphere. The fundamental physics of nuclear fission are straightforward (see Figure 7.2).

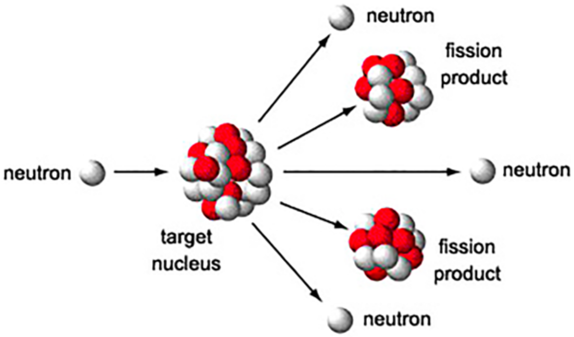

Figure 7.2 The fundamentals of nuclear fission (*Source:* Atomic Archive).

When a heavy (i.e., high atomic weight) nucleus (such as uranium or plutonium) is hit by a neutron it can split (fission) into lighter nuclei (fission products) and release additional neutrons. The mass of these fission products and released neutrons is less than the mass of the original target nucleus, and the lost mass is converted into energy according to the Einstein equation $e = mc^2$. This energy manifests as heat in a nuclear power reactor in which the target fuel, enclosed in fuel rods, is surrounded by water. The heated water turns into steam which is then converted to electricity in a turbine-generator. The fission products are radioactive, some with extremely long half-lives, and must be separated from human or other ecosphere contact.

7.1.2 Introduction to nuclear issues

I was reintroduced to the nuclear power issue in 1969 as a young physics professor at the University of Massachusetts. Given the strong feelings on all sides of the nuclear power debate, a few words on how I got into this issue may be helpful in understanding my personal views. I discussed this background in a 1982 speech at the University of Delaware (43), part of which I reproduce here.

> ‘Before I get into the substance of my talk, let me tell you a little about my background and my involvement with energy issues. I am trained as a low-temperature solid-state physicist, who was happily engaged in teaching and setting up and operating a new laboratory at the University of Massachusetts in 1969 when I first became involved with energy as a social issue. New England utilities, because of heavy dependence on imported oil, had early on looked to nuclear power as a response to this dependence. As a result, organized opposition to nuclear power also developed early in New England.
>
> Thus it was in December 1969 that a colleague in the physics department asked me to attend an all-day seminar on the problems of nuclear power, which he could not attend because of a prior commitment. I did so, more out of respect for my colleague than curiosity, but that event surely has had its impact on my career. For the

> first time I began to ask whether our nation's development of this power source may have left something to be desired. I also became painfully aware of how little I knew about commercial nuclear power, and decided to do something about it.
>
> By talking with colleagues I was able to identify five other faculty members who were willing to meet once a week at lunch to discuss nuclear power issues and help to educate one another. This lasted about one year. During this period I found my interest in energy issues growing, and once-a-week discussions soon left me frustrated at my own pace of learning. Thus, I took the next step, which was to offer to teach an energy course to undergraduates, which I began to do in the fall of 1970. I know of no better way to learn something new than to teach a course where you have to keep ahead of your students. Shortly thereafter I was asked to serve as a science advisor to a newly founded New England citizens' group concerned about nuclear power, and I agreed. One thing led to another, and soon I was engaged in public debates on nuclear power with utility executives, scientists from Brookhaven National Laboratory, and the nuclear engineering department of MIT.
>
> As my knowledge of nuclear power increased, and as I watched nuclear power become an important political issue at local, state and federal levels in the US and other countries, I came to several conclusions: I am not anti-nuclear, recognizing its carbon-free and large energy potential, but am sensitive to the concerns that many people have. These include high cost, routine releases of radioactivity from operating plants, shipping of nuclear wastes through populated areas, lack of long-term waste storage options, the remote but real possibility of accidents, and the potential for nuclear weapons proliferation. Alvin Weinberg, former Director of Oak Ridge National Laboratory, may have said it best in 1947 when he called nuclear power a 'Faustian bargain', defined by the Cultural Dictionary as follows: 'Faust, in the legend, traded his soul to the devil in exchange for knowledge. To 'strike a Faustian bargain' is to be willing to sacrifice anything to satisfy a limitless desire for knowledge or power.'

Clearly, there is a clash of values in our national debate on nuclear power. On the one hand we have advocates who, having looked at US dependence on imported fuels and at declining fossil fuel reserves, see little hope for energy independence and '… little long-range hope for the achievement of decent living standards everywhere …' without broadened use of nuclear power. They point to the unemployment that results when energy is scarce or very costly, and to the poor living conditions of a good part of the world, and ask how can we deny the benefits of nuclear electricity to these people. They also point to the risks of coal mining and coal burning, oil spills, the CO_2 problem from combustion of fossil fuels, and suggest that nuclear power, even with its risks, may be a reasonable choice in that context.

On the other hand, and exhibiting equal conviction and sincerity, are those who see viable alternatives to nuclear power, who question the feasibility and practicality of nuclear power for capital-poor nations without adequate roads, let alone power grids, who see any move toward a plutonium economy as a step down the road to nuclear war, who question the legacy a nuclear economy would leave for future generations, and who question the impact of human fallibility on the safe operation of the nuclear fuel cycle.

7.1.3 Issues

As a person committed to advancing our use of renewable energy, I have devoted most of my professional career to helping make that possible. Nevertheless, there are realities about how fast that can come about, and how to meet people's needs for electricity while that transition takes place. Nuclear power is a possible option for meeting that need, as well as a long-term, carbon-free energy source. The need for energy during the transition period is also an argument put forth for continued use of fossil fuels.

As for my personal views: while recognizing nuclear power's positive attributes, I have been distressed about how the nuclear industry has presented this technology to the public and often been resistant to acknowledging legitimate concerns associated with a nuclear economy. The cost issue is front and center with power utilities, especially now that natural gas costs are low due to fracking. It is my belief that a safe (i.e., non-meltdown) nuclear reactor can be built today – for example, a high-temperature gas reactor (HTGR) – unlike the early pressurized water reactors (PWRs) and boiling water reactors (BWRs) built at 3-Mile Island and Fukishima. Care and maintenance are critical, and human error and trying to cut costs have a tendency to get in the way. Nevertheless, the likelihood of a nuclear plant accident is arguably small, and if one rules out a meltdown, coal-burning plants may put more radioactivity into the environment than occasional radioactive gaseous releases.

The waste issue is a tough one, but one that has to be solved as we started off the nuclear era with tens of millions of gallons of high-level waste from weapons programs in WWII. Civilian wastes are adding to this total in an increasing number of countries around the world, and the long-term waste issue is being actively explored. I believe a solution will be found, probably in deep geologic storage, but at this point we don't know enough to be confident.

The weapons proliferation issue is the one that scares me the most, not just because of the growing knowledge of how to build a 'nuclear device' (i.e., a bomb), but also the potential availability of radioactive wastes that can be incorporated into a 'dirty bomb'. This latter possibility does not require great technical and manufacturing capabilities (it requires chemical explosive dispersal of radioactive materials) but can do immeasurable harm by creating uninhabitable radioactive zones. When I raised this issue with a representative of the US Nuclear Energy Institute his response was the US can handle such wastes safely, which may be true. But when I asked him about the many other countries that were adding nuclear power plants he went silent, illustrating the problem. Many countries will not have the means, technical and financial, to control these wastes as well as the US and a few other counties can, and the only answer I can come up with is internationalization of the waste disposal/recycling process. Another approach for future nuclear power plants may be to use a different fuel cycle that produces and consumes its own high-level waste. Modular reactors are also being discussed (100–300 MW units, as opposed to today's standard 1000 MW units) which in principle can be mass produced, be less capital intensive, and sealed without refueling for years to decades. Regardless, there will still be a waste problem that has to be addressed.

Assuming that the problems associated with nuclear fission power can be addressed successfully, which is still not clear, society will have some choices to make. Renewable energy is well on its way to entering the energy mainstream as a carbon-free, distributed, and large energy source, and one possibility is an energy future, post-fossil fuels, where nuclear power and renewable energy coexist. Other possibilities are a nuclear future or a renewables future. Given the complex issues presented by nuclear power my clear preference has been and continues to be a future energy system based largely on renewable energy in its many forms (see Chapter 8).

7.2 NUCLEAR FUSION

Nuclear fusion, the process that powers our Sun and other stars, is considered by many to be the 'holy grail' of energy supply. Why? The numbers tell the story.

7.2.1 Fusion fundamentals

The basic physics of fusion is well known and easily understood. When the nuclei of light elements (lighter than iron) are forced together, under extreme conditions of pressure and temperature, they will fuse – that is, form a heavier nucleus that is lighter than the combined mass of the two fusing nuclei. The mass that is lost is converted to energy according to $e = mc^2$ (see Figure 7.3).

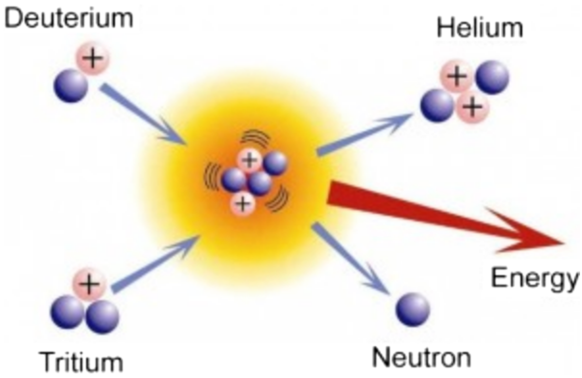

Figure 7.3 The D–T to helium fusion reaction (*Source:* Atomic Archive).

It turns out that so much energy is released in this process (a simple, back-of-the-envelope calculation is shown below) that, if the process can be harnessed on Earth, an unlimited source of energy is available. Fusion has other advantages as well as serious technological problems, which are discussed below. First, why are the numbers so intriguing?

While many fusion reactions are possible and take place in stars, most attention has been directed to the deuterium–tritium (D–T) fusion reaction that has the lowest energy threshold. Both deuterium ($_1H_2$) and tritium ($_1H_3$) are heavier isotopic forms of the common element hydrogen ($_1H_1$). Deuterium is readily available from seawater (most seawater is two parts ordinary hydrogen to one part oxygen; one out of every 6240 seawater molecules is two parts deuterium to one part oxygen). Tritium supplies do not occur in nature – it is radioactive and disappears quickly due to its short half-life – but can be bred from a common element, lithium, when exposed to neutrons:

$$^{6}_{3}\mathrm{Li} + ^{1}_{0}\mathrm{n} \rightarrow ^{4}_{2}\mathrm{He} + ^{3}_{1}\mathrm{H} + 4.8\mathrm{MeV}$$

D-T is also the reaction that largely powers our sun (although other fusion reactions do occur), routinely converting massive amounts of hydrogen into massive amounts of helium and releasing massive amounts of energy.

It has been doing this for more than four billion years, and is expected to continue doing this for about another five billion when its hydrogen supply will finally dwindle. At this latter point the fusion reactions in the core of the Sun will no longer be able to offset the gravitational forces acting on the Sun's very large mass and the Sun will explode as the Crab Nebula did in 1054. It will then expand and swallow up the Earth and its other planets.

7.2.2 Numbers

To understand the quantity of energy released: every cubic metre of seawater, on average, contains 30 grams of deuterium. As mentioned in Chapter 1, there are 300 million cubic miles of water on Earth, 97% in the oceans. Each deuterium nucleus (one proton + one neutron) weighs so little (3.3 millionths of a trillionth of a trillionth of a kilogram) that these 30 grams amount to close to a trillion trillion nuclei. Each time one of these nuclei is fused with a tritium nucleus (one proton + two neutrons) 17.6 MeV (millions of electron volts) of energy is released which can be captured as heat. Now MeV sounds like a lot of energy but it isn't – a Btu, a more common energy unit, is 6.6 thousand trillion MeV).

Now this is a lot of numbers, some very small and some very large, but taking them all together that cubic metre of seawater can lead to the production of about 7 million kWh of thermal energy, which if converted into electricity at 50% efficiency corresponds to 3.5 million kWh. If one were to convert the potential fusion energy in just over 1 million cubic metres of seawater (a small fraction of a cubic mile) one could supply the total annual US electricity production of 4 trillion kWh – and remember that our oceans contain several hundred million cubic miles of water. This is why some people get excited about fusion energy.

7.2.3 Barriers to fusion

Unfortunately, there are a few barriers to overcome, starting with how to get D and T, both positively charged nuclei, to fuse. The positive electrical charges repel one another (the so-called Coulomb Barrier) and you have to bring the distance between them to an incredibly small separation before the 'strong nuclear force' can come into play and allow creation of the new, heavier helium nucleus (two protons + two neutrons). It is this still mysterious force that holds protons and neutrons together in our various nuclei (the other three 'fundamental forces of nature' are the gravitational force, the weak nuclear force, and the electromagnetic force).

So how does one bring these two nuclei close enough together to allow fusion to occur? The answer in the Sun is extremely high temperatures and enormous gravitational pressure which we cannot reproduce on Earth. The pressures in the Sun, due to its large mass, are beyond our ability to achieve in any sustained way but the temperatures are not (temperature is a way of characterizing a particle's kinetic energy, or speed) and fusion research is focused on achieving extremely high temperatures (hundreds of millions of degrees or higher) at achievably high pressures. The fact that this is not easy to achieve is why fusion energy is always a few years away.

Two techniques are the focus of global fusion research activities – magnetic confinement (as in tokamaks and ITER) and inertial confinement (as in laser-powered or ion beam-powered fusion) (44). Several hundred million US dollars a year are being spent on these activities, mostly in international collaborations.

Fusion on Earth has been achieved but not in a controlled manner, and then only in very small amounts and for very short time periods with just one exception – the hydrogen bomb. This is an example of an uncontrolled fusion reaction (triggered by a fission atomic bomb) that releases a large amount of energy in a few millionths of a second. As the French physicist and Nobel laureate Pierre-Gilles de Gennes once said: ‘We say that we will put the Sun in a box. The idea is pretty. The problem is, we don’t know how to make the box.’

7.2.4 Pros and cons

The pros and cons of fusion energy can be summarized as follows:

Pros:

- virtually limitless fuel availability at low cost
- no chain reaction, as in nuclear fission, and so it is easy to stop the energy release
- fusion produces no greenhouse gases, and little nuclear waste compared to nuclear fission (the radioactive waste from fusion is from neutron activation of containment materials)

Cons:

- still unproven, at any scale, as a controlled reaction that can release more energy than required to initiate the fusion (‘ignition’)
- requires extremely high temperatures that are difficult to contain
- many serious materials problems arising from extreme neutron bombardment
- commercial power plants, if achievable, would be large and expensive to build
- at best, full scale power production is not expected until at least 2050.

7.2.5 Thoughts

Where do I come out on all this? I am not trained as a fusion physicist and so lack proximity to the efforts of so many for so long to achieve controlled nuclear fusion. Nevertheless, I support the long-term effort to see if ignition can be achieved (some scientists believe the ITER experiment is that critical point) and if the many engineering problems associated with commercial application of fusion can be successfully addressed. In my opinion the potential energy payoff is too big and important for the world to ignore. In fact I was once asked for my advice on whether the US Government should support fusion R&D by a member of the DOE transition team for President-elect Carter. I answered yes then and my answer hasn’t changed.

Chapter 8

Renewable energy

Renewable energy can be defined as energy that comes from resources which are continually replenished such as sunlight, wind, rain, tides, waves and geothermal heat. A more detailed breakdown and list of renewable energy technology options would comprise the following:

- Solar energy
    - Photovoltaics (PV)
    - Solar thermal technologies
        - Concentrating solar power (CSP)
        - Solar hot water
        - Passive solar
- Wind energy
    - Onshore wind
    - Offshore wind
- Geothermal energy
    - Power generation

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  - Direct use
  - Ground source heat pumps
- Biomass energy
  - Plant material
  - Waste materials
  - Algae
- Hydropower
  - Traditional technology
  - Barrage technology
- Ocean energy
  - Wave
  - Tidal
  - Ocean current
  - OTEC

What might be noted is that most of the entries are direct or indirect forms of solar energy. PV and solar thermal are direct forms. Wind is an indirect form arising from uneven heating of the Earth's surface. Biomass is organic matter grown with the aid of sunlight. Hydropower depends on water delivered by the hydrological cycle which is solar-driven. OTEC (ocean thermal energy conversion) depends on solar heating of the ocean's surface. Wave energy is partly wind-driven, but is also affected by the gravitational attraction between the Earth and the Moon. Tidal energy is water energy that is driven by ocean heating as well as gravitational effects. The one exception is geothermal energy that derives from radioactive decay in the Earth's core.

8.1 THE SUN'S ENERGY SOURCE AND RADIATION SPECTRUM

As an introduction to a more detailed look at each renewable energy technology in subsequent sections of this chapter, let us begin with a brief discussion of the source of the Sun's energy.

Energy from our medium-sized star is abundant and renewable, and is the principal factor that has enabled and shaped life on our planet. Our Sun belongs to the class of dwarf yellow stars whose members are more numerous than those of any other class. The energy radiated into space by the Sun is fueled by a fusion reaction in the Sun's central core where the temperature is estimated to be about 10 million degrees Celsius. At this temperature the corresponding motion of matter is so violent that all atoms and molecules are reduced to fast-moving atomic nuclei and stripped electrons, collectively known as a plasma. The nuclei collide frequently and energetically, producing fusion reactions of the type that occur in thermonuclear explosions.

While about two-thirds of the elements found on Earth have been shown to be present in the Sun, the most abundant element is hydrogen, constituting about 80% of the Sun's mass – approximately 2 trillion trillion million kilograms. When hydrogen nuclei collide in the Sun's core they fuse and create helium; roughly 20% of the Sun's mass is in the form of helium. Also created in each fusion reaction are two neutrinos, high-energy particles with no net electrical charge that escape into outer space, and high-energy gamma radiation that interacts strongly with the matter that surrounds the Sun's core. As this radiation streams outward from the core it collides with and transfers energy to nuclei and electrons, heating the mass of the Sun so that it achieves a surface temperature of several thousand degrees Celsius. The energy distribution of the radiation emitted by this surface is fairly close to that of a classical 'black body' (i.e., a perfect emitter of radiation) at a temperature of 5500°C, with much of the energy radiated in the visible portion of the electromagnetic spectrum. Energy is also emitted in the infrared, ultraviolet, and x-ray portions of the spectrum (see Figure 8.1).

The Sun radiates energy uniformly in all directions, and at a distance of 93 million miles the Earth's disc intercepts only 4 parts in 10 billion of the total energy radiated by the Sun. Nevertheless, this very small fraction is what maintains life on Earth, and on an annual basis is approximately 10,000 times larger than all the energy currently used by the Earth's human inhabitants (which is approximately 600 quads).

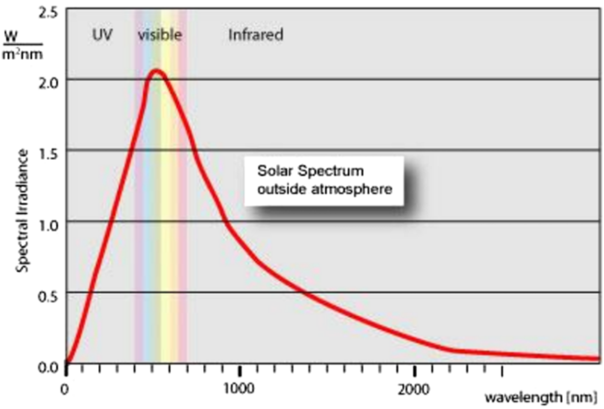


Figure 8.1 Radiation spectrum of the Sun (*Source:* Green Rhino Energy).

What happens to the 6 million quads of solar energy that annually reach the Earth's atmosphere? While the amount of energy radiated by the Sun does vary slightly due to sunspot activity, this variation is negligibly small compared to the energy released by the Sun's basic radiative process. As a result the amount of energy received at the outer boundary of the Earth's atmosphere is called the Solar Constant because it varies so little. This number, averaged over the Earth's orbit around the Sun, is 1367 W/m^2 on a surface perpendicular to the sun's rays. In fact, the Earth's orbit around the sun is not circular but elliptical, and the 'Solar Constant' varies by about 3% during the year. In the northern hemisphere the highest value is in the winter and the lowest in the summer.

About a quarter of the radiation incident on the Earth is lost by reflection back into space from the top of the atmosphere and tops of clouds. For the radiation penetrating the Earth's atmosphere a not insignificant amount is lost due to scattering and absorption by air molecules, clouds, dust and aerosols. One must also take into account the Earth's rotation and the resultant day–night (diurnal) cycle. To put a number on all this, if one assumes 30% is lost due to the above factors and the sun shines only 12 hours per day on to a 1 m^2 surface, that square metre receives no more than (1367 W/m^2) × (70%) × (12 hours/day) × (365 days/year) = 4200 kWh of solar energy per year. Since on average the sun actually shines less than 12 hours/day at any location, the maximum solar radiation a site can receive is closer to 2600 kWh/m^2 per year. To put this number into perspective, today the average person on Earth uses about 23,000 kWh per year (600 quads for 7.6 billion people).

Clearly, the energy we receive from the Sun is more than enough to meet human needs. Nevertheless, for many years some people have asked whether we can rely on renewable energy as a reliable and practical energy source. A definitive answer to this question was presented in the June 2012 NREL *Renewable Electricity Futures Study* (45) which concluded that 'Renewable electricity generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total US electricity generation in 2050 while meeting electricity demand on an hourly basis in every region of the country.' This is not a prediction but a statement that renewable electricity can meet our needs if we so choose. It will not happen without overcoming many barriers (need for new transmission lines and storage, technology cost, political opposition) but it is possible if we have the political will to make it so. We must also recognize that renewable resources can be used to supply thermal energy as well as electricity, for space heating and cooling and water heating, and transportation fuels via chemical conversion of biomass materials. This is why people get excited about our renewable energy resources.

8.2 DIRECT SOLAR ENERGY

Direct solar energy comes in two forms: photovoltaics (PV) and concentrated solar power (CSP). The latter category includes concentrating solar thermal power (CSTP) and concentrating photovoltaics (CPV). All are discussed below.

8.2.1 Photovoltaics

PV is now a well known and widely deployed form of renewable energy, in which radiation from the Sun is converted directly into electricity via panels of solar cells. This energy conversion process employs the photovoltaic effect, in which light absorbed by a semiconducting material (e.g., doped silicon) generates charge carriers of opposite type that are collected and delivered as electrical energy to an external circuit.

The solar panels, assemblies of solar cells, can be roof-mounted or ground-mounted, as shown in Figures 8.2 and 8.3. Large arrays of panels can provide utility-scale power and the

Figure 8.2 Roof-mounted PV (*Source:* U.S. National Renewable Energy Laboratory).

Figure 8.3 Ground-mounted PV (*Source:* NetZero Renewable Resources).

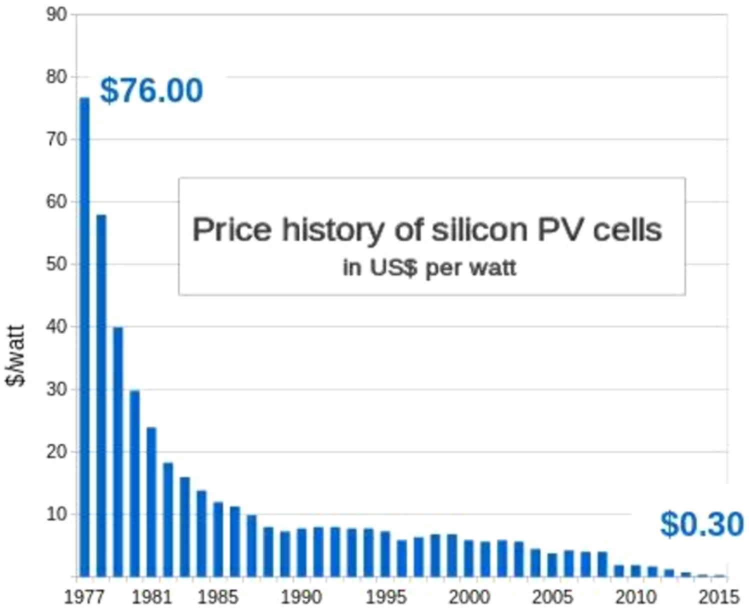
energy needed to desalinate large quantities of saline water via reverse osmosis.

Small numbers of solar cells or panels can also be used to provide electricity to handheld calculators, roadside telephones, battery chargers, remote microwave relay stations, solar lanterns, water pumps, water decontamination units, and numerous other applications. It is a modular technology that can be scaled up from watt to megawatt size as needed. It also lends itself to integration with various building and other materials – e.g., as roof tiles, building facades, blankets, clothing, and other flexible materials.

The photovoltaic effect was first demonstrated in 1839 by Edmond Bequerel, first explained in 1905 by Albert Einstein, and the first practical solar cell was developed at Bell Laboratories in 1954. They gained visibility when flown on the US Vanguard satellite in 1958 as an alternative power source to a traditional battery. By the 1960s solar cells were the principal power source for most Earth orbiting satellites, and remain so to this day. Development of solar cells for terrestrial applications became a priority of the US National Science Foundation's RANN (Research Applied to National

Needs) program, and is now a major part of DOE's renewable energy program.

The cost of solar PV cells was initially very high (several hundred US dollars per watt), with its market limited to space applications where cost was not a major issue. Eventually these costs started to come down as the technology improved, and more and more solar cells were manufactured. In recent years, with large-scale deployment of PV, and production in quite a few countries, the cost has come down dramatically, as shown in Figure 8.4:



Source: Bloomberg New Energy Finance & pv.energytrend.com

Figure 8.4 Price per watt (crystalline silicon solar cells).

It is important to remember that the full cost of a PV installation includes not only the cost of the solar cells but also the 'balance of system' costs associated with permitting, wiring, mounting systems, installation, and inverters that convert dc electricity to ac. Today, with reduced cell costs, balance of system costs are dominant and are an R&D focus.

As a result of large price drops, and increasing experience with PV, the amount of PV installed has increased dramatically in recent years (see Figure 8.5):

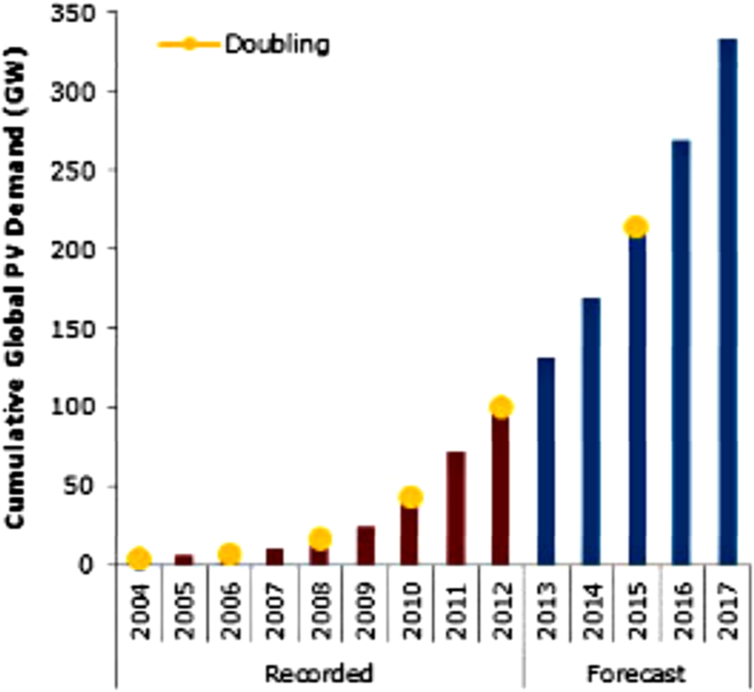


Figure 8.5 Global installed PV capacity (GW) (*Source:* Wood Mackenzie).

According to the latest Global Solar Demand Monitor from GTM Research, new installations will reach 104 GW in 2018, representing 6% annual growth. Other industry monitors put this number even higher, and 2018 is the first time

100 GW/year has been achieved. It is anticipated that annual installations will easily exceed the 100 GW milestone through at least 2022. In the US solar energy (PV + CSP) has ranked first or second in new electric capacity additions in each of the past 5 years, and its increasing competitiveness against other technologies has allowed it to quickly increase its share of total US electrical generation from 0.1% in 2010 to nearly 2% in 2017.

Solar cells are made from a variety of materials for a number of uses, ranging from terrestrial to space applications. First-generation cells were made of monocrystalline and polycrystalline silicon. Such devices today achieve conversion efficiencies (sunlight to electricity) of about 20%, while specialized cells designed for use at high solar concentration levels can achieve 40% or more.

Second-generation cells utilize thin-film technology, which reduces material demand and facilitates large-scale manufacture. Examples are cells made from amorphous silicon, cadmium telluride, and copper indium gallium diselenide. Their efficiencies are approaching those of monocrystalline silicon. Third-generation cells include a number of thin-film technologies that are in active, pre-commercial development; many use organometallic compounds or inorganic materials.

In general PV is a transformative technology that changes the way we generate and use electricity. It can be used wherever the sun is shining, e.g., in space to power satellites and space stations, in remote areas on Earth, and even on Mars to power robotic vehicles. It can generate power where it is needed without the need for power lines, it is modular and easily and quickly scaled up, and its cost is coming down dramatically as more and more PV is manufactured and deployed. Our infrastructure is already highly dependent on PV – think about satellites used for wireless telephone communication and GPS, and terrestrial PV that increasingly is supplying electricity to utilities as well as individual homes and businesses.

It should also be noted that terrestrial use of PV is only beginning. An industry that started in 1973 in the US is today the vanguard of a rapidly unfolding global energy revolution that will replace fossil fuels with renewables and bring energy services to all portions of the globe. For example, in Africa, which has enormous solar energy resources, electrification will finally become possible for the hundreds of millions of people in sub-Saharan Africa currently without access to electricity. Solar power generation at large scale is also likely to be critical to mitigating global climate change.

Finally, a word about PV's distributive/decentralized nature and the challenge this presents to traditional electric utilities: this challenge arises from the fact that PV generation is often maximum at peak periods of electricity demand (e.g., when air conditioning drives the demand) when utilities are used to charging higher than average kWh prices. If this peak demand on the utility system is reduced by home- or business-generated electricity, then utility revenues will be adversely affected based on current utility business models. With increasing penetration of PV solar it seems clear that these business models will have to change. Based on historical experience, most utilities initially will resist this. German utilities faced this problem first because the German government introduced a feed-in-tariff (FiT) for PV in the 1990s, stimulating a massive deployment of PV in Germany. Today Germany leads the world in PV deployment with more than 40 GW installed. On very sunny summer days more than half of Germany's electrical demand has been met by PV. When faced with this reality German utilities got into the PV business and are now even offering energy storage services to the German public.

While a number of other countries are now offering FiTs to their citizens, the US federal government has not yet done so. Nevertheless, more than half of all US states are taking the lead in stimulating deployment of PV and other renewable energy technologies via use of renewable-energy portfolio standards (RPS) that require increased production of energy from renewable sources such as solar, wind, biomass, and geothermal. RPS-type mechanisms have been adopted in other countries as well, including Sweden, Italy, Belgium, Poland, the United Kingdom, and Chile.

A recent trend in several countries is a movement toward deployment of community solar projects in which the output from a solar PV power plant is shared by more than one household. The term 'community solar' can refer to both community-owned projects as well as third-party-owned power plants whose electricity output is shared by a community. It is in this second category that utilities see a role for themselves, as their traditional business models are forced to change. Several groups that study the renewable energy industry have projected that community solar will be a significant growth market in the US and other developed nations, and will be a major factor in the electrification of remote areas in developing countries.

8.2.2 Concentrating solar power (CSP)

Concentrating solar thermal power (CSTP), the most common type of CSP, uses mirrors to focus/concentrate sunlight, delivering heat which can then be used to generate electricity. This can be done by heating water to generate steam that drives a conventional turbine generator, or to power a heat-driven engine. The three types of CSTP are power tower, linear concentrator, and dish-engine systems. Each is discussed below.

Note: using mirrors to concentrate sunlight is not new. It has been reported for more than 2000 years that Archimedes used mirrors to concentrate sunlight and set Roman ships afire during the siege of Syracuse in 213 BC. While much evidence has been presented to refute this claim, it is probably too powerful a legend to die. Nevertheless, the legend supports a saying heard often in the early days of modern solar energy that if solar had been a weapon of war it would have been fully developed by now.

8.2.2.1 Power tower

Following the OPEC-imposed Oil Embargo of 1973–74 and increased global interest in energy issues, the US DOE started a CSTP project called Solar One. It involved hundreds of ground-mounted reflecting mirrors, called heliostats, individually tracking the Sun and directing their sunlight to a water receiver at the top of a 400 foot high centrally located tower (see Figure 8.6). It was located in the Mojave Desert just east of Barstow, CA, and was the first test of a large-scale power tower plant.

Figure 8.6 Solar One power tower plant (*Source:* U.S. National Renewable Energy Laboratoty).

The heated water was converted into steam and fed into a steam-turbine generator. Construction of Solar One was completed in 1981 and it was operational from 1982 to 1986. It was then redesigned to incorporate molten salt (60% sodium nitrate, 40% potassium nitrate) as the thermal collection and storage medium, and relabeled Solar Two. The redesign was needed to address the instability of Solar One when sunlight was disrupted by passing clouds. Solar Two was successfully tested at a 10 MW electrical output, but operation was discontinued in the mid-1990s when the CSTP industry was unwilling to share further development costs with DOE. The Solar Two tower was eventually demolished in 2009 and its heliostats are now being used for astronomy research.

8.2.2.2 Linear concentrator

The most common type of linear concentrator system captures the Sun's energy with long rectangular curved mirrors (parabolic troughs) that track the Sun and focus sunlight on glass tubes that run along the troughs' focal lines. The tubes are filled with a dark, heat-absorbing fluid that transfers its heat to water to generate steam (see Figure 8.7).

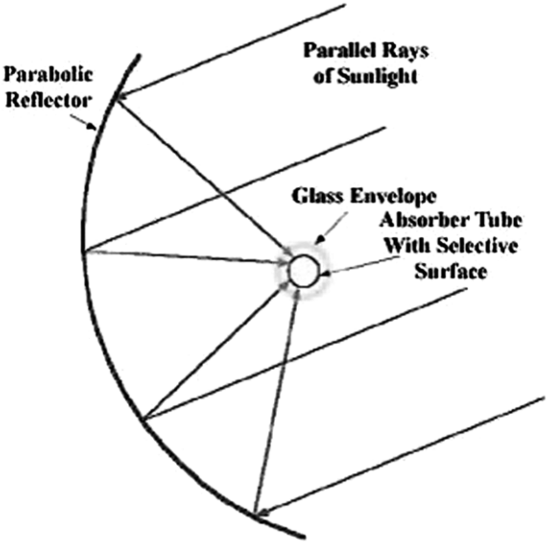


Figure 8.7 Parabolic trough CSTP system (*Source:* U.S. National Renewable Energy Laboratory).

A separate type of linear concentrator system is the Fresnel reflector system, where one receiver tube is positioned above several curved mirrors. This configuration allows the mirrors greater flexibility in tracking the Sun.

8.2.2.3 Dish engine

The third type of CSTP technology is the dish engine system in which a dish-shaped receiver (usually multi-faceted to reduce manufacturing costs) directs sunlight onto a thermal receiver at the focal point of the dish (see Figure 8.8). The receiver absorbs the heat and transfers it to a heat-driven engine generator (typically a Stirling engine) with a working fluid such as hydrogen gas. Each dish rotates along two axes to track the Sun.

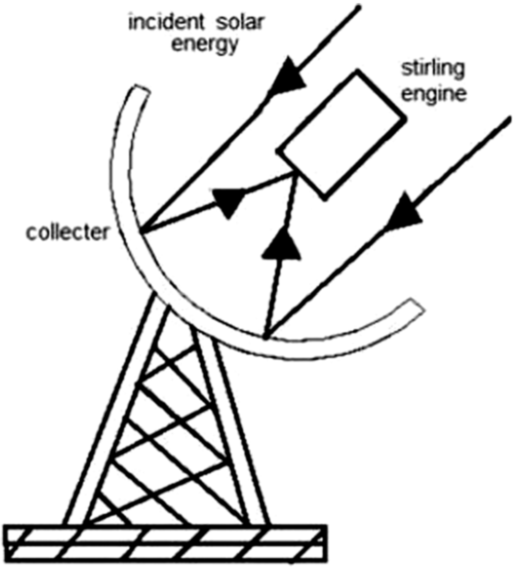


Figure 8.8 Dish engine CSTP system (*Source:* U.S. National Renewable Energy Laboratory).

8.2.2.4 CSTP history

CSTP has a long history, dating back to the 1980s in its demonstration phase, and then as a commercial effort when Luz International installed 354 MW of parabolic trough technology in nine separate projects in Kramer Junction, CA. The 354 MW, installed between 1984 and 1990, consisted of SEGS 1 (13.8 MW), SEGS II–VII (30 MW each), and SEGS VIII and IX (80 MW each). These plants fed their power into the Southern California Edison power grid and are still operating today. Regulatory and policy obstacles forced Luz into bankruptcy in 1991. The original owner of Luz is now head of Bright Source Energy Company, which operates a complex of three CSTP power towers in California, and has operations in China, Europe, Israel, and South Africa.

8.2.2.5 Advantages and disadvantages

One of CSTP's key advantages is its close resemblance to traditional thermal power plants – it uses many of the same technologies and equipment, and substitutes concentrated high-temperature solar heat for the heat derived from the combustion of fossil fuels or from nuclear reactors. While it underwent a period of low visibility in the 1990s and early 2000s, there has been renewed interest in CSTP as its costs have come down. It is seen as a means of meeting RPS requirements, and as a means of reducing carbon emissions from electricity generation.

CSTP's other advantages include: it can be built in small sizes and added to as needed; can achieve high steam operating temperatures, allowing more efficient power generation; is capable of combined-heat-and-power generation, providing steam for absorption chillers and industrial process heat; is a non-carbon-emitting power generator; and most importantly, incorporates thermal storage. This storage does not add significantly to generation costs, can be added to an existing steam power plant that lacks storage without increasing the size of that steam plant, enables generation to match the utility load profile, allows power generation after the Sun goes down and for up to 24 hours, and can be partnered with intermittent renewable energy sources to provide firmed-up power.

Disadvantages include high upfront capital costs for concentrators and storage, although these costs have been coming down, and the fact that CSTP requires unscattered ‘direct normal’ solar radiation, thus limiting where CSTP plants can be located. This suggests desert locations with limited cloud cover, which are often arid. CSTP also needs exhaust cooling, as with any steam power plant, creating a requirement for water or air cooling. Water limitations necessitate air cooling in some locations, with a penalty in generating efficiency, and capital and energy costs. CSTP power plants also require large surface areas for placement of concentrators, typically 5–10 acres per MW of capacity.

8.2.2.6 Thermal storage

SEGS units used organic heat transfer fluid (HTF) as their storage medium. Organic HTFs can only be used below 800°F. Parabolic troughs can operate at just over 1000°F, and thus use of HTF storage limits plant efficiency by up to 12%. Power Towers can reach higher temperatures (greater than 2000°F) but have only been used to date with molten salt storage. Molten salts (mixtures of sodium nitrate and potassium nitrate) melt at 430°F and thus must be kept heated when used to transfer and store heat. Their maximum storage temperature is 950°F.

An interesting question with respect to thermal storage is: can we do better? Modern high-efficiency thermal power plants can be designed to use steam at 1300 to 1400°F. An ideal storage temperature for these plants would be 1500 to 1700°F. A heat transfer fluid and storage method that operates at temperatures above those of HTF and molten salt would lead to significant energy cost reductions (>30%).

Such a heat transfer and storage system was invented by Dr Ruel Shinnar at the City University of New York (46). It uses pressurized CO_2 as the heat transfer fluid flowing in a closed loop through the solar collectors and either through the power plant or the heat storage system. Compressed CO_2 is one of the most effective gaseous high-temperature heat transfer fluids used in industry. Shinnar's heat storage system would use commercially available vessels (cylindrical metal pipe) filled with a ceramic solid filler, and can be designed to operate at temperatures up to 3000°F. It incorporates a special feature, a cyclic counter-current pebble bed. Pebble-bed heat exchangers date back to the 1920s and have been used reliably for many industrial processes, Heat propagates as a sharp front: one end of the storage remains cold, the other end is hot and at constant temperature, allowing recovery of heat at the same top temperature at which it was stored.

8.2.2.7 Current status

What is the current status of CSTP? Despite its ability to store energy and, in some cases, provide electricity on demand, CSTP has not seen the rapid growth in recent years that has characterized PV markets. Economics has been an important constraining factor, but with costs coming down and more interest in low- or zero-carbon generating sources, CSTP has experienced a comeback. After many years of sitting at 354 MW total installed capacity (the SEGS installations in California), today over 1800 MW of CSTP plants operate in the United States, and more than 5000 MW globally, led by Spain and the US.

Examples of operating plants are the Ivanpah Solar Power Facilty in the US (392 MW), the Solaben Solar Power Station in Spain (200 MW), NOOR 1 in Morocco (160 MW; under construction to soon expand to 500 MW), and the Dhursar Power Station in India (125 MW). Many more CSTP plants have been announced or are under construction. Bid prices for

CSTP energy have reached impressively low levels in recent auctions: \$0.063/kWh in 2016, to less than \$0.05/kWh in 2017. Further reductions are anticipated.

CSTP's future possibilities were explored in a joint study by the IEA's SolarPACES Working Party, Greenpeace International, and the European Solar Thermal Electricity Association (47). It concluded that '… concentrated solar thermal power could account for up to 25% of the world's energy needs by 2050.'

8.2.2.8 Concentrating photovoltaics (CPV)

In CPV power plants curved reflectors or lenses are used to focus sunlight onto small, highly efficient multi-junction solar PV cells. They have the potential to drive down electricity generation costs at large power stations in very sunny locations. They often use solar trackers and cooling systems to increase their conversion efficiencies, are modular so that individual arrays can easily be combined into much larger power generating facilities and can be used in smaller spaces; higher-power, smaller PV arrays also reduce balance-of-system costs. Systems using high-concentration photovoltaics (HCPV) possess the highest individual cell efficiency of all existing PV technologies, more than 40%, and the potential exists to increase the efficiency of this technology to 50% by the mid-2020s. In 2016 cumulative installed CPV totalled 350 MW, with installations in the US, Spain, China, South Africa, and Italy.

8.3 SOLAR POWER SATELLITE (SPS) SYSTEM

No SPS systems currently exist, but, as proposed, such systems would use electricity generated by a collection of solar PV panels in geosynchronous orbit (i.e., orbiting above a fixed point on Earth) to power an Earth-facing microwave generator. The generated microwave energy would be beamed through the atmosphere to a ground-mounted receiver ('rectenna') that would convert the received microwaves to electricity that would be distributed to consumers via the terrestrial grid (see Figure 8.9).

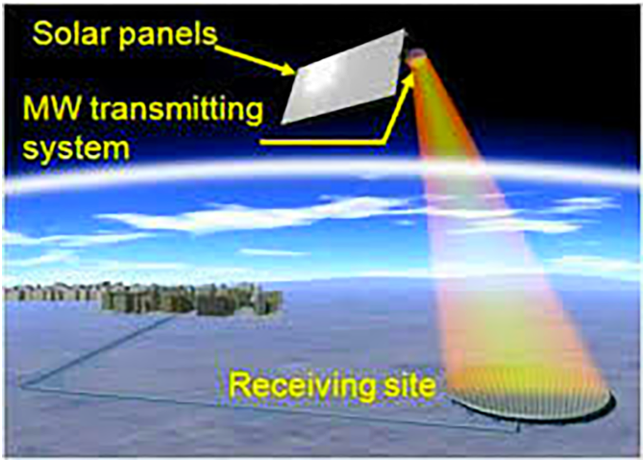


Figure 8.9 Schematic of solar power satellite system (*Source:* American Journal of Physics, Maqsood and Nasir, 2013).

This concept first received NASA attention and review in the 1970s which raised a number of issues which still remain problematic. A small group of SPS enthusiasts still promote the technology but broad support is lacking.

The obvious advantage of SPS is its access to unimpeded radiation from the Sun, without the interference of clouds or atmospheric absorption and scattering. This is partially offset by the need for the microwaves to pass through the atmosphere to the rectenna, but presumably a microwave frequency would be chosen with minimal atmospheric absorption. It should also be noted that every step of SPS technology is technically feasible and well established – solar radiation conversion to electricity, microwave generation, microwave transmission through air, microwave collection and conversion to electricity, and grid transmission.

What are the arguments against SPS?

- Putting anything into orbit is expensive, and until these costs are reduced significantly SPS will not be cost competitive.
- Economics dictate that large individual SPS units (hundreds to thousands of megawatts) be placed in orbit. One suggestion was to place a 10 GW unit in geosynchronous orbit to supply the electrical needs of New York City. In my opinion this is highly problematic since you would be putting all your eggs in one highly vulnerable basket. (These vulnerabilities include exposure in space to higher-than-usual levels of damaging radiation which will shorten expected equipment lifetimes; the possibility of collisions with micrometeorites and space debris; ordinary technical failures with a large amount of electricity potentially at risk; and vulnerability to sabotage/attack in the event of international tensions).
- Aircraft will need to avoid the beams passing through the atmosphere to avoid any possible impacts on humans from exposure to relatively high-strength microwave signals. Birds are another potentially impacted species.
- The large land areas required for rectennas which would ideally be located in close proximity to cities with large electricity demand.

It is therefore reasonable to ask: is SSP a viable option for future electricity supply? In my opinion, not in the near- to mid-term. Long-term may be a more optimistic story. Solar PV costs are now much lower than they were just a few years ago and still decreasing, radiation resistance of solar cells and microwave generating equipment may be improved, the cost of insertion into geosynchronous orbit will hopefully come down significantly, and small SPS units (100–300 MW) may become sufficiently practical to be worth considering. The other problems would remain, and terrestrial competition from other renewable electric technologies will increase.

At a time when I was responsible for the US government's renewable electricity programs I had concluded that R&D investment in SPS was not then a prudent use of government funds. Nevertheless, if the problems enumerated above can be addressed successfully, SPS may be a viable option for the future.

8.4 HYDROPOWER AND WIND ENERGY

Hydropower and wind energy are closely related in that both are systems that use turbine blades to convert the kinetic energy of a moving fluid into electricity. In the case of hydropower the fluid is water, in the case of wind energy it is air. In both cases the energy available for conversion is proportional to the third power of v, the fluid speed past the turbine: v^2 from the kinetic energy in the flow ($\frac{1}{2} mv^2$) and v from the rate at which fluid is moving through the blades. Thus, if the fluid speed is doubled, the available energy increases by a factor of $2^3 = 8$.

8.4.1 Hydropower

The use of fast-moving or falling water for human purposes has a long history. India utilized water wheels and water-powered mills more than two thousand years ago; the Romans used water power to saw wood and stone, and to produce flour from grain; and watermills have been used for centuries in China. In the late 1800s hydropower became a source for generating electricity, and the first commercial hydroelectric power plant was built at Niagara Falls in the US in 1879. Today the term hydropower is used almost exclusively to refer to the modern development of hydroelectric power, which is seen as an important means for economic development. Resistance to these hydropower schemes can arise from the human displacement sometimes involved and adverse environmental impacts.

Deployment of hydropower falls into two categories: traditional hydropower generation (flow-of-river and high-head; see Figure 8.10) and pumped storage, a means of storing excess electricity.

As of the end of 2017, global installed traditional hydropower capacity was 1267 GW, while installed pumped storage capacity was 153 GW. It currently is producing 17% of the world's electricity and is the largest source of renewable electricity in the world (71%). China leads the world in hydroelectric

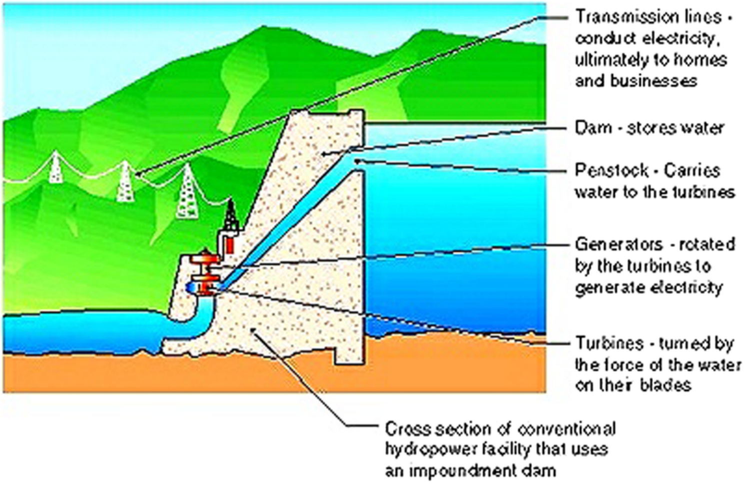


Figure 8.10 Schematic of high-head hydropower plant (*Source:* U.S Department of Energy).

generation, followed by the US, Brazil and Canada. Capacity growth has slowed in recent years, but cumulative capacity is still expected to increase by more than 100 GW by 2022, with hydropower remaining the world's largest source of renewable electricity generation. Some studies of hydropower's future development indicate the potential to reach more than 2000 GW of installed capacity by 2050.

While it is widely known that hydropower is a renewable and carbon-free generating source, what is less widely known is its value to the electric grid. It offers: load-following and flexible reserve, on time scales ranging from minutes to hours; smoothing of power demand–supply mismatches; spinning reserve that can respond quickly to outages and other system events; reactive power and voltage support; and black-start power – the capability to restart sections of the grid after a blackout.

8.4.2 Wind energy

Wind energy is a variable (intermittent) renewable energy source that can be used as an energy saver for fossil-fuel-powered generating systems when the wind is blowing, but requires some kind of storage of excess wind-generated electricity if it is to supply electricity at other times. Water reservoirs associated with hydropower dams can serve as a natural 'storage battery' for variable wind (or variable solar) as hydroelectric generators have short response/startup times and offer flexibility as to when water can be released to the generators from reservoir storage. The combination of wind and hydropower thus provides a system capable of firming up power availability even when the wind is not blowing, and reducing water releases when the wind is blowing.

However, this hybrid system has its limitations. It works extremely well as long as the wind component is not too large and the variations can be handled by the hydropower system's flexibility. When wind generation gets too big, that flexibility no longer exists (or becomes increasingly expensive) and excess wind energy must be utilized elsewhere. The US Department of Energy's Pacific Northwest Smart Grid Demonstration, underway in five Pacific Northwest states, is exploring options for addressing this growing problem.

8.4.2.1 Onshore wind

Wind farms consist of many individual wind turbines, which are connected to the electric power transmission network (see Figure 8.11).

The Whitelee, commissioned in 2009, in the south of Scotland, is one of Europe's largest onshore wind farms. It was built in two stages to reach its current configuration: 215 turbines (140 at 2.3 MW, 69 at 3 MW, 6 at 1.67 MW) with a maximum capacity of 539 MW. Wind energy is Scotland's fastest-growing renewable energy technology, reflecting the fact that Scotland is

Figure 8.11 Whitelee Wind Farm, Scotland (*Source:* personal photo, author).

the windiest country in the European region (25% of all of the region's wind crosses the Scottish landmass and its surrounding seas). Scotland's wind energy potential is estimated to be more than 150 GW onshore (current peak demand in Scotland is 10.5 GW) with significant opportunities for additional onshore and offshore development. Scotland's offshore potential is estimated to be 206 GW and offshore wind power generation is predicted to be about 10 GW in 2020. As result, the Scottish government has set a target of generating 100% of Scotland's electricity from renewable energy by 2020, with most of this likely to come from wind power. Scotland is also a world leader in development of wave and tidal power.

On a global basis wind is a rapidly growing energy technology, for many years the fastest growing (48). It now ranks second to solar energy, which has experienced significant cost reductions in recent years. In 2017 52 GW of wind energy were installed and cumulative installed wind capacity reached 539 GW (see Figure 8.12).

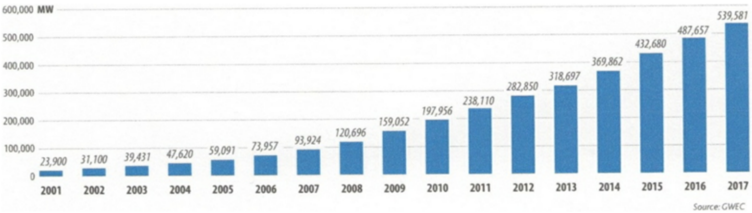


Figure 8.12 Global cumulative installed wind capacity (MW) (*Source:* Global Wind Energy Council).

Beyond these numbers, it is important to recognize that wind energy is rapidly becoming a commodity, an unsubsidized technology competitive with subsidized traditional technologies (fossil fuel and nuclear). It is a plentiful, renewable, widely distributed energy resource that produces no greenhouse gas emissions during operation, consumes no water, and uses relatively small amounts of land. Today, onshore wind is, in many cases, the least expensive of the new sources of electricity generation.

Wind power does have negative impacts, which are generally less problematic than those from nonrenewable energy sources. These include the noise generated by whirling wind turbines, the visual impact of large wind structures, bird and bat kills that arise from collisions with turbine blades, and the complications that arise from the fact that wind is a variable resource. While the electrical output from an individual turbine may be relatively consistent from year to year, it can have significant variation over shorter timescales and create problems of grid integration. To address these issues the wind industry has switched from traditional (lattice) support structures to cylindrical supports on which birds cannot roost, stopped wind turbine operations during periods of heavy bat activity, conducted extensive R&D on noise suppression techniques, firmed up wind farm output with backup fossil fuel sources, combined the output from geographically distributed turbine sources to average out variations from individual turbines, and used various methods to store excess wind-generated electricity for use as needed. In addition, weather prediction permits the electric power network to be better prepared for the predictable variations in production that occur, and offshore power production (discussed below), where noise and visual impacts are mitigated, is receiving increasing attention.

8.4.2.2 History

Wind energy has a long history. For more than two thousand years wind power has been used to pump water and grind grains, wind-powered ships supported Dutch economic dominance in the 17th century, wind-powered pumps drained the Dutch wetlands, and in arid regions wind-powered pumps have provided water for livestock and agriculture.

The first windmill used for the production of electric power was built in Scotland in 1887. Shortly thereafter a more reliable 12 kW machine was designed and built in the US, and remained in use until 1900. Further development occurred throughout the 20th century, resulting in turbines suitable for use on farms and for utility-scale power generation. Today, wind turbines range in size from small units suitable for individual homes, to 2–3 MW turbines for use in onshore wind farms, to 6–8 MW turbines for deployment offshore. Larger offshore wind turbines are in development.

8.4.2.3 An onshore limitation

An interesting aspect of US onshore capacity is the limitation imposed by existing highways – components for wind turbines beyond a given size (about 3 MW) cannot be accommodated on existing roads (see Figure 8.13).

One response being examined is manufacturing turbine components (towers, blades, generators) in place, using movable manufacturing systems. Another response is to move power production offshore.

Figure 8.13 Transporting a wind turbine blade (*Source:* Huson Media).

8.4.2.4 Offshore wind

Offshore wind (OSW) involves the location of wind turbines in offshore waters, whether near-shore shallow waters, relatively low-depth waters above continental shelves, or deeper waters further offshore. It draws on a large energy resource and has the potential, when widely deployed, to address two critical needs: the need for new sources of electricity that are renewable, indigenous, and carbon-free, and the need to stimulate economies and create jobs. I believe it to be the most important emerging renewable energy technology.

Because of the higher wind speeds and steadier winds offshore, OSW power plants can produce considerably more electricity than their onshore equivalents – increasing average wind speed by 15% increases available power by 52%. OSW plants, given their coastal locations, would be in close proximity to large population centers with high average electricity costs, important markets for their outputs (note: 50% of Americans live within 50 miles of a US coast). Ocean sites also allow deployment of larger wind turbines (improving the economics of power generation), as well as reduced onshore visual and noise impacts. The trade-off is that OSW farms, subject to harsh ocean conditions, can be more expensive, difficult to build, and maintain than onshore wind farms.

Offshore wind resources are abundant, many countries are exploring its potential, and by the end of 2017 nearly 19,000 MW of capacity had been installed in 17 markets around the world. Almost 16,000 MW (84%) were installed in the waters off the coasts of 11 European countries. The remaining 16% was located largely in the waters off China, followed by Vietnam, Japan, South Korea, the US and Taiwan. The US, which is today far behind other countries in deploying offshore wind, sited its first offshore wind turbines in the waters off Rhode Island in 2016. Nevertheless, on a global basis, the potential US OSW energy resources are second only to those of China. China has a very long coastline and the US has a broadly distributed OSW resource associated with four coastal regions (East Coast, West Coast, Gulf Coast, Great Lakes), and thirty US states border an ocean or a Great Lake.

In its report '2016 Offshore Wind Energy Resource Assessment for the United States' (49) the NREL estimated the US potential 'net technical resource capacity' to be 2058 GW. This was calculated by estimating the US's potential gross OSW energy capacity out to 200 nautical miles (the outer edge of the US Exclusive Economic Zone), excluding ocean areas with water depths greater than 1000 m and wind speeds less than 7 m/sec (15.7 miles per hour), water deeper than 60 m in the Great Lakes (to avoid damage from winter ice), and other exclusions for shipping lanes and marine protected areas. The net result was that the gross resource potential area was reduced by 75% to arrive at the technical resource potential area (after exclusions), and the gross energy resource number was reduced by 84% to arrive at the 2058 GW figure. To put this latter number into context, total installed US electricity generating capacity today is just over 1000 MW.

The global OSW market is projected to continue growing at a 16% annual rate, reaching a cumulative installed capacity of 115 GW in 2030 but slowing down thereafter.

It is important to note that much of the global OSW resource is located in areas where the water is so deep that conventional turbine support structures – large steel piles or lattice structures attached to the seabed – cannot be used. This has stimulated the development of floating offshore wind platforms, building on the floating technology developed for the oil and natural gas industries. These platforms, tethered to the sea floor, provide the top-heavy turbines with enough stability to operate effectively. Installation of test and demonstration projects, which began in 2007, employs the ‘tow-out’ concept in which the support structure and turbine are constructed in port and then towed out to the anchor site. Statoil built its first floating wind turbine off the Norwegian coast in 2009, and this 2.3 MW turbine, Hywind, is still operating today and has endured category 1 hurricanes and 62 ft waves while achieving annual capacity factors of up to 50%. Statoil has also reported that its five-turbine, 30 MW wind farm Hywind Scotland (the first commercial floating wind farm in operation), installed 20 miles off the Scottish coast in 2017, has achieved a 65% capacity factor. To put this in context, the US onshore wind fleet’s average capacity factor is 37%.

Many other floating wind farms exist today (see Wikipedia’s ‘List of offshore wind farms’). As of February 2018 the London Array in the UK is the largest offshore wind farm in the world at 630 MW. Other large OSW farms in operation include the Gemini Wind Farm in the Netherlands (600 MW), Code Wind in Germany (582 MW), Gwynt y Mor in the UK (576 MW), Race Bank in the UK (573 MW), and many others in the range 200–504 MW. Quite a few other OSW farms with nameplate capacity of more than 300 MW are under construction, including Hornsea Project One in the UK (1218 MW), East Anglia One in the UK (714 MW), Kriegers Flak in Denmark (605 MW), Hohe See in Germany (497 MW), and Binhai North in China (400 MW). OSW farms still in the proposal stage, of which there are many, include Korea Offshore in South Korea (2500 MW), Hornsea Project Three in the UK (2400 MW), Formosa III in Taiwan (1900 MW), and Borssele Offshore (phases 1–4) in the Netherlands (1400 MW).

Finally, a word about the future of OSW turbines and how OSW-generated electricity is delivered to shore: while early OSW turbines were small (2.3 MW or less), today turbines 6–8 MW in size are being installed routinely. Vestas is developing a 9.5 MW wind turbine, and GE has recently unveiled its 12 MW Haliade-X offshore wind turbine. 15 MW turbines are being designed as well.

OSW farms use undersea, low-loss, HVDC (high-voltage dc) cables, which are buried under the sea floor, to deliver power to coastal load and distribution centers. In the US a transmission system of this type, the Atlantic Wind Connection, is being built in stages in coordination with the build-out of East Coast OSW farms. It will span the mid-Atlantic 300 mile region, beginning in northern New Jersey and eventually extending to southern Virginia. It will connect wind farms that are built in the federally designated ‘Wind Energy Areas,’ at least ten miles off the coast. When completed, the Connection will be capable of delivering up to 7000 MW of power from OSW farms.

8.5 BIOMASS ENERGY

Biomass energy is both an old and a future technology. As a feedstock, biomass is defined by Wikipedia as 'biological material derived from living, or recently living organisms.' It includes plant material and animal (and human) wastes.

8.5.1 Sources of biomass

Combustion of biomass has been used throughout human history to provide heat, ever since the discovery of fire, and it is the oldest form of renewable energy. Wood has long been a source of biomass energy and is still widely used today for heating and cooking purposes.

More recently, other ways to obtain useful energy from biomass have been developed, including gasification and conversion to liquid fuels. Each of these applications is discussed below, as is biomass' significant potential.

A considerable amount of biomass is produced globally each year, about half in the oceans and half on land. It is biologically produced matter based on carbon (as well as hydrogen and oxygen). Estimated annual production involves about 100 trillion kilograms of carbon. An important point to keep in mind is that the chemical arrangements of these organic materials can be changed, an important focus of biomass research.

8.5.2 Wood

Wood, in the form of trees, tree stumps, branches, wood chips, and yard clippings remains the largest source of biomass energy today. In many developing countries it is still the only combustion fuel source for domestic use. Other common fuel sources include municipal solid wastes, animal wastes (e.g., 'cow chips' or bio-digested manure), and landfill gas (primarily methane and carbon dioxide). In recent years pellet fuels, made from compressed biomass, have been used increasingly for heating in power plants, homes, and other applications. Wood pellets are the most common type, but grasses can also be pelletized. Pellets are extremely dense and can be produced with a low moisture content that allows them to be burned with a high combustion efficiency. Furthermore, their uniform shape and small size facilitate automatic feeding.

Wood pellet markets are of two types: industrial wood pellets that are used as a substitute for coal in power plants, and pellets used in pellet stoves and pellet boilers for heating. A broad range of pellet stoves, central heating furnaces, and other heating appliances has been developed and marketed since the 1980s. According to the IEA wood pellet production more than doubled between 2006 and 2010 (to more than 14 million tons), and was expected to keep growing. For a while this growth was challenged by a series of warm winters in Europe compounded by low natural gas prices. Nevertheless, fully automatic high-efficiency wood pellet boilers are common in Europe and they are beginning to penetrate markets in the US and other countries. The Asia-Pacific region will occupy more market share in future years, especially in China, as well as India and regions in Southeast Asia.

8.5.3 Biofuels

Another important application of biomass is its direct conversion into liquid fuels (biofuels), which can replace petroleum-based fuels such as gasoline, diesel and jet fuel. These ‘alternative’ fuels fall into two categories: first-generation biofuels, such as ethanol, that are derived from sugarcane and corn starch (and therefore compete with food crops); and second-generation biofuels that use as feedstock non-food and low-value agricultural and municipal wastes that are not edible. Production of first-generation biofuels is well underway in Brazil and the US, but second-generation production is still limited by high production costs. The problem is the difficulty in breaking down and chemically converting – at a competitive cost – the lignocellulosic biomass that constitutes the bulk of plant matter. Governments and many private sector firms are attacking this problem, given the large potential market and the potential for reducing CO_2, and a number of second-generation biofuels are being actively explored.

Ethanol, which is usually mixed with gasoline to produce E-10 (90% gasoline and 10% ethanol) can also be produced by gasification of biomass such as corn.

Gasification processes use high temperatures in a low-oxygen environment to convert biomass into synthesis ('syn') gas, a mixture of hydrogen and carbon monoxide. This gas can then be chemically converted into ethanol and a wide variety of other C-H-O molecules and fuels.

8.5.4 Algae

An emerging and potentially major biomass field is the production of alternative fuels using algae (algaculture). Algae (Latin for 'seaweed') are photosynthetic organisms that occur in most habitats. They range from single-celled organisms to much more complex forms, such as giant kelps that can reach lengths of more than 60 m. 'Photosynthetic' refers to algae's ability to capture light energy to power the production of sugars, carbohydrates that can then be converted to other C-H-O molecules. Algae differ from plants in that they are primarily aquatic.

Interest in algae was triggered by the need for alternatives to petroleum fuels and the world food crisis. Algae produce lipids (a variety of organic compounds) that can be used for making biodiesel, bioethanol, biogasoline, biojetfuel, biomethanol, biobutanol, and other biofuels. They can be grown on land that is not suitable for agriculture – for example, land with saline soil. They can be produced using seawater, brackish water, and wastewater, and are biodegradeable. An important, and perhaps critical, aspect of algaculture is that it is claimed that algae farming can yield 10–100 times more fuel per unit area than other second-generation biofuel crops. It is estimated that growing enough algae to replace all US petroleum fuels would require only 0.4% (15,000 square miles) of the US land area, or a small fraction of the land currently devoted to corn production. Algae crops also have a short harvesting cycle – 1 to 10 days – and so can be harvested repeatedly in a short time-frame.

The biggest barrier to greater use of algae-derived biofuels is the cost of scaling up to commercial production levels. Another concern, for open-pond algae facilities, is contamination by invasive algae and bacteria and vulnerability of monocultures to viral infection. Many schemes for reducing costs and potential contamination are being explored, given the large potential markets available. One obvious target is ground transportation. Another such market is the US military which is already testing biofuels in aircraft and ships. A third large potential market is commercial air transportation. Finally, like all energy sources, biomass has environmental impacts and risks – for example, water demand, and deforestation if land is cleared for biomass production.

8.5.5 Biochar

Biochar is a form of charcoal that is created by pyrolysis (low- or no-oxygen heating) of biomass. It is believed that pre-Columbian Amazonians used biochar to increase soil productivity. In addition, biochar has attracted growing attention because of its ability to sequester carbon for centuries (and thus reduce global warming) and its ability to attract and retain water because of its porous structure and high surface area. Its production also does not compete with food production.

8.5.6 The future

In my view, and that of many others, biomass will be a major part of our renewable energy future. It is available worldwide, grows in great and diverse quantity, can be used for direct heating and electricity production via heating of water, can be converted to liquid fuels and other C-H-O commodities, and, if used carefully, has significant potential to reduce greenhouse gas emissions.

8.6 GEOTHERMAL ENERGY

Geothermal energy is heat from the Earth and has been used by mankind for bathing and heating for centuries. The first power plant to use geothermal heat came online in 1904 in Larderello, Italy and is still generating electricity. Geothermal is an extremely large energy resource, and one that is still in the early stages of realizing its potential.

8.6.1 Sources of geothermal energy

Geothermal energy derives largely, but not exclusively, from radioactive decay of uranium, thorium and potassium in the Earth's core. Lesser amounts of core heating derive from heat released when iron cools and solidifies at the Earth's central core, mineral phase changes, friction heating associated with Earth's tides, and even impact collisions with matter from space. This heat convects and conducts up to the Earth's thin crust (which comprises just 1% of the Earth's mass) through various pathways, and manifests itself as hot water and steam, hot rock, warm earth, magma and volcanic eruptions. We can think of the crust as a blanket on the rest of the planet (see Figure 8.14).

Geothermal heat has been flowing from the center of the Earth for more than 4.5 billion years and will continue as long as the Earth exists – about another 5 billion years. Since this flow is essentially limitless, geothermal may be considered a renewable energy source. Also, it is available 24/7 and is thus a baseload energy source.

Temperatures close to the Earth's center are about as hot as the Sun's surface, and geologists estimate that the rate at which energy flows from the Earth's interior is of the order of 44 TW (terrawatts, i.e., millions of megawatts). The replenishment rate from radioactive decay is estimated to be about 30 TW. To put this number in perspective, today's global installed electrical generating capacity is just over 5 TW.

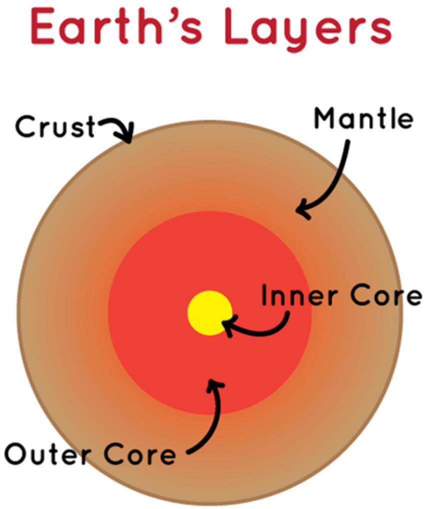


Figure 8.14 Schematic cross section of the Earth.

8.6.2 Manifestations of geothermal energy

Initially, the core of the Earth was a hot liquid but it has cooled over geological time, and the core is now seen as an anisotopic high-temperature mass of solid iron created under conditions of extremely high pressure. Somewhat above the core some rock is still molten, forming magma which convects upwards since it is lighter than rock. The magma heats rock and water in the crust, creating hot water and steam at various points on and near the Earth's surface. It is estimated that the amount of heat in hot rock and water within 6 miles of the Earth's surface is more than 50,000 times as much as all the energy stored in the planet's oil and natural gas resources.

8.6.3 Uses of geothermal energy

How has this heat been used in the past, how is it being used today, and how might it be used in the future? Historically, hot springs have been used for bathing by humans since the Stone Age and for space heating since Roman times. These uses are still present and growing, and the first district heating system in the US, in Boise, Idaho in 1892, was powered by geothermal energy. In Iceland 90% of households are heated by geothermal energy. Other applications include desalination, agricultural drying and industrial heating, for a total of about 30 thermal gigawatts.

8.6.3.1 Geothermal power generation

In modern times geothermal energy is best known for its application to power generation, where its potential is huge. Today's hydrogeothermal power plants tap geothermal heat in the form of dry steam issuing from the ground, or hot water that can be flashed into steam, to drive a turbine generator. Geothermal heat can also be tapped to vaporize volatile liquids such as isobutane, which can then also drive a turbine generator.

The U.S. currently leads the world in geothermal power generation (3567 MW), followed by the Philippines (1868 MW), Indonesia (1450 MW), and New Zealand (980 MW) (see Figure 8.15).

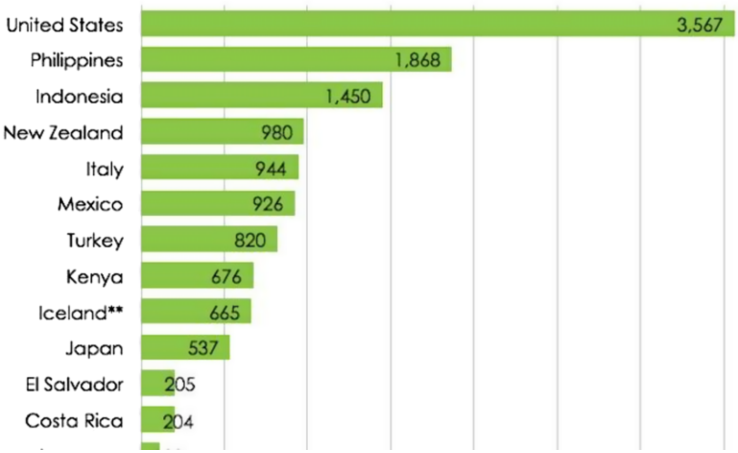


Figure 8.15 Installed geothermal capacity (GW) 2017 (50).

Twenty four countries currently have geothermal power plants, for a total generating capacity of just over 13 GW. Based on current data, total installations should reach 18 GW by 2021, and could reach 32 GW by the early 2030s. Based on country-by-country estimates, total hydrothermal geothermal potential could reach up to 200 GW (50).

Future geothermal power plants will use so-called 'enhanced geothermal systems' (EGS), previously called 'hot dry rock' systems, in which deep wells are drilled into hot rock with no natural water; water is introduced into these wells from the surface to which it returns, heated and ready for power generation (see Figure 8.16).

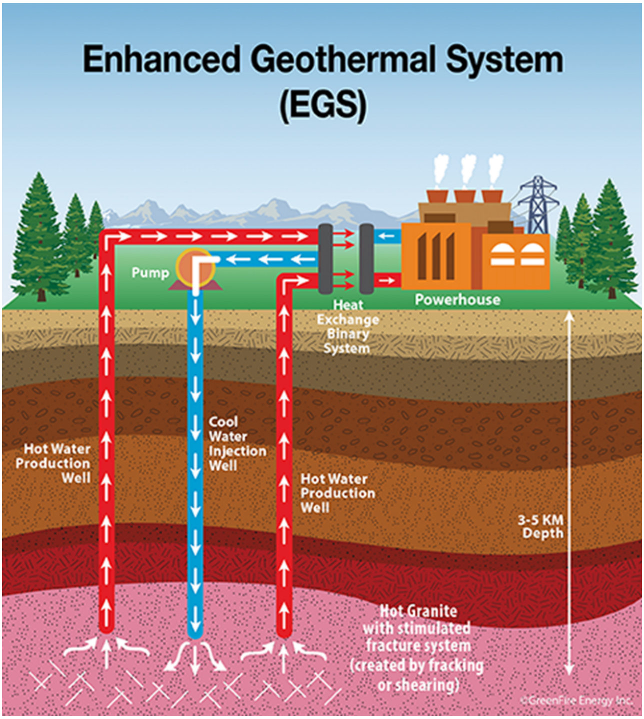


Figure 8.16 Schematic of EGS power generation (*Source:* AltaRockEnergy).

Estimated global potential varies from 0.04 to 2 TW, depending on the depth of drilling and level of investment (wells as deep as 6 miles are now common in the petroleum industry). Research on EGS is underway in several countries, including Australia, France, Portugal, the UK, and the US.

8.6.3.2 Ground-source heat pumps

Air-source heat pumps, well known and widely used, deliver heat that is drawn from outside air into a house or other building. The problem with such heat pumps is threefold: they sit outside and are exposed to the weather, they use electric-powered air conditioning, and when heat is required and the outside air gets cold enough the heat pumps are effectively electric heaters. This increases electricity demand on the grid and can cause brownouts, as happened during a winter cold snap on the US East Coast a number of years ago. Ground-source heat pumps (GHPs), also known as geothermal or geo-exchange heat pumps, in contrast, exchange energy with the ground (or underground water aquifers), taking advantage of the fact that a few feet below the Earth's surface the ground temperature remains relatively constant. Depending on latitude, these ground temperatures can range from 45°F (7°C) to 75°F (21°C).

This enables a GHP, which can be located inside a building where it is shielded from weather effects and more rapid aging, to provide cooling in the summer and heating in the winter – basically a reversible refrigeration cycle (see Figure 8.17). If so equipped, the heat pump can also supply the house with hot water.

Other advantages of GHPs are their quieter operation compared with air-source heat pumps, reduced peak demands on utility grids, and reduced consumer energy costs. 'System life is estimated at 12–15 years for the inside components and 50+ years for the ground loop (51).'

The downside for consumers is the need to drill holes for the heat exchange with the ground: either deep vertical holes with

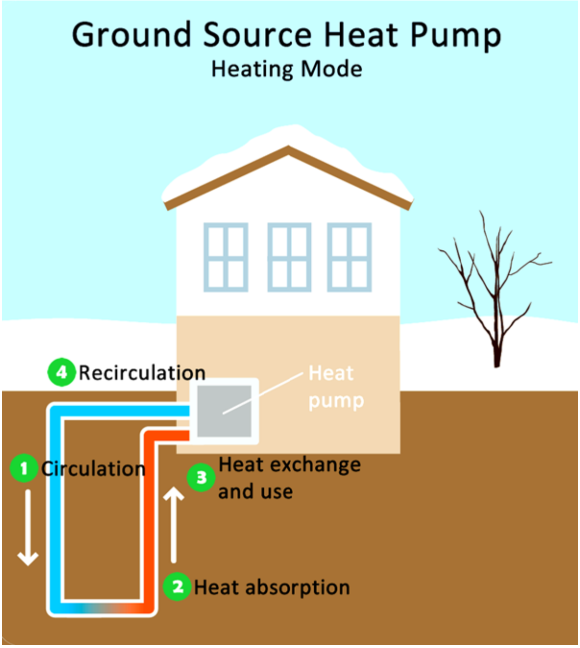


Figure 8.17 Schematic of GHP used for cooling and heating (*Source:* U.S. Environmental Protection Agency).

heat exchanger tubing or more shallow holes with more numerous heat exchange loops of tubing. The tubing, filled with heat exchange fluid, is grouted to the earth to enhance heat exchange.

Initially, in the mid 1990s, many heating and cooling contractors were not familiar with GHPs. Thus, they did not bring them to consumers' attention, despite the fact that there was some encouraging history. A GHP had been installed in a hotel in Kentucky in the 1980s and its energy demand was shown to be less than that of an identical hotel in the same location outfitted with a traditional air-exchange heat pump. Nevertheless, no subsequent commercialization took place. In response, once the benefits of using GHPs were understood, the DOE initiated a joint program with the US electric utility industry to educate people about GHPs and facilitate their deployment. This led to establishment of the Geothermal Heat Pump Consortium, now known as GeoExchange. One important response on the part of some utilities was to advance the money to homeowners for drilling the heat exchange holes, a major barrier to heat pump deployment. The utilities clearly recognized the benefits from peak power reductions. Consumers repaid the loans from the savings on reduced energy bills.

Today, GHPs are widely used around the world, with more than 700,000 installed in the US, where new installations are occurring at about 50,000 per year. The US Department of Defense is a major user of GHPs, and pioneered in their use in the late 1990s by installing over 4000 GHPs in housing at a military base in Louisiana. A side effect of the US program was the introduction of GHPs to China in 1998, when I first went to China on a government-to-government visit. Today China is incorporating GHPs into many if not most of its new buildings.

8.6.4 An unusual source of geothermal energy

An unusual way to use geothermal heat is tapping the hot fluids being expelled from hydrothermal vents (also called 'Black Smokers') at spreading ridges on the ocean floor.

They are the result of cold seawater leaking through fissures in the ocean crust into hot magma below the crust, being heated and reemerging as hot water vents enriched with dissolved minerals (sulfur, copper, zinc, gold, iron). These minerals deposit out on the ocean floor when the heated water (some of these vents reach temperatures of over 700°F) hits the cold seawater, creating massive deposits which obviously will attract commercial attention. The energy content of this hot water is also immense and represents one way of tapping the heat energy in magma. Needless to say, tapping this heat energy requires operating at great depths in oceans under extreme conditions, possibly bringing the hot water to the surface, and trying to do all this in a reliable and cost-effective manner. This is an intriguing possibility, given the amount of energy potentially available, but obviously not on any anyone's short- or mid-term agendas.

8.7 OCEAN ENERGY

Ocean energy comes in four distinct types (five if you include offshore wind energy): wave energy, ocean current energy, tidal energy, and OTEC (ocean thermal energy conversion). Together they represent a major new energy source for the world and all have been shown to work. The major problems are reliability and cost, and all are in early stages of development.

8.7.1 Wave energy

Wave energy is the most advanced of the ocean energy types, with several operating demonstration sites. Wikipedia defines 'wave energy' as '… the transport of energy by ocean surface waves, and the capture of that energy to do useful work – for example, electricity generation, water desalination, or the pumping of water (into reservoirs).' Wikipedia further explains that 'Waves are generated by wind passing over the surface of the sea. As long as the waves propagate slower than the wind speed just above the waves, there is an energy transfer from the wind to the waves.'

8.7.1.1 Wave energy conversion devices

It is interesting to note that since wind energy is an indirect form of solar energy (winds are generated by uneven heating of the Earth's surface by solar radiation), then so is wave energy. Waves are irregular, varying in frequency and height, and successful wave energy conversion (WEC) systems will tap as much as possible of the kinetic energy in the up and down motion of waves to generate electricity or mechanical power. R&D efforts, of which there are now many, with a major testing/demonstration site off the coast of Scotland, are focused on doing this energy capture at the lowest possible cost. Many different designs are being created and tested (see, e.g., Figure 8.18).

Figure 8.18 WEC concept and demonstration unit (*Source:* Pelamis Wave Power Ltd.).

Utilization of wave energy is not a new concept. The first patent for use of energy from ocean waves was issued in 1799 in Paris, and many more patents were issued in the subsequent century. The OPEC cutoff of oil supplies in 1973–74 triggered renewed interest in wave energy, which dissipated quickly in the mid-1980s when oil prices fell below $10 per barrel. More recently, as global change became a focus of attention, and oil prices rose, interest in all forms of non-traditional energy has grown, including wave energy.

WEC devices are usually characterized by how the energy is captured, and today includes such names as the Salter duck, point absorber buoy, oscillating wave surge converter, oscillating water column, and submerged pressure differential.

8.7.1.2 Potential and pros and cons

What is wave energy's potential? The kinetic energy in wave motion is significant. According to the Ocean Energy Council

(52), ‘An average 4-foot, 10-second wave striking a coast puts out more than 35,000 horsepower per mile of coast.’ Another estimate (Wikipedia, ‘Wave power’) is that ‘In major storms, the largest waves offshore are about 15 meters high and have a period of about 15 seconds, such waves carry about 1.7 MW of power across each meter of wavefront.’ The global potential is estimated to be more than 2 TW. Areas with the most potential include the Pacific coastlines of Australia, New Zealand, Southern Africa, and North and South America. Other promising areas are the western coasts of Europe and the northern coast of the UK.

Wave energy offers several advantages over other renewable energy technologies: it is produced 24/7, is more steady in output and more predictable than wind or solar, can be located close to large coastal population centers with large energy demand, generally has lower infrastructure costs, and is less obtrusive visually than offshore or land-based wind turbines. It still requires cabling to deliver power to shore, incurs all the difficulties of operating reliably in an ocean environment, and can be disruptive to ocean life and thoroughfares for coastal vessels of all types.

The world’s first commercial wave energy device was installed off the coast of Scotland in 2000, and the first experimental wave energy farm (three units) in 2008 by Portugal. Today, Australia, the UK, and the US have experimental wave energy farms in operation.

8.7.2 Ocean current energy

A second ocean energy technology under development is ocean (marine) current power, which began to draw attention after the 1973–74 Oil Embargo. As with wave power useful energy is derived from the kinetic energy found in the oceans, but in this case it is derived from ocean currents flowing beneath the ocean’s surface (53). An example is the Gulf Stream that flows around Florida in the US at an average speed of 2 m/s (4.5 mph). Other areas with high ocean current flows that can be usefully tapped by underwater 'turbines' are between islands, around headlands, and entrances to bays and large harbors.

While few studies have been carried out to date on this resource's global potential, in 2000 one study (54) put the number at 450 GW. A 2006 study from the US Department of the Interior estimates that capturing just 1 part in 1000 of the available kinetic energy of the Gulf Stream would supply one third of Florida's electrical demand (55). Other countries where studies have been carried out include the UK, Canada, and Japan. One study confirmed that the UK ocean current energy resource was theoretically capable of meeting one-fifth of UK electricity demand. The EU's JOULE-CENEX study identified many 'European sites ranging from 2 to 200 km^2 of sea-bed area, many with power densities above 10 MW/km^2.' In addition, ocean current energy can be tapped with little environmental impact and is a reasonably predictable energy resource, lending itself to base-load applications.

While ocean currents move at lower speeds than air currents passing through wind turbines, the density of water, more than 800 times that of air, means that the m in $\frac{1}{2}mv^2$ in the kinetic energy of the moving ocean current is large and compensates for the lower speed. This is reflected in the fact that a water speed of 10 mph delivers the same power as an air speed of 42 mph for the same size of turbine system. The Sun is the prime driving force for ocean currents through its creation of winds and temperature differences in the ocean, but other factors like salinity and the Earth's rotation also play a role.

Underwater turbines used to capture this energy can be thought of as smaller-sized, underwater wind turbines designed for ocean environments. Turbine types being developed and tested include horizontal axis turbines, similar to wind turbines, vertical axis turbines, and oscillating hydrofoils with flap-like structures.

8.7.3 Tidal energy

A related form of ocean energy is tidal energy, in which the potential energy in a body of water trapped at high tide is converted to kinetic energy when this water is released. Generally, strong tidal flows exist where the water depth is relatively shallow and there is a broad vertical range beneath high and low tides. This occurs in only a few locations. These tides are created by the gravitational interactions of the Earth, Moon and Sun, and are also impacted by the Earth's rotation and regional ocean temperature differences. These periodic gravitational forces create a bulge in the ocean water, creating a temporary increase in sea level. Tides result when such a bulge, impacted by the Earth's rotation, meets shallow water adjacent to coastlines. The consistent nature of these gravitational attractions makes tidal power a highly predictable energy source.

An interesting aspect of tidal power is that energy is lost in the Earth–Moon system due to friction mechanisms in the oceans. This results in a slowing of the Earth's rotation, and it is estimated that over the past 620 million years the Earth has lost 17% of its rotational energy and the length of an Earth day has increased from 21.9 to 24 hours (56).

8.7.3.1 Barrage

One form of tidal energy (barrage) captures water at high tide and releases it at low tide, a form of hydroelectricity. Essentially, barrages are dams across the full width of a tidal estuary. Several other tidal power configurations are also being investigated – for example, at the European Marine Energy Centre in Orkney, Scotland.

Tidal power is still in an early stage of development relative to other forms of renewable energy, having suffered from high costs and limited availability of suitable sites. Nevertheless, recent technological developments suggest that tidal power's potential may be much higher than previously anticipated, and that its costs may be brought down to competitive levels. For example, it has been proposed that tidal power generators be attached to the structures of existing bridges, thus minimizing infrastructure costs.

8.7.3.2 History

Historically, tidal power is not a new technology. Incoming high tide water was impounded as far back as Roman times, and then was used to turn waterwheels to grind grain. Using impounded water for electricity generation was first achieved by the 240 MW La Rance Tidal Power Plant in France in 1966. It remained the largest tidal power station until 2011 when the 254 MW Sihwa Lake Tidal Power Station went on line in South Korea. Today, smaller tidal power plants exist in Canada (20 MW), China (3.2 MW), Russia (1.2 MW), Ireland (1.2 MW), the Netherlands (1.2 MW), and the US (1.05 MW). More are under construction or being planned by several countries, including South Korea, Scotland, England and India.

8.7.3.3 Environmental impacts

In-water turbines can injure or kill sea life, the noise from turbines can disrupt sea-life patterns and sediment processes, and installing a barrage can change shorelines, affecting local ecosystems and shipping lanes.

8.7.4 Ocean thermal energy conversion (OTEC)

OTEC was first demonstrated in the 1880s and continues to be of interest today. The world currently has only two operating OTEC power plants, both in Japan.

OTEC uses the temperature difference between cooler deep and warmer shallow or surface ocean waters to run a heat engine and produce useful work, usually in the form of electricity (57). It is a baseload technology that allows for production of electricity on a constant basis. However, the temperature differential is small and this affects the economic feasibility of ocean thermal energy for electricity generation.

8.7.4.1 Barriers

Using cooling water from depths where the water temperature is close to freezing, OTEC systems are then geographically limited to the tropics, where surface water temperatures are highest (85–90°F, 29–32°C). In such situations the maximum thermodynamic heat engine (Carnot) efficiencies are still in the low range of 6–7%. Actual efficiencies achieved to date are only in the range 2–3%. Nevertheless, it is important to point out that a small percentage of a very large number (the thermal energy stored in the oceans) is still a large number. It is estimated that OTEC's resource potential is larger than that of any other ocean energy technology.

Where OTEC struggles is that the low conversion efficiencies require pumping large amounts of seawater and large heat-exchanger surfaces to make the technology feasible. Large amounts of pumping impose requirements for large amounts of parasitic power on OTEC systems, and large heat exchangers built for reliability in ocean environments are expensive and hard to maintain (e.g., maintaining good thermal conductivity of the heat exchanger surfaces in the presence of microbial biofouling). To date these factors have kept the technology from commercial application.

8.7.4.2 OTEC technologies

The technology comes in three types: closed cycle, open cycle, and hybrid. All three require that near-freezing deep seawater be brought to the ocean surface. The *closed-cycle* system pumps warm seawater through a heat exchanger to vaporize a fluid with a low boiling point (e.g., ammonia) to power a turbine to generate electricity. Cold water is pumped through a second heat exchanger to condense the vapor to a recycled liquid.

Open-cycle technology directly vaporizes the warm seawater by introducing it into a low-pressure container which causes it to expand and boil (flash evaporation). The resulting 'steam' drives a low-pressure turbine-generator. This form of OTEC offers a significant benefit in addition to electricity: the steam is free of salt and other seawater contaminants, and can be condensed as fresh water. In many applications, particularly for isolated island locations, the desalinized fresh water may be more valuable than the electricity. A *hybrid* version of OTEC has also been developed, incorporating features of both types.

OTEC facilities can be located in deep water (on ships) but can also be land-based or located near shore. The latter locations offer several advantages: reduced exposure to extreme weather events, reduced cabling requirements, and no need for expensive offshore moorings in deep water. All locations require a long, large diameter pipe to deliver deep cold water, which can be problematic if not properly engineered. There have been several reports of such pipes breaking loose and being lost.

8.7.4.3 Other cold water applications

The OTEC-extracted deep, cold water can also be used for non-power applications. These include use of the near-freezing water for air conditioning, chilled-water agriculture (which allows growth of crops not usually grown in tropical climates), and aquaculture, which makes productive use of the nutrient-rich content of the extracted deep water.

8.7.4.4 OTEC R&D

Japan leads the world in OTEC R&D, centred at the Institute of Ocean Energy at Saga University. In 1981 a 120 kW closed-cycle power plant went into operation on the Japanese island of Nauru. In 2013 Saga University, working with several Japanese companies, installed two 50 kW OTEC units that are connected to the grid when not being used for research.

The US has been active in OTEC R&D via its Natural Energy Laboratory on the Big Island of Hawaii, and the US Department of Defense has supported efforts to develop OTEC units for its island-based military bases. New projects have also been proposed for Japan, China, South Korea, Martinique, the Maldives, the Bahamas, and the US Virgin Islands.

Chapter 9

Energy storage

Energy storage, the capture of energy produced at one time for use at a later time, is not a new concept. Without understanding the details, man has long understood that when wood is burned, something stored within the wood changes and heat is released. In more modern times the need for storage to steady the output from a variable energy source such as wind was widely recognized. Since the discovery of electricity generation by Michael Faraday in 1820 people have sought ways to store that energy for use on demand. Without such storage, or use in some other way (e.g., to heat water, bricks, or phase change materials that store heat, refrigerate water to create ice, or electrolyze water to create and store hydrogen), the energy delivered by electricity is lost.

9.1 STORAGE AND GRIDS

Today, with modern societies increasingly dependent on energy services delivered by electricity, the need for electric energy

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storage technologies has become critical. Try to imagine life without your mobile telephone or computer. The Energy Storage Association, a national trade association for the energy storage industry, describes its importance as follows: ‘Energy storage fundamentally improves the way we generate, deliver, and consume electricity. Energy storage helps during emergencies like power outages from storms, equipment failures, accidents or even terrorist attacks. But the game-changing nature of energy storage is its ability to balance power supply and demand instantaneously – within milliseconds – which makes power networks more resilient, efficient, and cleaner than ever before.’ The Smart Electric Power Alliance is even more concise: ‘The role of energy storage can be summed up in two words: grid empowerment.’

Because electric grids must balance supply and demand, and because demand is highly variable and hard to control, the balancing is achieved routinely by controlling the output of electricity generators. If these generators are variable, for example, solar and wind, and their grid contributions become significant, achieving the balance is more difficult, and a means of compensating for these variations is needed. This is one important role that storage plays.

9.2 TYPES OF STORAGE

Energy storage comes in many different forms and can provide short or long-term storage. The different forms can be divided into seven broad categories (58):

- Traditional and Advanced Batteries: a range of electrochemical storage devices, including advanced chemistry batteries and capacitors
- Flow Batteries: batteries where the energy is stored directly in the electrolyte solution for longer cycle life and quicker response times

- Flywheels: mechanical devices that use rotational energy to store and deliver electricity
- Superconducting Magnetic Energy Storage: energy is stored in persistent magnetic fields
- Compressed Air Energy Storage: uses compressed air to create an energy reserve
- Pumped Storage Hydropower: uses water stored at an elevated height to create an energy reserve
- Thermal Storage: capturing heat and cold to create energy on demand

9.2.1 Traditional and advanced batteries

Traditional batteries are those that have been in use for many years – for example, lead–acid batteries, which are still the dominant battery storage technology today.

9.2.1.1 Lead–acid

They are widely used in cars, trucks and many other applications because of their low cost, high power (power per unit volume), and high reliability.

Disadvantages are low energy density (stored energy per unit volume), large size and weight, and the need for an acid electrolyte. Lead (Pb) is also a toxic material when inhaled or ingested. Research to improve lead–acid batteries has been underway for more than a century, and considerable progress has been made – for example, lead–acid batteries that require no maintenance, and widespread recycling of used batteries to recover the Pb electrodes. Further progress is anticipated.

9.2.1.2 Sodium sulfur

Sodium sulfur batteries, which operate at high temperatures (300–350°C) use molten sulfur as the positive electrode and molten sodium as the negative electrode.

They are separated by a solid ceramic barrier that serves as the electrolyte. It was developed in the 1960s by the Ford Motor Company and subsequently sold to the Japanese company NGK. It has now been widely demonstrated in Japan, and more than 270 MW of peak shaving capacity has been installed. US utilities are beginning to explore the technology for peak shaving, backup power, firming up intermittent wind power, and other applications.

9.2.1.3 Nickel–cadmium

Nickel–cadmium (Ni–cad) batteries have been in commercial production since 1910. They are a traditional battery type that, while not known for high energy density or low first cost, provides a simple-to-manage, long-lived and reliable electricity storage option. For many years, in small battery form, they were a primary electricity source for mobile devices.

9.2.1.4 Lithium-ion

Most battery attention today is focused on a relatively new development, lithium-ion (Li-ion) batteries. They were first developed in Japan and released to the market in 1991. Initial applications were in consumer markets, but today many companies are examining the use of large collections of Li-ion battery cells for use in other energy storage applications. These include their use in passenger electric vehicles (3–3.5 miles of travel per kWh of stored energy), residential and business storage of solar-generated electricity, and multi-megawatt containerized batteries for utility applications.

Li-ion batteries are widely used today because they have high energy density: ‘pound for pound they’re some of the most energetic rechargeable batteries available.’ For example, it takes six kilograms of lead–acid battery to store the same energy as one kilogram of Li-ion battery. They also hold their charge well (today’s Li-ion batteries lose about 5% per month), have no memory effect (removing the need to fully discharge the battery before recharging), can handle hundreds to thousands of charge–recharge cycles, and have good round-trip electrical efficiency.

Li-ion batteries do have a downside: they are sensitive to heat, can't be fully discharged, are still costly (although costs are coming down rapidly), and battery cells with certain chemical formulations can occasionally burst into flame if damaged or otherwise overstressed. The term 'lithium-ion' refers not to a single chemistry but to a number of chemical combinations where lithium ions are transferred between the electrodes during the charge–discharge cycles. The lithium ions are derived from electrode materials that contain lithium compounds, and different compounds present different cell voltages, energy densities, lifetime, and safety characteristics. Battery management systems are required – Li-ion batteries lack the ability to dissipate overcharge energy – and safety characteristics are a function of system design and control algorithms, regardless of battery cell chemistry.

9.2.1.5 Supercapacitors

Supercapacitors, also a relatively new battery technology, store energy in electric fields created by stored electric charge. They fill a gap between ordinary capacitors and rechargeable batteries. Because the charge is stored physically, with no chemical or phase change occurring, the charge–discharge processes are fast and highly reversible.

They can be repeated over and over again, with virtually no limit, at high round-trip efficiency. Depending on the design, supercapacitors (also called ultracapacitors) can have reasonably high energy densities and can deliver quick bursts of energy during peak power demands. Because of these characteristics they are now widely used as low-current power sources for computer memories, medical devices, and in cars, buses, trains, cranes and elevators, including energy recovery from braking. As a result, the number of market applications and manufacturers is growing steadily.

9.2.2 Flow batteries

Flow batteries are large-scale rechargeable energy storage systems where rechargeability is provided by chemical compounds dissolved in liquids which, when mixed together, generate electricity.

A major advantage of flow batteries is that they can be recharged quickly by replacing the electrolyte liquid while allowing recovery of the active chemical components in the used electrolyte. By storing energy in the electrolyte fluid they differ from conventional batteries, in which energy is stored as electrode material.

Redox (reduction/oxidation) flow batteries are particularly well suited to storing large amounts of energy – for example, the surplus energy created by solar or wind power generation – and are on the verge of wide application in the electric utility industry. The energy storage materials are liquids that are stored in separate tanks, and when energy is needed the liquids are pumped through a ‘stack’ where they interact to generate electricity. Many different chemical liquids have been tested for flow battery operation, with most current attention being focused on vanadium compounds. Disadvantages are that flow batteries have relatively low round-trip efficiencies, long response times, and the ratio of power to energy is fixed at the design stage. Because of vanadium cost concerns other chemical possibilities are being examined, for example, zinc–bromine, zinc–chlorine, and iron–chromium.

An important flexibility in the design of flow batteries is that the energy storage capability, that is, the size of the storage tanks, can be tailored to the need of the particular application. They are well suited for a broad range of applications, with power requirements ranging from tens of kilowatts to tens of megawatts, and energy storage requirements ranging from several hundred kWh to hundreds of megawatt-hours. They are also easy to control and maintain, and fluid flow can be stopped quickly in an emergency situation.

9.2.3 Flywheels

Flywheels store energy by using electrical power to accelerate a cylindrical assembly called a rotor (the flywheel) to a very high speed and maintaining the energy in the system via rotational motion. The rotational energy is converted back to electricity by slowing down the flywheel. The flywheel system itself is a kinetic, or mechanical, battery, spinning at very high speeds to store energy that is instantly available when needed.

At the core of most modern-day flywheels is a carbon-fiber composite rim, supported by a metal hub and shaft, with a motor/generator mounted on the shaft. Together, the rim, hub, shaft and motor/generator assembly form the rotor. When charging (i.e., absorbing energy), the flywheel's motor acts like an electrical load and draws power from the grid to accelerate the rotor to a higher speed. When discharging, the motor is switched into generator mode, and the inertial energy of the rotor drives the generator which, in turn, creates electricity that is then injected back into the grid. Multiple flywheels may be connected together to provide various megawatt-level power capacities.

To illustrate the industry's current capabilities, one major flywheel manufacturer offers a high-performance rotor assembly that is sealed in a vacuum chamber and spins at up to 16,000 rpm. At that rotational speed, the speed at the rim would be approximately Mach 2, about 1500 mph, if it were operated in a normal atmosphere. At that speed the rotor must be enclosed in a high vacuum to reduce friction and energy losses. To reduce losses even further, the rotor is levitated with a combination of permanent magnets and an electromagnetic bearing. At 16,000 rpm the flywheel can store and deliver 25 kWh of extractable energy. Advanced flywheel energy systems can spin at speeds from 20,000 to over 50,000 rpm in a vacuum enclosure. Such flywheels can come up to speed in a matter of minutes.

In addition to providing a steady source of electricity, a flywheel may also be used to supply short pulses of energy at high power levels that exceed the abilities of its own energy source. This is achieved by accumulating energy in the flywheel over a period of time, at a rate that is compatible with the energy source, and then releasing energy at a much higher rate over a relatively short time when it is needed.

An obvious issue associated with flywheels is catastrophic failure. With rotors moving at high rotational speeds and the flywheel structure experiencing large physical stresses, what would happen if a flywheel flew apart? The industry addresses this possibility by using in-ground concrete foundations to ensure a stable platform to support each high-speed spinning mass. This ensures that any problem with a single flywheel is contained and cannot affect other units.

Advantages of a flywheel are high energy density and substantial durability that allows them to be cycled frequently with no degradation in performance. They also have very fast response and charge/discharge rates, being able to go from full discharge to full charge quickly. They are particularly well suited for high-power, relatively low-energy applications.

9.2.4 Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage (SMES) devices store energy in the magnetic field of a circulating dc electrical current in a superconducting coil. The cooled superconductor (at liquid nitrogen temperatures or lower) has no electrical resistance and the current continues indefinitely unless its energy is tapped by discharging the coil. A typical SMES device has three parts, a coil of wire that can become superconducting, a cryogenic cooler that cools the superconducting wire below its transition temperature at which it loses its electrical resistance, and power conditioning circuitry that allows for charging and discharging the coil.

Its advantages are ultra-fast charge and discharge times, no moving parts, nearly unlimited cycling capability, and an energy recovery rate greater than 95%. Disadvantages are the cost of the specialized wire, the need for continuous cooling to very low temperatures, large-area coils needed for appreciable energy storage, and the possibility of a sudden, large energy release if the wire's superconducting state is lost. SMES devices are often used to provide grid stability in distribution systems and for power quality at manufacturing plants requiring ultra-clean power (e.g., microchip production lines). At present 1 MWh SMES units are common and a 20 MWh engineering test model is under development.

9.2.5 Compressed air energy storage (CAES)

Compressed air energy storage (CAES) utilizes surplus electricity to compress air to high pressures in underground caverns or other large storage vessels, which can then be heated and released as needed to power expansion turbines that generate electricity.

One interesting feature of CAES is that, while being compressed from atmospheric pressure (14.7 psi/101 kPa) to storage pressures of about 1000 psi, the air heats up strongly (to more than 1000°F, 538°C). Some of this heat can be removed by cooling to protect the multi-stage air compressors, or stored thermally and used for subsequent adiabatic expansion of the stored air. Energy is also added to the compressed air during the expansion/power generation cycle by heating with natural gas. Gases other than air, for example, carbon dioxide, can be used as well.

CAES systems were first built in the 1870s in Europe and Argentina. The first utility-scale CAES project was the 1978

290 MW Hunters Plant in Germany, using an excavated salt dome as the storage container. In 1991 a 110 MW plant with a capacity of 26 hours was built in McIntosh, Alabama. The world's third CAES project, opened in 2012, was a 2 MW facility in Gaines, Texas. More recently, the Utah-based Intermountain Power Project has announced a 1.2 GW CAES project in underground salt domes, with the first 300 MW to serve as storage for solar PV power. The next 900 MW will serve as storage for anticipated new wind energy generation. The US DOE is also supporting several proposed CAES projects in California and New York.

9.2.6 Pumped storage

Pumped storage uses surplus, low-cost electricity, usually at night, to pump water from a lower reservoir to a higher one, and then this water is allowed to run downhill through turbines to generate electricity as needed.

It is a form of hydroelectricity, but the upper reservoirs used with pumped storage are quite small when compared with conventional hydroelectric dams of similar power capacity, and generating periods are often less than half a day. Because of the large scale possible in such schemes pumped storage is – based on MW installed – the most common type of utility storage today. As of 2017 total installed global capacity was 184 GW, of which 25 GW was in the US (59).

The round-trip efficiency of pumped storage is in the range 70–80%, but such losses are compensated for financially by its ability to offer electricity to the grid during periods of peak demand when electricity prices are highest.

The main disadvantage of pumped storage is the need for sites offering both geographical height and water availability, usually in hilly or mountainous regions. They are often areas of natural beauty, and therefore subject to public opposition.

In many ways pumped storage is similar to CAES in that surplus electricity is used to store energy in a large reservoir. It should also be noted that the substance moved against gravity to a higher level (and therefore to a higher potential energy) doesn't have to be water. Some companies today are revisiting a concept first proposed in the mid-19th century whereby a windmill would be employed to raise a quantity of iron balls, and these balls would then be allowed to fall into buckets on one side of a wheel, causing the wheel to rotate and thus drive a machine. Modern versions of this concept substitute gravel for iron balls and the mechanical system drives a turbine and generates electricity.

9.2.7 Thermal storage

Thermal storage allows us to store energy in the form of heat or cold for use at another time. Power-generating examples include modern solar thermal power plants which use concentrated sunlight to produce all of their energy during daylight hours. Surplus energy produced during these hours can be stored thermally in the form of hot oil or molten salt, and other higher-temperature storage schemes are being explored. Another approach is to use off-peak electricity to cool water or create ice, which can be used in a building's cooling system to lower air-conditioning electricity demand during the day. Both types of thermal storage are in use today.

9.3 APPLICATIONS

Energy storage systems can be used to deliver a broad range of benefits to both the electrical grid and the grid's customers. For customers these include backup power, increased self-consumption of PV-generated electricity, reduction of peak demand charges, and optimized management of time-of-use utility rates. For utilities, energy storage provides a range of important ancillary services such as frequency and voltage control, peak shaving, deferral of investments in distribution and transmission infrastructure, relief of transmission congestion, adequacy of supply, energy arbitrage (buying electricity at a lower price and selling at a higher price), spinning/non-spinning reserve, and energy for black start after a shutdown.

Historically, energy storage has been expensive, and initial attempts at evaluating its economic value have focused on single applications of the type mentioned above. Early studies concluded that storage was too costly for widespread use. Nevertheless, several recent studies have questioned this conclusion, pointing out that storage batteries and other storage devices can be used for more than one purpose, each with its own revenue potential (60, 61). They point out that focusing just on levelized cost of energy (LCOE), the usual metric used in comparing electricity costs, can be misleading. When applied to energy storage such an approach fails to take into account the full range of values and revenue benefits offered by storage, and that the full economic value offered by a storage technology varies depending on the application. This perspective can change the financial viability of energy storage projects, and the broad conclusion now is that energy storage should be evaluated as a totally new and different entity. Admittedly, evaluating the economics of energy storage is difficult. For example, batteries are not strictly a supply or demand-side technology, but rather can serve as either load or generation depending on whether they are charging or discharging. In many cases today storage devices are used for only a small fraction of their availability, and they could be used for more so-called ‘stacked’ applications.

9.4 COSTS

The cost of energy storage is a rapidly moving target, as more and more companies announce storage products, and consumers and utilities begin to appreciate the full value of storage technologies. Today, costs are falling and markets are expanding rapidly. $230/kWh has been identified as the price point at which battery storage wins out over conventional fossil fuel generation. This cost point should be reached in markets within the next few years, and is expected to decrease further to $100/kWh. Significant market growth is anticipated in storage of solar-generated electricity by households and businesses, utility-scale applications, and use in electric and hybrid-electric vehicles. The market research firm HIS expects the energy storage market to increase from its 2017 installation rate of 6 GW to an annual installation rate of over 40 GW by 2022.

9.5 FUNDAMENTAL CHANGE

What is becoming increasingly clear is that energy storage is bringing fundamental change to the electrical energy system. Over the past century and more, we developed electrical grids throughout the world that immediately consumed what they produced, and managed that by overproducing a bit to make sure that backup exists in case of unforeseen outages. However, if you have energy storage there is no need to overproduce and no need for backup reserves. It allows you to store electricity and use it as needed.

Chapter 10

Policy considerations

The purpose of this chapter is to focus on policy issues associated with the water–energy–environment nexus. At first blush this is more than an imposing task since the provision of water and energy services is essential to all human activities. Providing a policy environment that touches all the necessary bases for successful provision of these services is obviously complicated and inevitably contentious, as policy studies and political history clearly document.

So how to proceed? I choose to begin with a definition of ‘policy’: ‘A policy is a deliberate system of principles to guide decisions and achieve national outcomes. A policy is a statement of intent …’ (62) For example, as stated by UK Prime Minister Theresa May on 19 February 2018, it is the policy of the United Kingdom to ‘… have an education system at all levels which serves the needs of every child.’ (63) Policy development in areas related to water, energy, and environment was a primary focus of my career in government, and I draw upon that experience in the discussion that follows.

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To a large extent public policies reflect widely held public values. In reviewing the literature of recent years on the policy issues associated with water, energy, and environment, there was one overriding issue: how to address the challenge of global warming and climate change. It encompasses all three elements of the nexus that this book discusses, and arises from a value reflected in all human societies, the need to protect members of those societies and leave a better world for our children and grandchildren. It is in this context that I will discuss policy issues.

10.1 IMPORTANT QUESTIONS

As a first step I list some of the more important questions that an attempt to address climate change must consider:

- Is there a physical basis for understanding global warming and climate change?
- Is there documented evidence for global warming and climate change?
- Can global warming and climate change be attributed to human activities, and what are those activities?
- What are the potential short- and long-term impacts of global warming and climate change with respect to water supply, environment, and health?
- What is the anticipated time scale for these impacts?
- What can be done to mitigate the onset and potential impacts of global warming and climate change?

I will address each of these considerations in turn, discuss its current policy context, and offer policy recommendations.

10.1.1 Is there a physical basis for understanding global warming and climate change?

As discussed in Chapter 4, global warming (also known as the greenhouse effect) is the process by which gases in the atmosphere allow sunlight to pass through while restricting the outward passage of infrared re-radiation from the Earth's land and water surfaces. This impacts on the energy balance between the Earth and the Sun, and determines the Earth's average temperature. In turn, the energy exchange among the Earth's atmosphere and its oceans and land masses determines climate, which Wikipedia defines as 'the statistics of weather over long periods of time.' The difference between weather and climate is that weather describes the conditions of the atmosphere over a short time period. Climate change refers to the shift in global weather patterns associated with an increase in global average temperatures.

While it is well documented that the climate system can exhibit random changes in global temperatures for short periods of time (up to decades), long-term temperature trends derive from so-called 'external forcings' such as changes in the Earth's orbit around the Sun, changes in the amount of radiation emitted by the Sun, and volcanic eruptions. Changes in the Earth's atmosphere due to increasing concentrations of greenhouse gases such as carbon dioxide and methane also fall into this latter category.

The link between CO_2 and the Earth's temperature was first suggested by Joseph Fourier in 1824. It was experimentally observed in 1860 by John Tyndall, and was first investigated quantitatively in 1896 by the Swedish scientist and Nobel Laureate Svante Arrhenius, who is often referred to as 'the father of climate change science'. His interest in this subject arose from the scientific debate about what could have triggered Earth's many ice ages and whether large swings in levels of atmospheric CO_2 were responsible. The science of this concept was developed further by Guy Stewart Callendar in the period 1930–1960.

Jim Hansen, then NASA's chief climate scientist, drew public attention to global warming with his 1988 testimony to the US Congress about the dangers of human-caused climate change.

This conclusion was questioned by some for many years (though not by the vast majority of the scientific community) but now is widely accepted by scientists and policymakers alike. Today Jim Hansen serves as director of the Program on Climate Science, Awareness and Solutions of the Earth Institute at Columbia University. His work, and that of his scientific predecessors, has laid a solid foundation for understanding the physical basis of global warming. Understanding the global energy exchanges and the weather changes associated with this warming may be the most important scientific activity currently underway.

10.1.2 Is there documented evidence for global warming and climate change?

Global warming is not a theoretical concept. Concern about global warming and associated climate change is based on physical, well documented measurements. Perhaps the most attention-getting are the impacts on water: melting of glaciers, rising sea levels, changes in rainfall patterns, and water and wind damage from more powerful storms. These effects are real, well documented, and increasingly well modeled.

Accurate measurements of atmospheric CO_2 were begun by Dave Keeling at Caltech in the early 1950s and moved to Mauna Loa in Hawaii in 1958. These measurements continue to this day, and similar measurements are now made routinely at many sites around the world.

Based on these measurements, deep geological core measurements, and related scientific analysis, it is understood that CO_2 concentrations have varied widely over the past 400,000 years, from about 180 ppm during periods of extensive glacier formation to 280 ppm during the interglacial periods (see Figure 10.1).

With the advent of the industrial revolution in the 1800s, and the increasing use of fossil fuels, atmospheric CO_2 concentrations have grown steadily (64), and as of 2018 have reached 410 ppm. Based on scientific estimates, this may be the highest level in millions of years.

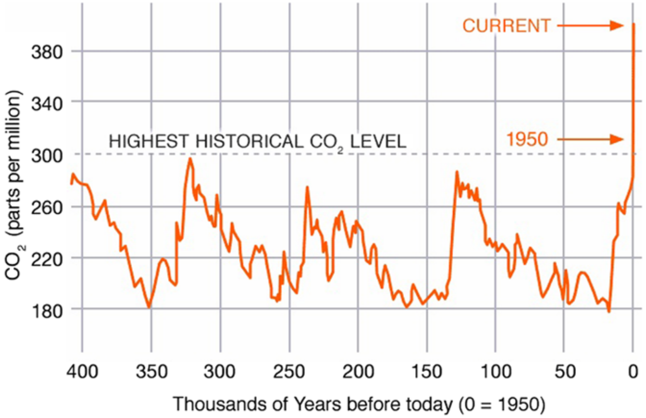


Figure 10.1 Carbon dioxide concentrations over time. (*Source*: U.S. National Aeronautics and Space Administration)

The impact on global temperature is shown in the so-called 'hockey stick chart' (65), which has been called by *The Atlantic* magazine 'The most controversial chart in science' (see Figure 10.2).

The sharp jump in the temperature curve from about 1900 to the present is the basis of the hockey stick analogy. When the chart was released in 1999 it was repeatedly attacked, and so were the authors of the accompanying article. Eventually, the US Congress got involved, no doubt encouraged by supporters of fossil fuels, and it was only after the National Academy of Sciences reviewed the issue in 2006, and declared the hockey stick to be good science, did the attacks begin to taper off. Today, research on the potential impacts of adding greenhouse gases to the atmosphere (which includes gases such as N_2O and chlorofluorocarbons in addition to CO_2 and CH_4), and their timing, are major foci of government and academic research. While there is some current opposition to such research by some governments (e.g., in the US and countries dependent on revenue from sale of fossil fuels), it is being supported by international scientific collaborations.

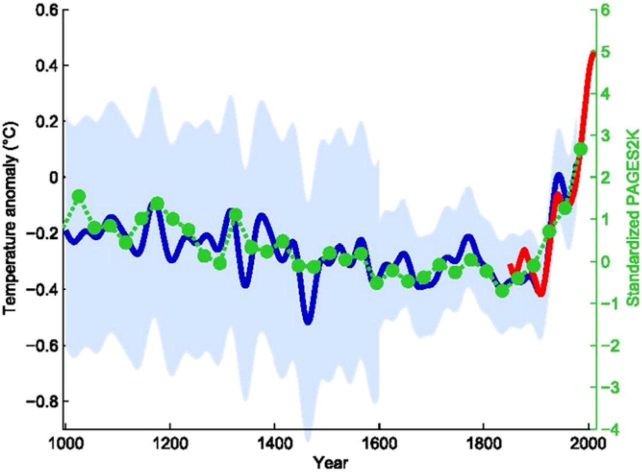


Figure 10.2 The original hockey stick chart (65) (*Source*: Wikipedia).

10.1.3 Can global warming and climate change be attributed to human activities, and what are those activities?

The CO_2 concentration chart and the hockey stick chart, together with large amounts of subsequent data gathering and related scientific analysis, provide a clear picture that something changed significantly after the industrial revolution gained momentum. The work of Arrhenius and others has illuminated the role of greenhouse gases in global warming. While some climate change deniers and minimalizers still attribute global temperature changes to normal global warming cycles, the vast majority of climate change scientists, and a steadily increasing number of policymakers and the general public, accept that combustion of fossil fuels and the subsequent release of CO_2, is responsible for recent increases in global temperatures.

While there is a release of CO_2 from natural biological processes, the observed recent temperature changes clearly have another origin. These ‘extra’ CO_2 emissions derive from the combustion of coal, oil, and natural gas in electricity production, the combustion of oil in transportation vehicles, and the combustion of fossil fuels in industrial processes. The increasing use of lower-cost natural gas (a powerful greenhouse gas) in power production and industrial processes, possibly resulting in increased leakage into the atmosphere through insufficiently sealed infrastructure, is also a major concern. In addition, the release of N_2O, another powerful greenhouse gas, from increased use of agricultural fertilizers, is a topic of increasing scientific study and concern.

Finally, it should be noted that as global warming proceeds, and more and more water vapor enters the atmosphere, this can have a feedback effect on global warming. For example, more clouds can bounce more solar radiation back into space, reducing the heating effect (negative feedback); but the presence of more water vapor can also amplify the global warming effect because water vapor absorbs infrared re-radiation from the oceans and land masses, a positive feedback mechanism. Volcanic eruptions can also have a mixed impact: the clouds of material produced by these eruptions, which can circle the globe, can reflect sunlight, but the small, dark-colored particulate matter they introduce into the atmosphere can absorb the Sun’s radiation and increase the heating effect. Other positive feedback mechanisms exist as well. Melting of Arctic Ocean ice changes the albedo (reflectivity) of the ocean from reflecting to absorbing, allowing increased ocean heating. The thawing of cold region permafrost, frozen layers below the Earth’s surface, can also exacerbate global warming by releasing trapped CH_4 and other hydrocarbons, which are powerful greenhouse gases. All in all, a complicated set of physical phenomena that many people are working hard to understand.

10.1.4 What are the potential short- and long-term impacts of global warming and climate change with respect to water supply, environment, and health? What is the anticipated time scale for these impacts?

I admit to being extremely concerned about global warming and its many potential impacts on human welfare. I am disturbed by the fact that those least responsible for global warming and the resultant climate change – for example, island nations – are likely to suffer the most serious impacts. I am also disappointed with those scientists and politicians who continue to deny the scientific basis for concern about global warming when the consensus among scientists is overwhelming, an unusual situation in science. I believe it is a failure for which the climate deniers and minimizers should be held accountable.

As stated earlier in Chapter 4, ‘climate change is worthy of our most careful attention.’ In most countries these concerns would lead to executive action and legislative hearings as a precursor to legislative responses. Such hearings took place in the US during the Obama Administration, and much useful testimony on the potential impacts of global warming and climate change was obtained from climate science experts (66). I will draw on this testimony to answer the question of potential impacts. (*Note*: With the advent of the Trump Administration, and the control of both houses of the US Congress by the Republican Party, no further hearings on global warming have been held.) In the following I quote from the highlights of their testimonies.

Dr Donald Wuebbles, Professor and Atmospheric Scientist, Department of Atmospheric Sciences, University of Illinois

- ‘The US and the global climate is changing now and this change is apparent across a wide range of observations. The evidence indicates that most of the climate change of the past 50 years is primarily due to human activities.’

- ‘Heavy downpours are increasing in most regions of the US, especially over the last three to five decades. Certain types of other extreme weather events, including heat waves, and floods and droughts in some regions have become more frequent and intense. The trends are projected to continue.’
- ‘Scientific analyses are now indicating a strong link between changing trends in severe weather events and the changing climate.’
- ‘There has been an increase in the overall strength of hurricanes and in the number of strong (Category 4 and 5) hurricanes in the North Atlantic since the early 1980s. The intensity of the strongest hurricanes is projected to continue to increase as the oceans continue to warm.’
- ‘Global sea level has risen by about 8 inches since 1880. It is projected to rise another 1 to 4 feet by 2100. Many coastal areas of the US will be increasingly affected.’

Dr James McCarthy, Professor of Biological Oceanography, Harvard University

- ‘Ocean processes are linked to many types of extreme weather and recent ocean studies are helping us understand the growing intensity of extreme weather events on land. Some of the observed changes in the ocean, which only a few decades ago were thought unimaginable in our lifetimes, are now occurring as a result of human-caused climate change.’
- ‘The additional heat in the climate system caused by the greenhouse gases that we release with the burning of fossil fuels and land-use practices is now penetrating deep within the oceans.’
- ‘For many of us in ocean science the compelling evidence for human-caused climate change came with the observations of deep ocean warming, the ice core data that demonstrates linkages between Earth’s past

temperature and atmospheric greenhouse gas content, the acceleration in sea level rise, the abrupt melting of land ice and ice shelves that had been in place for many thousands of years, and global changes in ocean chemistry. Such changes in these phenomena can only be consistently explained by an unusual rate of greenhouse gas release to the atmosphere.'

Dr J. Marshall Shepherd, President, American Meteorological Society, and Professor of Geography and Director, Atmospheric Sciences Program, University of Georgia

- 'Key Takeaway Points:
  - This topic is about impact to people – your constituents, my fellow citizens, my two kids – not just polar bears.
  - Most of the warming of the past 50 years is due to human activity, and extensive evidence supports this conclusion.
  - Climate change is increasing the probability of extreme events, and in some cases maybe strengthening their intensity or increasing their frequency (i.e., we are loading the dice towards more Sandy or blizzard type storms).
  - There is strong evidence that increases in some types of extremes are linked to human induced climate change, notably extreme heat, coastal flooding, and heavy downpours. For other types of extremes, such as tornadoes, current evidence is much more limited.'

Dr John M. Balbus, Senior Advisor for Public Health, National Institute of Environmental Health Sciences and Lead Author/ Human Health, 2013 US National Climate Assessment

- 'Rising temperature will increase human exposure to mold, microbial pathogens and infectious diseases. … studies are indicating that the greatest heat-related harm may come not from extreme exposure but rather from the lower but more frequent stress of increasingly hot summer days.'

- '… we've seen the geographical range of ticks that cause Lyme disease shift northward, and is predicted to shift further northward in the United States and Canada …'

Opposing views on global warming and climate change do exist, and are perhaps most strongly expressed by The Heartland Institute (67). As described in Wikipedia, 'The Heartland Institute is an American conservative and libertarian public policy think tank based in Chicago, which advocates free-market policies. In the 1990s, the group worked with the tobacco company Philip Morris to question the science linking secondhand smoke to health risks, and to lobby against government public health reforms. More recently, The Institute has focused on questioning the science of human-caused climate change, and was described by the New York Times as 'the primary American organization pushing climate change skepticism. … The Institute has sponsored meetings of climate change skeptics, and has been reported to promote public school curricula challenging the scientific consensus on human-caused climate change.' What they are saying, in their own words, is the following:

- 'The environmental movement needs voices devoted to sound science and market-based, rather than government-based, solutions to environmental problems.'
- *Roosters of the Apocalypse: How the Junk Science of Global Warming Nearly Bankrupted the Western World* (published in April 2012 by the Heartland Institute)
    - It 'compares societal belief in climate change to a prophecy that instructed the tribe to massacre its livestock, resulting in the death of 35,000 people and slavery for the survivors. … A similar 'economic suicide' is looming for the United States of America if Americans continue to pursue policies restricting the use of fossil fuels in order to avoid a false climate 'apocalypse'…' (68)
    - 'human emissions have an impact on the environment, but it is so small that people and the economy won't be

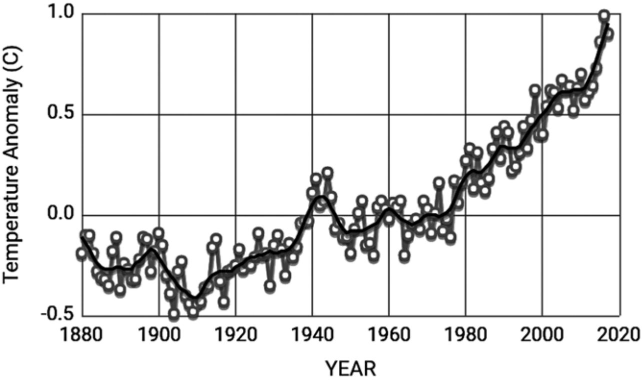
> affected … a scientific myth … believing in man-made global warming – after all the scientific discoveries and Revelations that point against this theory – is more than a little nutty. In fact, some really crazy people use it to justify immoral and frightening behavior.' (69)

A highly respected source of information on atmospheric and climate changes in the 21st century is the NASA Goddard Institute for Space Studies, which was established in 1961 and led by Jim Hansen from 1981 to 2013. In January 2018 it reported that:

- Earth's surface temperatures in 2017 were the second warmest since 1880, when global estimates first become feasible.
- Global temperatures in 2017 were second only to 2016, which still holds the record for the hottest year. However, 2017 was the warmest year without an El Niño. (*Note*: In a separate, independent analysis, NOAA scientists found that 2017 was the third-warmest year in their records. The minor difference is due to different methods to analyze global temperatures used by the two agencies, although over the long-term the records remain in strong agreement.)

NASA also reports that global surface temperature relative to an average for the years 1951–1980 had increased by 0.9°C (1.6°F) by 2017 (70). See Figure 10.3.

To add to this discussion of potential global warming impacts I mention two disturbing newspaper articles that caught my attention. They both point out the seriousness and potential scale of these impacts and the timescales involved. The first, by Dana Milbank, appeared in the *Washington Post* on 12 June 2013. Entitled 'Bloomberg's race to protect NYC from climate change' it discussed the $19.5 billion plan announced by Michael Bloomberg (then Mayor of New York) to 'prepare for the impacts of a changing climate.' In his remarks announcing the plan Bloomberg addressed the 'inevitability that rising temperatures and sea levels would bring even worse than the damage from Hurricane Sandy.' He also stated that 'By mid-century, up to a quarter of all New York City's land area, where 800,000 residents live today, will be in the flood plain, and 40 miles of our waterfront could see flooding on a regular basis just during normal high tides. We no longer have the luxury of ideological debate. The bottom line is we can't run the risk.'



Source: climate.nasa.gov

Figure 10.3 Global surface temperature. (*Source*: U.S. National Aeronautics and Space Administration)

To me an even more disturbing article, by Justin Gillis published in the *New York Times* on 12 August 2013, discussed in some detail the potential future implications of possible sea level rise. He quotes the work of Dr John Mercer who 'pointed out the unusual topography of the ice sheet sitting over the western part of Antarctica' and speculated that 'climatic warming could cause the whole thing to degrade rapidly on a geologic timescale, leading to a possible rise in sea level of 16 feet.' He also refers to a paper (71) co-authored by Dr Michael O'Leary of Curtin University in Australia, who together with five colleagues 'spent more than a decade exploring the remote western coast of Australia, considered one of the best places in the world to study sea levels of the past.' To quote further from the Gillis article, 'the paper focuses on a warm period in the Earth's history that preceded the most recent ice age. In that epoch, sometimes called the Eemian, the planetary temperature was similar to levels we may see in coming decades as a result of human emissions, so it is considered a possible indicator of things to come.'

'Examining elevated fossil beaches and coral reefs along more than a thousand miles of coast, Dr O'Leary's group confirm something we pretty much already knew. In the warmer world of the Eemian, sea level stabilized for several thousand years at about 10 to 12 feet above modern sea level. The interesting part is what happened after that. Dr O'Leary's Group found what they consider to be compelling evidence that near the end of the Eemian, sea level jumped by another 17 feet or so, to settle at close to 30 feet above the modern level, before beginning to fall as the ice age set in. In an interview, Dr. O'Leary told me he was confident that the 17 foot jump happened in less than a thousand years – how much less, he cannot be sure.' Of course, this group's findings must be subject to critical scrutiny, but 'if the work does hold up, the implications are profound. The only possible explanation for such a large, rapid jump in sea level is the catastrophic collapse of a polar ice sheet, on either Greenland or Antarctica. Dr. O'Leary is not prepared to say which; figuring that out is the group's next project. But a 17 foot rise in less than a thousand years, a geologic instant, has to mean that one or both ice sheets contain some profound instability that can be set off by a warmer climate. That, of course, augers poorly for humans. Scientists at Stanford calculated recently that human emissions are causing the climate to change many times faster than at any point since the dinosaurs died out. We are pushing the climate system so hard that, if the ice sheets do have a threshold of some kind, we stand a good chance of exceeding it.'

Other scientific research supports the conclusion that even if greenhouse gas emissions were to stop tomorrow we have probably locked in several feet of sea-level rise over the long-term. As a result, adaptation is the current buzzword in global warming/climate change circles, a recognition that climate change is with us and the world has no choice but to adapt or suffer serious consequences. To repeat a point made in an earlier chapter, an important impact that is already showing up is the impact on precipitation patterns which affect water supplies. Many people see access to clean water as a principal, if not the principal, 21st century environmental, public health, and even national security issue.

10.1.5 What can be done to mitigate the onset and potential impacts of global warming and climate change?

This of course is the '\$64,000 question' and a major focus of scientific and legislative policy work. Nevertheless, a number of important suggestions have been made as to how to address this question.

It is widely recognized that in the short-term very little can be done. The initial response to global warming in the US and Europe was 'mitigation', that is, reducing the amount of CO_2 going into the atmosphere. This was unsuccessful, as developing nations with growing economies became the principal source of atmospheric CO_2. While reducing CO_2 emissions is still a critical goal, and is being pursued worldwide, considerable effort is going into adaptation.

Some of the mitigation measures we can undertake include:

- To move, in the long term, to low- or zero-carbon fuels as replacements for hydrocarbon fuels, and restrict the release of both CO_2 and other greenhouse gases.

- This is consistent with the historical pattern over the past few centuries to move to lower and lower carbon content fuels, from coal to oil, to natural gas.
- Other long-term energy options are to move to both renewable energy and nuclear power, subject to resolution of the concerns associated with nuclear power discussed in Chapter 7.
- A 2015 interdisciplinary MIT study, ‘The Future of Solar Energy’, in its Summary for Policymakers, concluded that ‘massive expansion of solar generation worldwide by mid-century is likely a necessary component of any serious strategy to mitigate climate change.’
- The MIT report goes on to state: ‘Fortunately the solar resource dwarfs current and projected future electricity demand. In recent years, solar costs have fallen substantially and installed capacity has grown very rapidly. Even so, solar energy today accounts for only about 1% of US and global electricity generation. Particularly if a substantial price is not put on carbon dioxide emissions, expanding solar output to the level appropriate to the climate challenge likely will not be possible at tolerable cost without significant changes in government policies.’
- Another possible goal is an energy economy that makes extensive use of hydrogen. Sometimes, hydrogen is referred to as ‘the hydrocarbon without the carbon.’ Not only can it be burned cleanly (its principal combustion products are water and heat), it can also serve as a source of clean electricity via its use in fuel cells if it is produced via electrolysis of water (H_2O), using electricity sources (renewables, nuclear) that do not put carbon in the atmosphere.
- Hydrogen may also play a critical role in energy storage. It can be stored in gaseous and liquid form, and in recoverable form in solid-state matrices.

As far as adaptation is concerned, government officials in many cities around the world are already taking steps to protect their threatened infrastructures. For them a critical question is exactly how long will it take for impacts to be felt? To quote again from the Gillis article: ‘On that crucial point, alas, our science is still nearly blind. Scientists can look at the rocks and see indisputable evidence of jumps in sea level, and they can associate those with relatively modest increases in global temperature. But the nature of the evidence is such that it is hard to tell the difference between something that happened in a thousand years and something that happened in a hundred. On the human timescale, of course, that is all the difference in the world. If sea level is going to rise by say, 30 feet over several thousand years, that is quite a lot of time to adjust – to pull back from the beaches, to reinforce major cities and to develop technologies to help us cope. But if sea level is capable of rising several feet per century, as Dr O’Leary’s paper would seem to imply and as many other scientists believe, then babies being born now could live to see the early stages of a global calamity.’ We surely live in uncertain and dangerous times.

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Index

Water, Energy, and Environment

A Primer

Access to clean water and energy are critical to economic growth and sustainable development. Providing water and energy services has important environmental impacts. Understanding the inextricable linkages among water, energy, and environment – the water-energy-environment nexus – will be a priority for all levels of government in the decades ahead as they develop and implement policies to enhance human welfare.

We are also experiencing the beginning of an energy revolution in these early years of the 21st Century. Understanding the nature of this revolution is important, and this book provides an introduction to and explanation of this revolution. Specific topics discussed, in addition to explaining the nexus, include:

- the global contexts for water and energy issues
- associated environmental impacts
- traditional and emerging energy options (fossil fuels, nuclear power, renewable energies)
- new approaches to providing clean water
- the emerging role of energy storage
- policy issues associated with water, energy, and environment
- recommendations for moving forward

There are a number of books on pieces of the nexus, most at a technical level. The purpose of this book is to explain the nexus and each of its components in a university-level, highly-readable 'primer' for those entering the water and energy fields. It will also serve as an introduction to these topics for a global, multidisciplinary audience that includes academic scholars in related technical and non-technical fields, government officials at national, state, and local levels, economists and others in the financial/investment communities, and those in the development community responsible for planning and delivering water and energy services to underserved populations.

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