PHYSICS OF Solar Energy

C. JULIAN CHEN

Science/Physics/Energy

The definitive guide to the science of solar energy

You hold in your hands the first, and only, truly comprehensive guide to the most abundant and most promising source of alternative energy—solar power.

In recent years, all major countries in the world have been calling for an energy revolution. The renewable energy industry will drive a vigorous expansion of the global economy and create more "green" jobs. The use of fossil fuels to power our way of living is moving toward an inevitable end, with sources of coal, petroleum, and natural gas being fiercely depleted.

Solar energy offers a ubiquitous, inexhaustible, clean, and highly efficient way of meeting the energy needs of the twenty-first century. This book is designed to give the reader a solid footing in the general and basic physics of solar energy, which will be the basis of research and development in new solar engineering technologies in the years to come.

As solar technologies like solar cells, solar thermal power generators, solar water heaters, solar photochemistry applications, and solar space heating-cooling systems become more and more prominent, it has become essential that the next generation of energy experts—both in academia and industry—have a one-stop resource for learning the basics behind the science, applications, and technologies afforded by solar energy. This book fills that need by laying the groundwork for the projected rapid expansion of future solar projects.

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Cover Photograph: iStockphoto.com/kativ

WILEY
wiley.com

ISBN 978-0-470-64780-6
90000
9 780470 647806

Physics of Solar Energy

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A.1 Energy and Power Units 305

Preface

One of the greatest challenges facing mankind in the 21st century is energy. Starting from the industry revolution in the 18th century, fossil fuels such as coal, petroleum, and natural gas, have been the main energy resources for everything vital for the human society: from steam engines to Otto and Diesel engines, from electricity to heating and cooling of buildings, from cooking and hot-water making, from lighting to various electric and electronic gadgets, as well as most of the transportation means. However, the fossil-fuel resources, as stored solar energy accumulated during hundreds of millions of years, is rapidly depleted by excessive exploration. Besides, the burning of fossil fuels has caused and is causing damages to the environment of the Earth on which the lives of all creatures are relying.

It is understandable that alternative or renewable energy resources, other than fossil fuels, have been studied and utilized. Hydropower, a derivative of solar energy, currently supplied about 2% of the world's energy consumption. The technology is matured, and the available resources are already heavily explored. Wind energy, also a derivative of solar energy, is being utilized rapidly. The resource of such a highly intermittant energy is also limited. Nuclear energy is not renewable. The mineral resources of uranium is limited, and the waste management is a difficult problem.

The most abundant energy resource available to human society is solar energy. At four million EJ per year, it is ten thousand times the energy consumption of the world in 2007. For example, if five percent of the sunlight shining on the state of New Mexico is converted into useful energy, it can satisfy all the energy needs of the United States.

The history of utilization of solar energy is as old as the human history. However, to date, among various types of renewable energy resources, solar energy is the least utilized. Currently, it only supplies about 0.1% of the world's energy consumption, or 0.00001% of the available solar radiation. The science and technology of solar energy utilization are more difficult than others. And despite decades of intensive research, the cost of solar energy conversion is still much higher that of fossil energy and other renewable energy resources. Nevertheless, as a result of intensive research and development, utilization of solar energy, especially solar photovoltaics, is enjoying an amazingly rapid progress. Therefore, it is reasonable to expect that in the later half of the 21st century, solar energy will become the main source of energy, surpassing all fossil energy resources.

Similar to other fields of technology, the first step to achieve success in solar energy utilization is to have a good understanding of its basic science. Since the years after the first energy crisis in the 1970's, many good books on solar energy have been published. However, those books are concentrating on thermal engineering of solar energy. Recently, several books about the physics of solar cells were published. But none of those books have expounded the basic physics of solar energy in general and its utilization.

Two years ago, Columbia University launched a master-degree program of solar energy science and engineering. I was asked to give a graduate-level course on the physics of solar energy. In the Spring semester of 2009, when the first course was launched, 46 students registered. Columbia's CVN (Columbia Video Network) decided to record the lectures and distribute to outside students. Because of the high demand, the CVN course of "Physics of Solar Energy" was repeated in the Summer and Fall semester, and another lectures series for regular students was arranged for the Fall semester of 2009. Because there is no single textbook for the course, I have no choice but to take the hard work to compile lecture notes. After intensive work for one and half years, the compilation of lecture notes as a book manuscript is gradually in shape.

The basic design of the book is as follows. The first chapter summarizes the energy problem and comparing various types of renewable energy resources, including hydropower and wind energy with solar energy. Chapter 2, Nature of Solar Radiation, presents the electromagnetic wave theory of Maxwell as well as the photon theory of Einstein. Understanding of black-body radiation is crucial to the understanding of solar radiation, which is described in details. Chapter 3, Origin of Solar Energy, summarizes the astrophysics of solar energy, including the basic parameters and the structure of the Sun. The gravitational contraction theory of Lord Kelvin and the nuclear fusion theory of Hans Bethe for the origin of stellar energy are presented. Chapter 4, Tracking Sunlight, is a more-or-less complete but elementary treatment of the positional astronomy of the Sun for non-astronomy majors. It includes an elementary derivation of the coordinate transformation formulas. It also includes an transparent derivation of Equation of Time, the difference of solar time and civil time, as the basis of tracking sunlight based on the time as we know. This chapter is supplemented with an brief summary of spherical trigonometry in Appendix B. The accumulated daily direct solar radiation on various types of surfaces over a year is analyzed with graphics. Chapter 5, Interaction of Solar Radiation with Earth, presents both the effect of atmosphere and the storage of solar energy in the ground, the basis for the so-called shallow geothermal energy. A simplified model for scattered or diffuse sunlight is presented. Chapter 6, Thermodynamics of Solar Energy, starting with a summary of basics of thermodynamics, followed by several problems of applications of solar energy, including the limit of energy conversion, as well as the basics of heat pump and refrigeration. Chapters 7 through 10 deal with basic physics of solar photovoltaics and Solar photochemistry. In Chapter 7, Quantum Excitation, basic concepts of quantum mechanics, presented in the format of Dirac's bras and kets, with examples of organic molecules and semiconductors, cumulated with a full derivation of the Golden Rule and principle of detailed balance. Chapter 8 is dedicated to the essential concept in solar calls, the *pn*-junction. Chapter 9 deals with semiconductor solar cells, including a full derivation of the Shockley-Queisser limit, with descriptions of the detailed structures of crystalline, thin-film, and tandem solar cells. Chapter 10, Solar Photochemistry, started with an analysis of photosynthesis in plants, to the research of artificial photosynthesis. Various organic solar cells are described, including dye-sensitized solar cells and bilayer organic solar cells. Chapter 11 deals with solar thermal applications, including solar water heaters and solar thermal electricity generators. The vacuum-tube collector and the thermal-cipher solar heat collectors are emphasized. Concentration Solar Energy is also presented, with four types of optical concentrators: though, parabolic dish, heliostat, and especially, the compact linear Fresnel concentrator. Chapter 12 deals with energy storage, including sensible and phase-change thermal energy storage systems, rechargeable batteries especially lithium ion batteries. The last Chapter, Building with Sunshine, introduces architectural principles of solar energy utilization, together with civil-engineering elements.

According to my experience of teaching that course, the student background is highly diversified: it includes physics, chemistry, electrical engineering, mechanical engineering, chemical engineering, architecture, civil engineering, environmental science, materials science, aerospace engineering, economy, and finance. Although it is a senior undergraduate and beginning graduate level course, it must accommodate a broad spectrum of student background. Therefore, necessary scientific background knowledge is part of the course. The book is also designed with respect to such a situation. For example, background knowledge in positional astronomy, thermodynamics, and quantum mechanics is included in the book. For students already taken those courses, the background materials serve as a quick review, and as a reference of the terminology and symbols used in this book. The presentation of the background science is for the purpose of solar energy utilization only, along a "fast track". For example, quantum mechanics is presented using an "empirical" approach, starting from direct perception of quantum states by a scanning tunneling microscope, thus the quantum states are not just an imaginary mathematical tool, but a perceptible reality. The scanning tunneling microscope is also an important tool of the research for novel devices in solar energy conversion.

At the beginning of the book, a gallery of color graphics and photographs is constructed and compiled. It serves as a visual introduction to the mostly mathematical presentation of the materials, which is useful for a intuitive understanding of the concepts.

During the course of giving lectures and writing the lecture notes, I have encountered many unexpected difficulties. Physics of solar energy is a multidisciplinary subject. The subject fields comprise astronomy, thermodynamics, quantum mechanics, solid state physics, organic chemistry, solid state electronics, environmental science, mechanical engineering, architecture, and civil engineering. As a unified textbook and reference book, a complete and consistent set of terminology and symbols must be designed, which should be consistent with the established terminology and symbols of the individual fields as much as possible, but yet concise and self-consistent. A list of symbols is included in Appendix A.

After several semesters of teaching, homework assignments and exams are accumulated. As a result, problems are appended at the end of each Chapter, to make it a viable textbook.

Acknowledgements (to be appended).

C. Julian Chen

Columbia University
in the City of New York

August 2010

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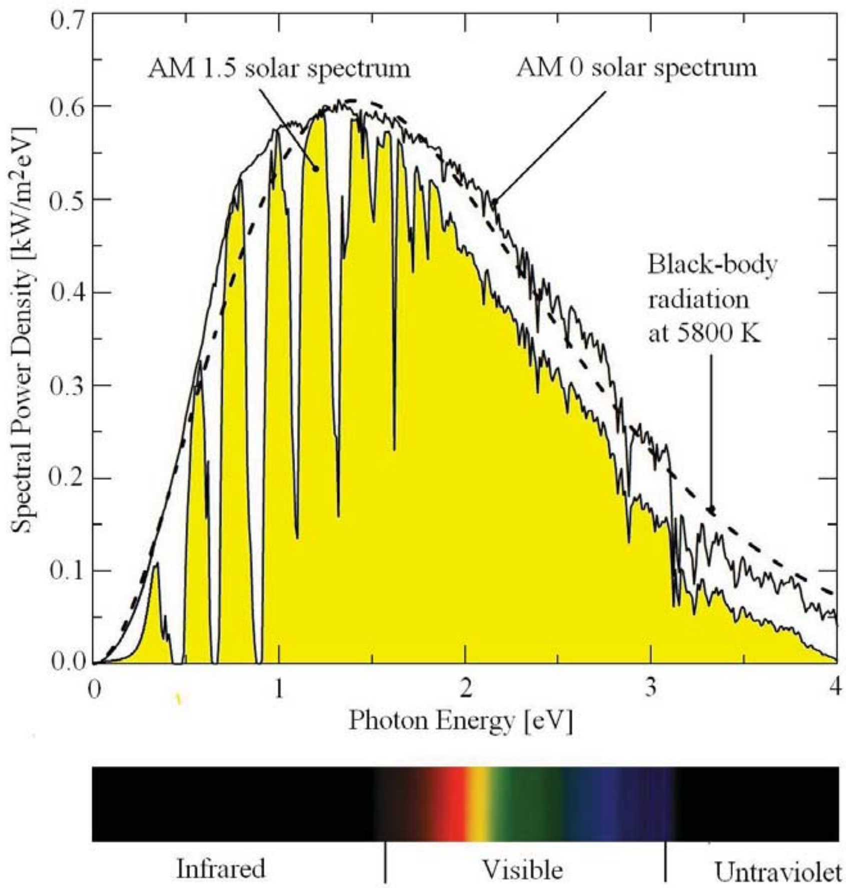

Plate 1. Spectral power density of solar radiation. Top curve: Solar spectrum just outside the atmosphere. The total power density is 1.366 kW/m^2. Curve filled with yellow: the standardized solar spectrum on the surface of the Earth, for performance evaluation of solar cells. AM 1.5 means air mass at an angle about 37° from the horizontal line in a clear day. The total power density is 1.0 kW/m^2. See Chapter 5 for details. The dashed curve is the solar radiation spectrum at the position of the Earth by modeling the Sun as a black-body radiator at 5800 K. As shown, the solar spectrum just outside the atmosphere, the AM0 spectrum, matches well with the black-boy radiation spectrum at 5800 K, diluted by the distance from the Sun to the Earth. The relation with human vision of colors is shown in the bar beneth. As shown, about one half of the solar radiation power is in the visible range. (Source of solar spectrum data: American Society for Testing and Materials (ASTM).)

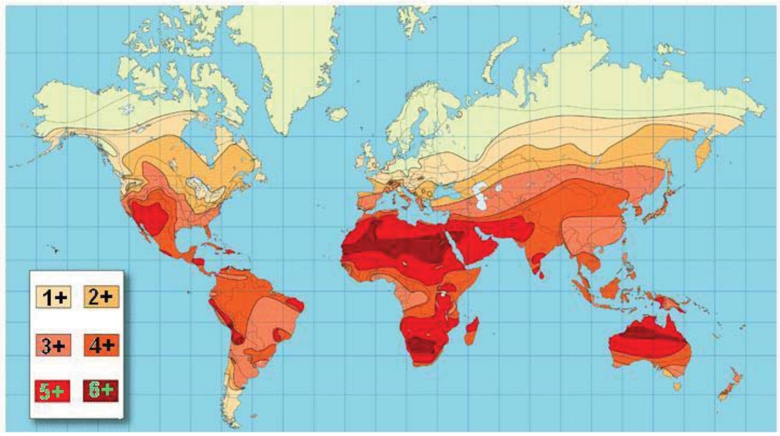

Plate 2. Insolation Map of the World. Solar radiation per day on a surface of one square meter in kilojoules, averaged over a year. As shown, large areas in Northern Africa have the highest insolation.

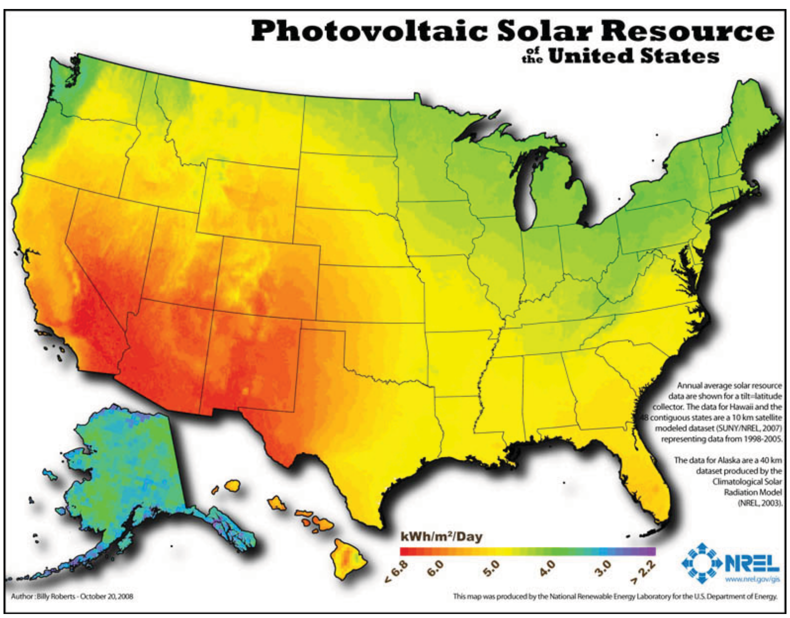

Plate 3. Insolation Map of the United States. Solar radiation per day on a surface of one square meter in kilojoules, averaged over a year. As shown, large areas in some Southwest States have the highest insolation. The areas around Great Lakes and the State of Washington have rather weak insolation due to cloudiness.

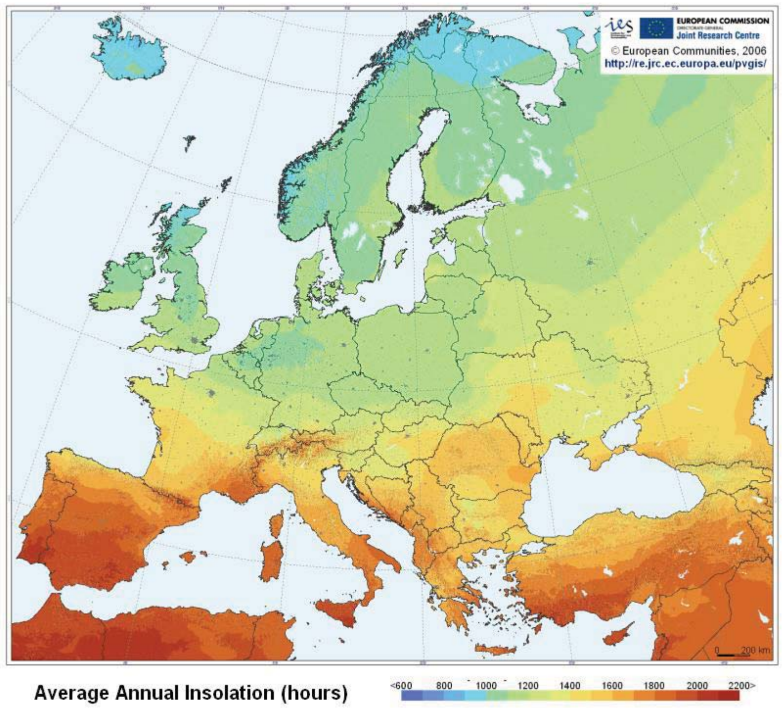

Plate 4. Insolation Map of Europe. The total solar radiation in kilojoules on one square meter area in Europe. Note that the definition of insolation in this graph is different from the previous ones: it is the total solar radiation energy received on a surface of one square meter over a year. Clearly, the total insolation in a calendar year equals 365.25 times the average daily insolation. As shown, the Southern parts of Portugal, Spain and Italy have the highest insolation in Europe. The insolation in Germany is much weaker than those areas. The Northern parts of Norway and Finland have rather weak insolation.

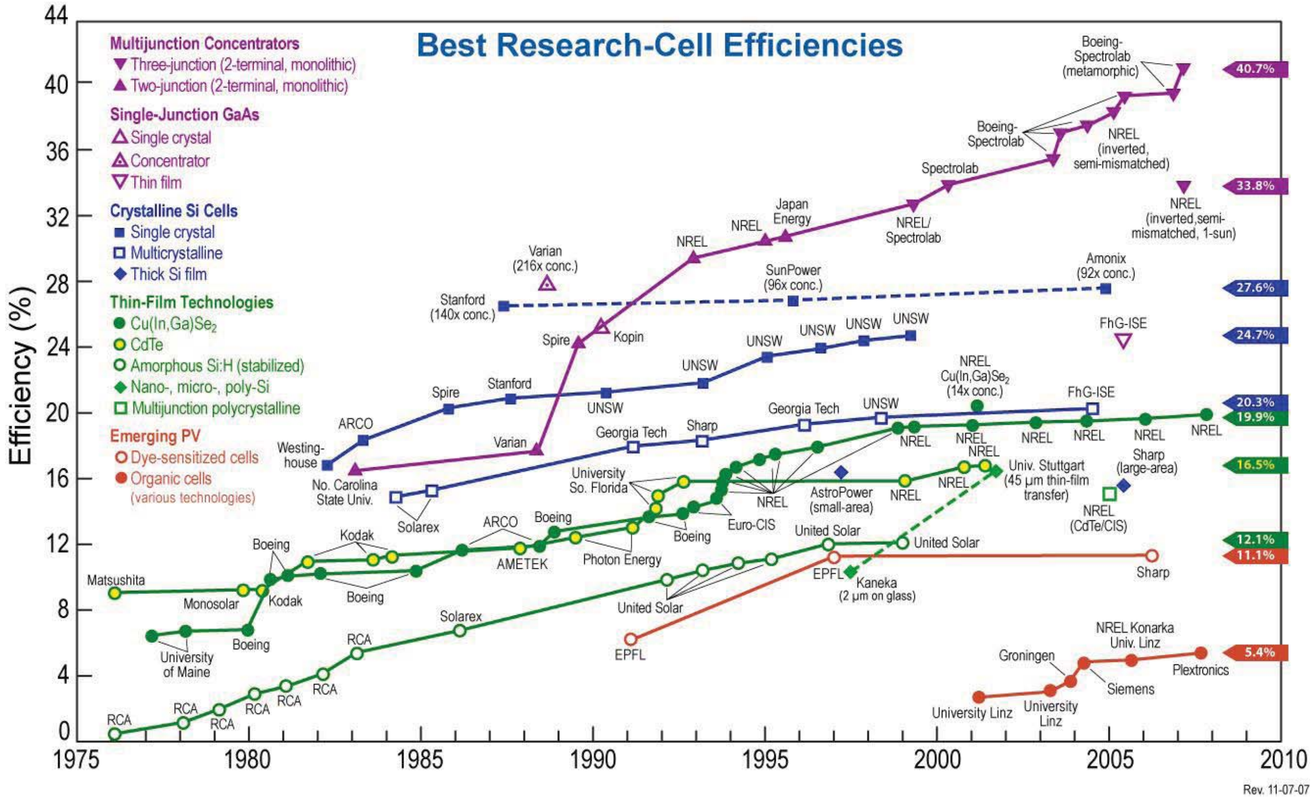

Plate 5. Best Research-Cell Efficiencies. Source: National Renewable Energy Laboratory, 11-07-2007.

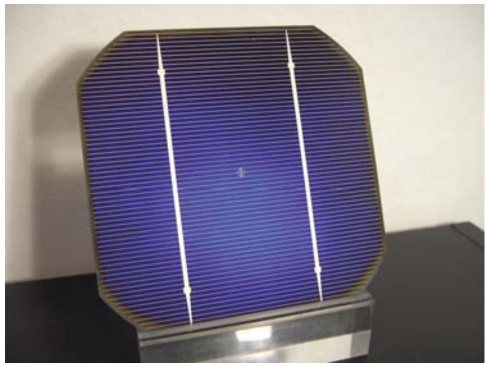

Plate 6. Monocrystalline silicon solar cell. The typical mono-crystalline silicon cell is cut from a cylindrical single crystal of silicon. After a *pn* junction is formed by a diffusion process, a net of interconnections, usually made of silver, is formed by screen printing process.

Plate 7. Crystalline silicon solar cells with single-axis tracking. The Nellis Solar Power Plant, located within Nellis Air Force Base in Clark County, Nevada. It generates in excess of 25 million kilowatt-hours (kWh) of electricity annually and supply more than 25 percent of the power used at the base. It occupying 0.57 km^2 of land. This ground-mounted solar system employs an advanced sun tracking system, with a peak power generation capacity of approximately 14 MW. Photo courtesy of U.S. Airforce.

Plate 8. CdTe and CIGS thin-film solar cells. The thin film solar cells use much thinner semiconductor materials than crystalline solar cells, thus the cost per watt could be much lower. Although the efficiency is lower than crystalline solar cells, in areas with plenty of vacant land, the economic advantage becomes obvious. Top, a 5 MW solar power system implemented at Bullas, Spain, manufactured by First Solar using CdTe technology. Lower, a 750 KW CIGS solar panel system installed in Tucson, AZ, manufactured by Nanosolar.

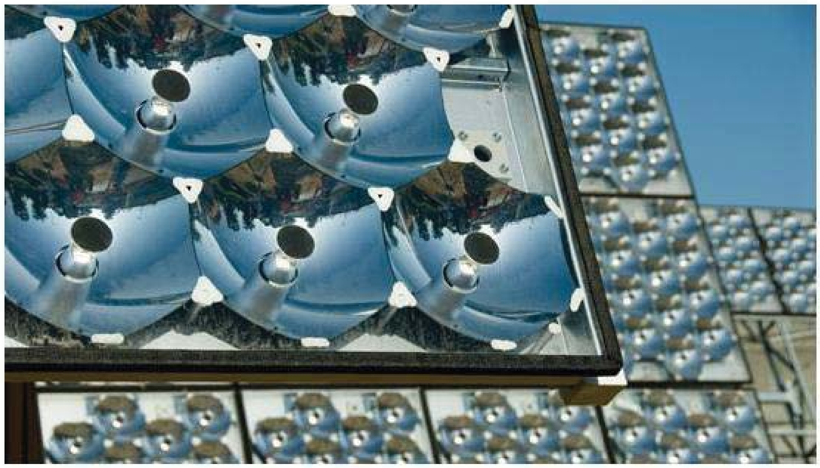

Plate 9. Concentration solar cells. Using optical systems to concentrate solar radiation and use high-efficiency multi-junction solar cells could reduce the cost of energy generation substantially. According to a report by National Renewable Energy Laboratory in September 2008 (NREL/TP-520-43208), using GaAs Multi-junction solar cells and dish concentrator, the projected cost for electricity generation could be the lowest among various technologies. The system shown was developed by Solfocus. The top photo shows the details of the dish concentrator, and the lower photo is a 500 kW system implemented at the site of Institute of Concentration Photovoltaic Systems (ISFOC) at Puertollano and Almoguera, Castilla La Mancha, Spain.

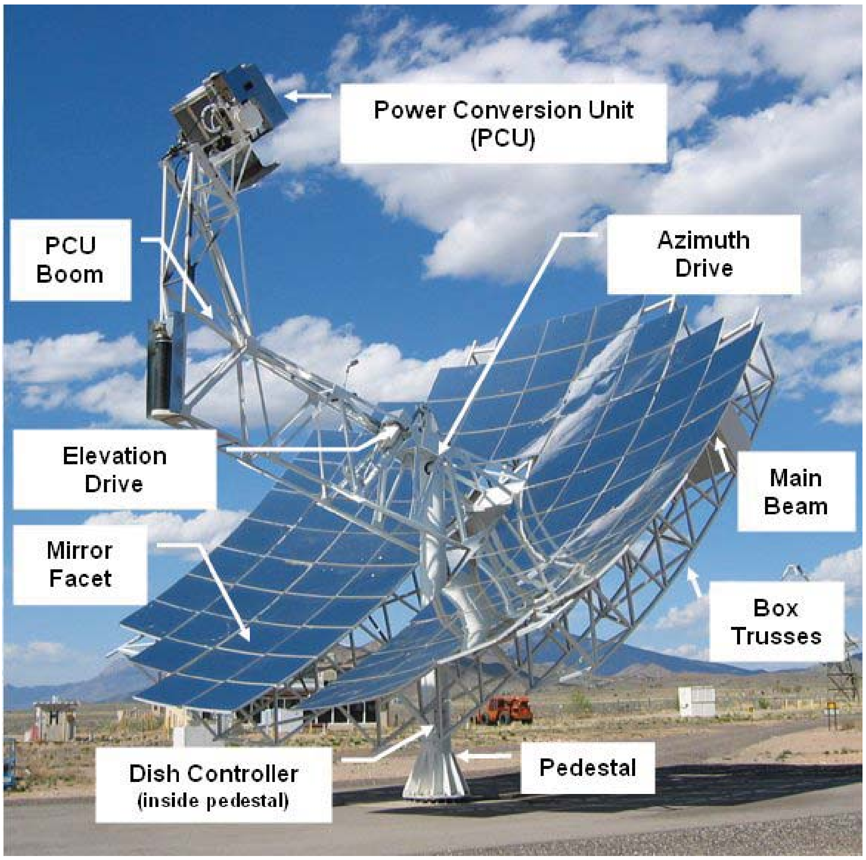

Plate 10. Solar dish Stirling energy system. The Stirling solar energy system developed by Sandia National Laboratories and Stirling Energy Systems (SES) in February 2008 has set a record of the highest solar-to-grid conversion efficiency of 31.25%. The solar dish generates electricity by focusing the radiation from the Sun to a receiver, which transmits the heat energy to a Stirling engine filled with hydrogen. The Stirling engine works best in a cold but sunny weather.

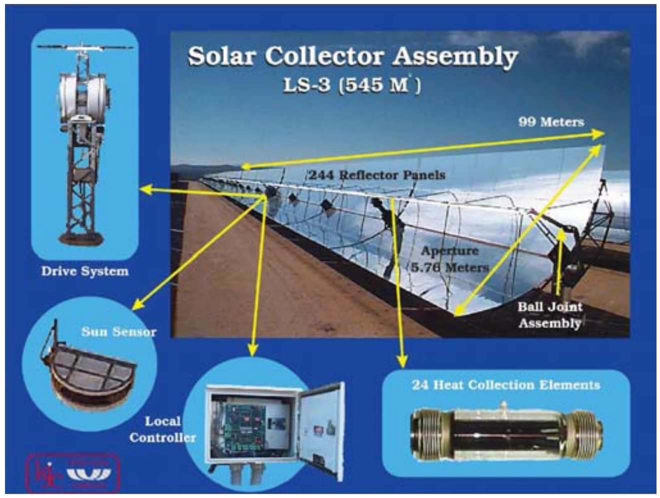

Plate 11. Solar collector assembly of a trough system. The axis of the parabolic troughs are aligned South-North. A tracking mechanism turns the troughs every day from East to West. The solar radiation is focused on the vacuum-tube heat collectors. The collectors heat synthetic oil to 400°C, then generates superheated steam to drive steam turbines. The highest efficiency on record was 20%.

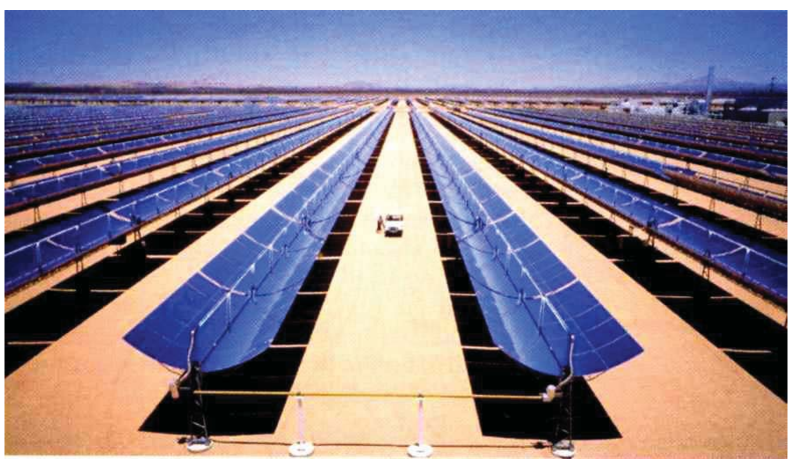

Plate 12. Parabolic trough concentrators at Kramer Junction, CA. The system, called the Solar Electricity Generating System (SEGS) installed at Kramer Junction in Mojave desert, California, starting from 1984. The SEGS system is the largest solar electricity generator set on the world. The total capacity is 354 MW.

Plate 13. Various types of vacuum-tube solar heat collectors. Currently, vacuum-tube solar heat collectors are the most used solar heat collectors. It uses selective coating to achieve maximum absorption of solar radiation, and minimum loss of heat by radiation. The vacuum between the outer tube and the heated element makes an almost perfect thermal insulation. Depending on ways of transferring heat, there are several types: The direct flow vacuum-tube heat collector allows water to flow by convection into the tubes. The heat siphon collector uses an ingenious phase change mechanism to transfer heat with very high efficiency and prevents heat to flow back to the tube (the thermal diode effect). Photo taken by the Author, courtesy of Beijing Solar Energy Research Institute.

Plate 14. Fully automatic facility for manufacturing of evacuated tubes. Top, the automatic evacuating machine. Bottom, the automatic conveying line. That facility alone produces 20 millions of evacuated tubes each year, with rated power more than that of Europe and U.S. combined. Courtesy of Himin Solar Energy Group, Dezhou, China.

Plate 15. Day-and-Night solar water heaters manufactured and installed in 1920s in Maimi. The Day-and-Night solar water heaters could be very durable. After approximately 80 years of operation in violent weather conditions in south Florida, thousands of such solar water heaters are still working properly today. The secret is its simplicity and complete absence of moving parts. Photos taken by the Author in August 2010, Maimi.

Plate 16. A 75,000 square meter solar building. As the venue of the 2010 International Solar City Congress, Himin Solar Energy Group designed and built a 75,000 square meter (800,000 sq. ft.) building in D'ezhōu, Shāndōng province, China, with more than 60% of energy supplied by solar devices.

Plate 17. An experimental solar house. As Steven Chu repeatedly advocated, using better building design to take advantage of solar energy, with a small incremental investment, tremendous energy savings can be achieved. Shown here is an experimental single family house designed by the Author. It is basically a medium-size central-hall colonial house very common in the United States. Nevertheless, the layout, roof design and windows placement are optimized for solar energy utilization. In a sunny Winter day, the sunlight through the large South-faced windows warm up all the often-occupied rooms such that the thermostat for gas heating is always turned off. In the Summer, the solar panels on the roof drive two central air conditioning systems to keep the entire house cool. A solar-powered attic fan (on the top of the roof, not shown here) further reduces the cooling load. The walls are well insulated and all windows are double-pane, air tight and filled with argon. Photo taken by the Author.

Plate 18: The Deepwater Horizon Explosion. As land-based oil fields in the U.S. are being essentially depleted, petroleum exploration is moving to offshore, to deeper and deeper sea. The cost of drilling is being increased dramatically, and the environment cost becomes even graver. One example of the engineering cost and the environmental cost is the recent Gulf of Mexico oil spill. On April 20, 2010, the Deepwater Horizon drilling rig, situated about 40 miles (60 km) southeast of the Louisiana coast in the Macondo Prospect oil field, exploded. It killed 11 workers and injured 17 others. It caused the Deepwater Horizon to burn and sink. An estimated 4.9 million barrels (780,000 cubic meters) of crude oil were released into the water of the Gulf of Mexico. It is now considered as the largest environmental disaster in U.S. history. The oil spill severely damaged the environment of the Gulf of Mexico, and significantly affected the fishing and tourism businesses of the Gulf states. It costs BP more than $32 billion for the clean-up. To ensure the safety of deep sea petroleum exploration, the engineering cost will become extremely high. The event vividly demonstrated the urgency to go beyond petroleum. Photograph courtesy of U.S. Coast Guard.

Chapter 1
Introduction

1.1 Solar energy

According to the well-established measurements, the average power density of solar radiation just outside of the atmosphere of the Earth is 1366 watt per square meter, widely known as the *solar constant*. About 30% of the solar radiation is reflected to the space. About 20% of the solar radiation is absorbed by clouds and molecules in the air, see Chapter 5. The average radiation power that reaches the surface of the Earth is about 50% of the solar constant, 683 watt per square meter. The definition of the meter is one over 10,000,000 of Earth's meridian, from North Pole to the Equator, see Fig. 7.3. This definition is still pretty accurate according to modern measurements. Therefore, the radius of Earth is $(2/\pi) \times 10^7$ m. The total power of solar radiation on the surface of Earth is then

$$\text{Solar power} = 683 \times \frac{4}{\pi} \times 10^{14} \cong 8.67 \times 10^{16}\ \text{W}. \tag{1.1}$$

Each day has 76800 seconds, and each year has 365.2422 days. The total energy of solar radiation reached the surface of Earth per year is

$$\text{Annual solar energy} = 8.67 \times 10^{16} \times 86400 \times 365.2422 \cong 2.73 \times 10^{24}\ \text{J}. \tag{1.2}$$

It is 2,730,000 EJ per year. To have an idea of how much that energy is, let us compare it with the global energy consumption, see Fig. 1.2. In years

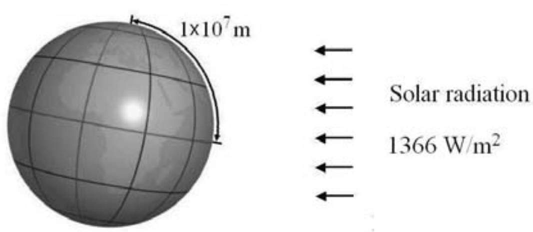

Fig. 1.1. Annual solar energy arriving at the surface of Earth. The average solar power on the Earth is 1 kilowatt per square meter. The length of the meridian of Earth, according to the definition of a meter, is 10,000,000 meters. The total solar energy arrive at the surface of Earth per year is 2,730,000 EJ.

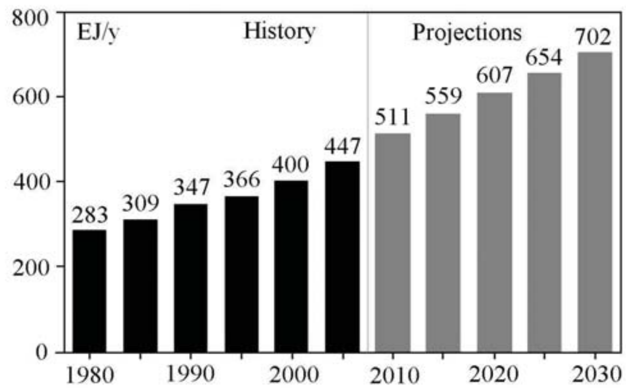

Fig. 1.2. World Marketed Energy Consumption, 1980-2030. Source of information: Energy Information Administration (EIA), the official Energy statistics from the US government. History: *International Energy Annual 2004* (May-July 2006), website www.eia.doe.gov/iea. Projections: EIA, *International Information Outlook 2007*.

2005 to 2010, the annual energy consumption of the entire world is about 500 EJ. A mere 0.02% of the annual solar energy received by the Earth can satisfy the energy need of the entire world.

It is also interesting to compare the annual solar energy arrived at the surface of Earth with the proved total reserve of various types of fossil fuels, see Table 1.1. The numbers show that the total proved reserves of fossil energy is approximately 1.4 percent of the solar energy arrived at the surface of Earth each year. Fossil fuels are solar energy stored as concentrated biomass over many millions of years. Actually, only a pitifully small percentage of the solar energy was able to be preserved for mankind to explore. The current annual consumption of fossil fuel energy is approximately 300 EJ. If the current level of consumption of fossil energy continues, the entire fossil energy reserve will be depleted in about 100 years.

Table 1.1: Proved resources of various fossil fuels. Source: *BP Statistical Review of World Energy*, June 2007, British Petroleum.

Item	Quantity	Unit Energy	Energy content
Crude oil	1.65×10^{11} tons	4.2×10^{10} J/ton	6,930 EJ
Natural gas	1.81×10^{14} m^3	3.6×10^7 J/m^3	6,500 EJ
High-quality coal	4.9×10^{11} tons	3.1×10^{10} J/ton	15,000 EJ
Low-quality coal	4.3×10^{11} tons	1.9×10^{10} J/ton	8,200 EJ
Total			36,600 EJ

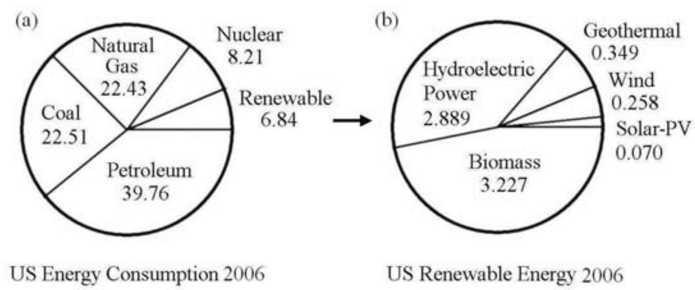

Fig. 1.3. Energy Consumption in the US 2006. Source of information: *Annual Energy Review 2006*, Energy Information Administration (EIA). The unit of energy in the Original report is quad, approximately 10^{18}J, or EJ, See Appendix A. In 2006, the total energy consumption in the US is 99.87 quad, almost exactly 100 EJ. Therefore, the value of energy in EJ is almost exactly its percentage. Solar photovoltaic energy (PV), only accounts for 0.07% of the total energy consumption in 2006.

Currently, the utilization of renewable energy is still a small percentage of total energy consumption, see Table 1.2. Figure 1.3 shows the percentage of different types of energy in the US in 2006. The utilization of solar energy through photovoltaic technology (PV) only accounts for 0.07% of the total energy consumption. However, globally, solar photovoltaic energy is the fastest growing energy resource. As we will analyze in Section 1.5.4, solar photovoltaics will sonner or later become the dominant source of energy. Figure 1.4 is a prediction published by the German Solar Industry Association in 2007.

The inevitability that fossil fuel would eventually be replaced by solar energy is simply a geological fact: the total recoverable reserve of crude oil is finite. For example, the United States used be the largest oil producer on the world. In 1971, about one half of the recoverable crude oil reserve in continental US (the lower 48 states) was depleted. Since then, the crude

Table 1.2: Renewable energy resources.

Type	Resource EJ/year	Implemented EJ/year	Percentage explored
Solar	2,730,000	0.31	0.0012%
Wind	2,500	4.0	0.16%
Geothermal	1,000	1.2	0.10%
Hydro	52	9.3	18%

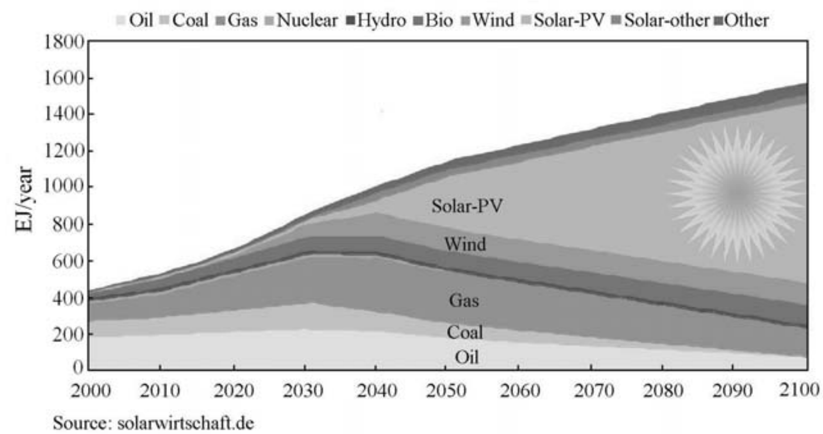

Fig. 1.4. Trend of Energy Industry in the 21st Century. Source of information: German Solar Industry Association. In 2007, Germany took over Japan as the leading provider of solar cells, and utilizes the largest percentage of solar energy worldwide. According to the predictions, solar photovoltaic energy (PV) will sooner or later become the dominating source of energy.

oil production in continental US started to decline. Crude oil from more difficult geological and environmental conditions must be explored. Not only the cost of oil drilling is increased, the energy consumed for generating the crude oil is also increased. To evaluate the merit of an energy production process, a number, the *energy return on energy invested*, EROI, also called *energy balance*, is often used. The definition is

$$\text{EROI} = \frac{\text{energy return}}{\text{energy invested}} = \frac{\text{energy in a volume of fuel}}{\text{energy required to produce it}}. \tag{1.3}$$

In 1930's, the EROI for produce crude oil was around 100. In 1970, it was 25. For deep sea oil drilling, it could be less than 10. Shale oil, shale gas and tar sands also have low values of EROI. If the EROI of an energy production process is decreased to nearly 1, there is no value to pursue. The 2010 Deepwater Horizon oil spill once again indicates the engineering cost and environment cost of oil exploration.

On the other hand, although currently, the cost of solar electricity is higher than that from fossil fuels, the technology of solar energy exploration is constantly being improved, and the cost is constantly being reduced. The current value of EROI for photovoltaics is 5-10, in line with the value for petroleum produciton in the US. But it is constantly being improved. Eventually, electricity produced by solar photovoltaics will be more economical than that from fossil fuel.

1.2 Go beyond petroleum

Fossil energy resources, especially petroleum, are finite, and depletion will happen sooner or later. The transition to renewable energy is inevitable. This fact was first recognized and quantified by a highly regarded expert in petroleum industry, Marion King Hubbert (1903-1989). He is not alone in oil industry. In 2000, recognizing the eventual depletion of petroleum, former British Petroleum changed its name to "bp beyond petroleum".

In 1956, M. King Hubbert, as a Chief Consultant of Shell Development Company, presented a widely cited report based on the data available at that time, and predicted that the crude oil production in the US will peak around 1970, then started to decline. His bold and original predictions were scoffed at that time, but has since proved to be remarkably accurate and then overwhelmingly recognized.[1]

His theory started with a discovery that the data plotted with the cumulative production of crude oil at a time Q as x and the ratio of production rate P over Q as y in the United States follows a straight line, see Fig. 1.5. (The data after 1956 follows a linear relation even better.)

The meanings of two intersections of the straight line with the coordinate axes are as follows. The intersection with the x-axis, Q_0, is the total recoverable crude oil reserve. The value found from Fig. 1.5 is $Q_0 = 228$ billion barrels. The intersection with the y-axis, a, has a dimension of inversed time. The inverse of a is a measure of the duration of crude oil depletion, see below. The value in Fig. 1.5 is $a = 0.0536$/year. The straight line can be represented by the equation

$$\frac{P}{Q} = a\left(1 - \frac{Q}{Q_0}\right). \tag{1.4}$$

By definition, the relation between P and Q is

$$P = \frac{dQ}{dt}, \tag{1.5}$$

where t is time, usually expressed in years. Using Eq. 1.5, Eq. 1.4 becomes an ordinary differential equation

$$\frac{Q_0\,dQ}{Q(Q_0 - Q)} = a\,dt. \tag{1.6}$$

Equation 1.6 can be easily integrated to

$$\int \frac{Q_0\,dQ}{Q(Q_0 - Q)} = -\ln\left(\frac{Q_0}{Q} - 1\right) = a(t - t_{\rm m}), \tag{1.7}$$

[1]The mathematics of Hubbert's theory is similar to the equations created by Pierre François Verhurst in 1838 to quantify Malthus's theory on population growth.[1]

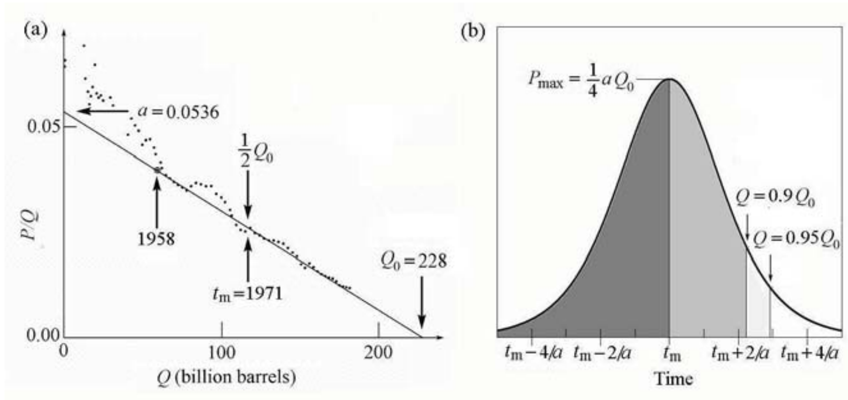

Fig. 1.5. Hubbert's curve. (a) In 1956, Merion King Hubbert of Shell Oil studied the data of the cummulative produciton of crude oil Q and the rate of production P in the US. He discovered a linear dependence between P/Q and Q. After Deffeyes (2005). (b) A curve of Q versus time can be derived from the linear relation, the Hubbert's curve, Eq. 1.9. The peak of production occurs at the time t_m when one half of the crude oil is depleted. At time $t_m + 2.197/a$, 90% of the recoverable crude oil is depleted. At time $t_m + 2.944/a$, 95% of the recoverable crude oil is depleted.

where t_m is a constent of integration to be determined. From Eq. 1.7,

$$Q = \frac{Q_0}{1 + e^{-a(t-t_m)}}. \tag{1.8}$$

The initial and final conditions, $Q = 0$ at $t = -\infty$ and $Q = Q_0$ at $t = +\infty$, are satisfied. The time one half of the crude oil is depleted, $Q = Q_0/2$ at $t = t_\text{m}$, can be determined from the historical data.

The rate of production P can be obtained using Eqs. 1.5 and 1.8,

$$P = \frac{dQ}{dt} = \frac{1}{4}aQ_0 \,\text{sech}^2 \frac{a(t - t_\text{m})}{2} . \tag{1.9}$$

Equation 1.9 represents a bell-shaped curve[2] symmetric with respect to t at $t = t_\text{m}$, see Fig. 1.5(b). Therefore, $t = t_\text{m}$ is also the time (year) of maximum production rate, $P_0 = aQ_0/4$. The quantity a is a measure of the speed of oil field depletion. Actually, the time when 90% of crude oil is depleted can be determined by Eq. 1.8,

$$\frac{Q_0}{1 + e^{-a(t_{0.9} - t_\text{m})}} = 0.9\, Q_0, \tag{1.10}$$

which yields $t_{0.9} = t_\text{m} + 2.197/a$. By defining the depletion time as the time when 95% of crude oil is depleted, then $t_{0.95} = t_\text{m} + 2.944/a$.

[2]By definition, $\text{sech}\, x = 1/\cosh x = 2/(e^x + e^{-x})$.

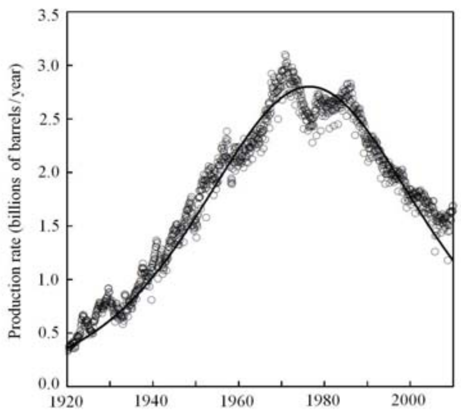

Fig. 1.6. Rate of production of crude oil in the US. Circles: actual production rate of crude oil on the US. Source of data: EIA (The United States Energy Information Administration). Solid curve: the Hubbert function, using a least squares fit to the actual data. The sudden increase of production at 1977 and the second peak at 1989 are due to the starting of oil production in Alaska, see Fig. 1.7.

Figure 1.6 shows the crude oil production rate in the United States from 1920 to 2010. The solid curve is a least-squares fitting with a Hubbert curve, Eq. 1.9. A peak was reached in 1971, represents the crude oil production of the lower 48 states (excluding Alaska and Hawaii). There is another peak at around 1989. Actually, in 1977, the US congress passed a law to start drilling for crude oil in Alaska. Because Alaska did not produce any crude oil before the 1970's, according to the theory of Hubbert, it should be treated as a stand-alone case independent of the lower 48 states. By plotting the data of crude oil production in Alaska published by EIA, except the earlier years, the ratio P/Q shows a rather accurate linear dependence on the accumulative production Q, see Fig. 1.7. From the plot one finds $Q_0 = 17.3$ billion barrels, $a = 0.1646$, and $t_m = 1989.38$, approximately May 1989. Using those parameters, a Hubbert curve is constructed, see Fig 1.7(b). As shown, except in the early years, the production data follows the Hubbert curve rather accurately.

The date of depletion can be estimated from the parameters. For the entire United States, $a = 0.0536$. The date of 95% depletion is

$$t_{0.95} = 1971 + \frac{2.944}{0.0536} \approx 2026. \tag{1.11}$$

For Alaska, the date of 95% depletion is

$$t_{0.95} = 1989 + \frac{2.944}{0.1646} \approx 2007. \tag{1.12}$$

The depletion date of Alaska crude oil is sooner than the depletion date for the entire United States. Actually, although the crude oil in Alaska was

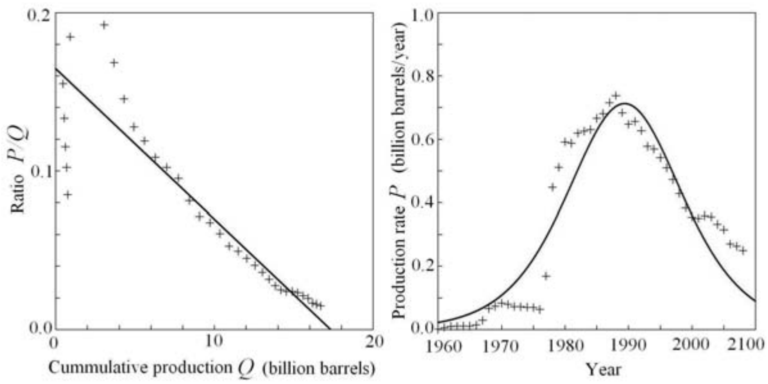

Fig. 1.7. Production of crude oil in Alaska. (a) The ratio of P/Q versus Q for Alaska. Source of data: EIA. Except the earlier years, the ratio shows a rather accurate linear dependence on Q. From the plot one finds $Q_0 = 17.3$ billion barrels, $a = 0.1646$, and $t_m = 1989.38$. (b) A Hubbert curve is constructed. As shown, except in the early years, the production data follows the Hubbert curve rather accurately.

started to produce much later then the lower 48 states, it is extracted much more aggressively than other states in the United States.

Because the starting years are different for different countries, for the entire world, a better way of applying the Hubbert theory is to do every country individually. Hubbert made an estimate based on the data available in the 1950's for the entire world, and predicted a peak of crude oil production in the 2000s. Estimates based on more recent data came up with similar results. Recent data shows that this peak actually already occurred. The process of discovery and depletion of other non-renewable energy resources, such as natural gas and coal, follow a similar pattern. As resources are dwindling, the engineering and environment cost of fossil fuel exploration in increasing rapidly. The Deepwater Horizon oil spill makes again a wakeup call that in the twenty-first century, the human society must find and utilize renewable energy resources to gradually replace fossil energy resources.

1.3 Other renewable energy resources

Because of the limited reserve of fossil fuel and the cost, from the beginning of the industrial age, renewable energy resources have been explored. Although solar energy is by far the largest resource of renewable energy, other renewable energy resources, including hydropower, wind power, shallow and deep geothermal energy, have been extensively utilized. Most of those are derived from solar energy except deep geothermal energy.

1.3.1 Hydroelectric power

Hydroelectric power is a well-established technology. Since late 19th century, it has been producing substantial amount of energy reliably at competitive prices. Currently, it produces about one sixth of world's electric output, which is over 90% of all renewable energy. As shown in Fig. 1.8, for many countries, hydropower accounts for a large percentage of total electricity. For example, Norway generates more than 98% of all her electricity from hydropower; whereas in Brazil, Iceland and Colombia, more than 80% of electricity is generated by hydropower. Table 1.3 lists the utilization of hydropower in various regions on the world.

The physics of hydropower is straightforward. A hydropower system is characterized by the *effective head*, the height H of the water fall, in meters; and the *flow rate*, the rate of water flowing through the turbine Q, in cubic meters per second. The power carried by the water mass is

$$P(\mathrm{kW}) = g \times Q \times H, \tag{1.13}$$

where g is the gravitational acceleration, 9.81 $\mathrm{m/s^2}$. Because an 2% error is insignificant, in the engineering community, it always takes $g \approx 10\,\mathrm{m/s^2}$. Thus, in terms of kilowatts, the hydropower is

$$P(\mathrm{kW}) = 10 \times Q \times H. \tag{1.14}$$

The standard equipment is the Francis turbine invented by American engineer James B. Francis in 1848. With that machine, the efficiency η of converting water power to mechanical power is very high. Under optimum conditions, the overall efficiency of converting water power into electricity

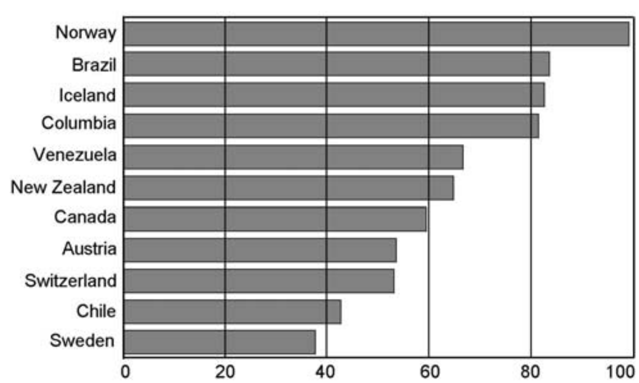

Fig. 1.8. Percentage of hydropower in various countries. The percentage of hydropower in total electricity generation in various countries. Norway generates virtually all her electricity from hydropower; whereas in Brazil, Iceland and Colombia, more than 80% of electricity is generated by hydropower. .

Table 1.3: Regional hydro potential and output.

Region	Output EJ/year	Resource EJ/year	Percentage explored
Europe	2.62	9.74	27%
N. America	2.39	6.02	40%
Asia	2.06	18.35	11%
Africa	0.29	6.80	4.2%
S. America	1.83	10.05	18%
Oceania	0.14	0.84	17%
World	9.33	51.76	18%

is greater than 90%, makes it one of the most efficient machines ever. The electric power generated by the hydroelectric system is

$$P(\text{kW}) = 10\,\eta\,QH. \tag{1.15}$$

One significant advantage over other renewable energy resources is that hydropower provides an energy storage mechanism of very high round-trip efficiency. The energy loss in the storage process is negligible. Figure 1.9 is a photo of one of the world's largest hydropower station, the Itaipu hydropower station, which supplies about 20% of Brazil's electricity.

Fig. 1.9. Itaipu hydropower station at the border of Brazil and Paraguay. With capacity of 14.0 GW, the Itaipu hydropower station is one of the world's largest, which generates about 20% of Brazil's electricity.

1.3.2 Wind power

The kinetic energy in a volume of air with mass m and velocity v is

$$\text{kinetic energy} = \frac{1}{2}mv^2. \tag{1.16}$$

If the density of air is ρ, the mass of air passing through a surface of area A perpendicular to the velocity of wind per unit time is

$$m = \rho\, vA. \tag{1.17}$$

The wind power P_0, or the kinetic energy of air moving through an area A per unit time is then

$$P_0 = \rho\, vA \times \frac{1}{2}v^2 = \frac{1}{2}\rho\, v^3 A. \tag{1.18}$$

Under standard conditions (1 atmosphere pressure and 18° C), the density of air is 1.225 kg/m^3. If the wind speed is 10 m/s, the wind power density P_0 is

$$P_0 \approx 610 \text{ W/m}^2. \tag{1.19}$$

It is of the same order of magnitude as the solar power density.

However, the efficiency of wind turbine is not as high as hydropower. Because the air velocity before the rotor v_1 and the air velocity after the rotor v_2 are different, the air mass flowing through area A per unit time is determined by the *average wind speed* at the rotor,

$$m = \rho A\, \frac{v_1 + v_2}{2}. \tag{1.20}$$

Thus, the kinetic energy picked up by the rotor is

$$\text{kinetic energy difference} = \frac{1}{2}mv_1^2 - \frac{1}{2}mv_2^2. \tag{1.21}$$

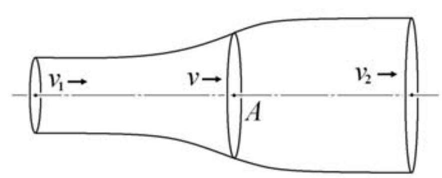

Fig. 1.10. Derivation of the Betz theorem of wind turbine. The wind velocity before the turbine rotor is v_1, and the wind velocity after the turbine rotor is v_2. The velocity at the rotor is the average velocity, and the power generated by the rotor is related to the difference in kinetic energy.

Combining Eqs. 1.20 and 1.21, we obtain an expression of the wind power P picked up by the rotor

$$P = \frac{1}{4}\rho A(v_1 + v_2)\left[v_1^2 - v_2^2\right]. \tag{1.22}$$

By rearranging Eq. 1.22, we can define the fraction C of wind power picked up by the rotor, or the *rotor efficiency*

$$P = \frac{1}{2}\rho v_1^3 A \left[\frac{1}{2}\left(1 + \frac{v_2}{v_1}\right)\left(1 - \frac{v_2^2}{v_1^2}\right)\right] = P_0\, C. \tag{1.23}$$

Hence,

$$C = \frac{1}{2}\left(1 + \frac{v_2}{v_1}\right)\left(1 - \frac{v_2^2}{v_1^2}\right). \tag{1.24}$$

Let $x = v_2/v_1$ be the ratio of the wind speed after the rotor and the wind speed before the rotor, we have

$$C = \frac{1}{2}\left(1 + x\right)\left(1 - x^2\right). \tag{1.25}$$

The dependence of rotor efficiency C with speed ratio x is shown in Fig. 1.11. It is straightforward to show that the maximum occurs at $x = 1/3$ where $c = 16/27 = 59.3\%$. This result was first derived by Albert Betz in 1919, and widely known as the Betz's theorem or the Betz limit.

The estimate for the worldwide available wind power varies. A conservative estimate shows that the total available wind power, 75 TW, is more than 5 times the world's total energy consumption. In contrast to hydropower, currently, only a very small fraction of wind power has been

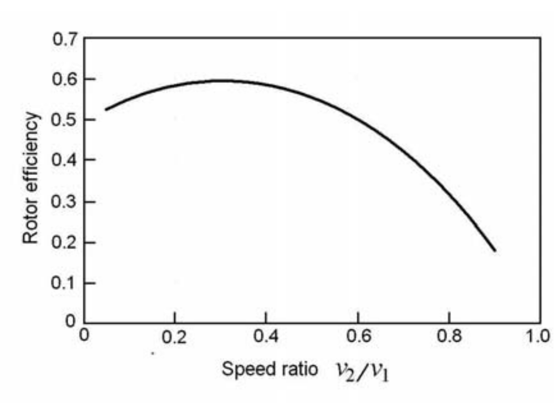

Fig. 1.11. Efficiency of wind turbine. The efficiency of wind turbine as a function of the ratio of wind speed after the rotor and the wind speed before the rotor. As shown the maximum efficiency is 16/27, which occurs at a ratio of 1/3.

Fig. 1.12. Wind turbines in Copenhagen. A photo taken by the Author in Copenhagen, Denmark, 2006. The statue of the little mermaid, a national symbol of Denmark, is starring at a dense array of wind turbines rather than the Prince.

utilized. However, it is growing very fast. From 2000 to 2009, the total capacity grew nine fold to 158.5 GW. Global Wind Energy Council expects that in 2014, the total wind power capacity would become 409 GW.

Because of a shortage of conventional energy resources, Denmark has developed wind power industry since late 19th century, and vigorously after the 1970 energy crisis. Up to recently, Denmark is still the largest manufacturer of wind turbines, led by Vestas Cooperation, and it has about 20% of wind power in its electricity blend. Figure 1.12 is a photo the Author took in Copenhagen. The little mermaid is starring at a dense array of wind turbine instead of the Prince.

However, Denmark's success in wind energy cannot be achieved without her neighbors: Norway, Sweden, and Germany.[2] Because wind power is intermittent and irregular, a stable supply of electricity must be accomplished with a fast-responding power generation system with energy storage. Fortunately, almost 100% of electricity in Norway is generated by hydropower, and the grids of the two countries share a 1000 MW interconnection. In periods of heavy wind, the excess power generated in Denmark is fed into the grid in Norway. By using the reversible turbine, the surplus electrical energy is stored as potential energy of water in the reservoirs. In 2005, the Author visited the Tonstad Hydropower Station in Norway in a Sunday afternoon. By curiosity, I asked a Norwegian engineer why the largest turbine was sitting idle. He explained that one of the missions of that power station is to supply power to Denmark. On Monday morning, when the Danes brew their coffee and start to work, that turbine would run full speed.

1.3.3 Biomass and bioenergy

Over the many thousands of years of human history, until the industrial revolution started the use of fossil fuels, the direct use of biomass was the main source of energy. Wood, straw, and animal wastes are used for space heating and cooking. Candle (made of whale fat) and vegitable oil are used for light. The mechanical power of horse is powered by feeding biomass. In less-developed countries on the world, this situation remains to be the norm. Even in well-developed countries, direct use of biomass is still very common: for example, firewood for fireplaces and wood-burning stoves.

Biomass is created by photosynthesis from sunlight. For details, see Section 10.1. Although the efficiency of photosynthesis is only about 5%, and the land coverage by leaves is only a few percent, the total energy currently stored in the terrestrial biomass is estimated to be 25,000 EJ, almost equals the energy content of known fossil fuel of the world, see Table 1.1. The energy content of annual production of land biomass is about 6 times the total energy consumption of the world, see Table 1.4.

The current interest in biomass is the generation of liquid fuels for transportation. Two approaches are widely used: to produce alcohol from sugar, and to produce biodiesel from vegetable oil or animal oil.

Alcohol from sugar fermentation

The art of producing wine and liquor from sugar by fermentation has been known for thousands of years. Under the action of the enzymes in certain yeast, sugar is converted into ethyl alcohol and CO_2:

$$C_6H_{12}O_6 \longrightarrow 2(C_2H_5OH) + 2(CO_2). \tag{1.26}$$

At the end of reaction, the concentration of alcohol could reach 10% to 15%, in the mixture, and using specially cultured yeast, up to 21%. The alcohol is then extracted by distillation.

One of the most successful example is the production of alcohol from sugar cane in Brazil. An important number of merit in energy industry is *energy balance*, or EROI, the ration of energy returned over the energy

Table 1.4: Basic data of bioenergy. *Renewable Energy, Second Edition*, edited by G. Boyle, Oxford University Press 2004, page 107.

Item	in EJ/year	in TW
Rate of energy storage by land biomass	3000 EJ/year	95 TW
Total worldwide energy consumption	500 EJ/year	15 TW
Worldwide biomass consumption	56 EJ/year	1.6 TW
Worldwide food mass consumption	16 EJ/year	0.5 TW

Fig. 1.13. The Costa Pinto Production Plant of sugar alcohol. The foreground shows the receiving operation of the sugarcane harvest, and in the right side of the background is the distillation facility where ethanol is produced. This plant produces the electricity it needs from baggasse left over by the milling process, and it sells the surplus electricity to public utilities. Courtesy of Mariordo.

invested, see Eq. 1.3. According to various studies, the energy balance in Brazil for sugar alcohol is over 8, which means that in order to produce one joule of alcohol energy, about 0.125 joule of input energy is required. Also, the cost of produce one gallon of alcohol in Brazil is about \$0.83, much lower than the cost of a gallon of gasoline. This is at least partially due to the climate and topography of São Paulo, the south-east state of Brazil, a flat subtropical region with plenty of rainfall and sunshine. Because the growth of sugar cane absorbs carbon dioxide, the net emission of CO_2 is almost zero. In Brazil, about one half of cars use pure alcohol. And Brazil is the world's primary exporter of fuel-grade alcohol. Figure 1.13 is a panoramic view of the Costa Pinto Production Plant for producing alcohol located in Piracicaba, São Paulo state. The foreground shows the receiving operation of the sugarcane harvest. In the right side of the background is the distillation facility where ethanol is produced. This plant produces all the electricity it needs from baggasse of sugar cane left over by the milling process, and it sells the surplus electricity to public utilities.

Although there is no direct government subsidy for the use of alcohol, there is a continuous government-supported research to improve the efficiency of production, and a progress of the mechanization of the process. It is an important factor for the success of the Brazilian sugar-alcohol project. From 1975 to 2003, the yield has grown from 2 m^3 to 6 m^3 per hectare. Recently, in the State of São Paulo, it has reached 9 m^3 per hectare. Figure 1.14 shows the evolution of annual production of fuel-grade alcohol in Brazil from 1975 to 2010. Although Brazil produces more than 50% of the

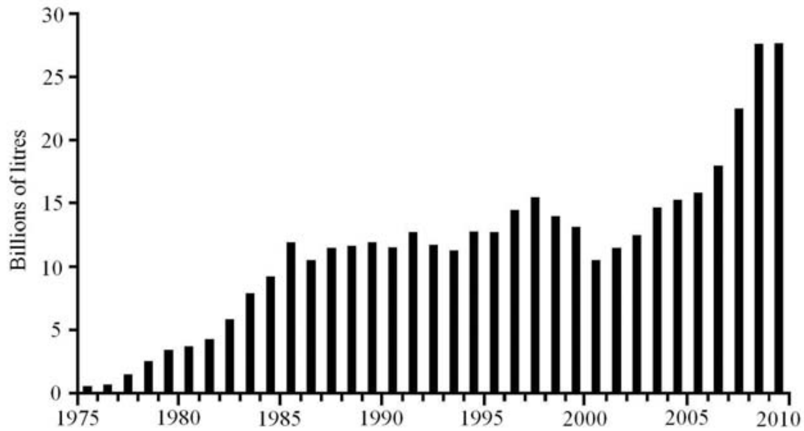

Fig. 1.14. Annual production of alcohol in Brazil. Source: *Anuário Estatístico da Agroenergia* 2009, Ministério da Agricultura, Pecuária e Abastecimento, Brazil.

fuels for domestic automobiles and about 30% of the world's traded alcohol, it only uses 1.5% of her arable land.

Biodiesel from vegetable oil or animal fat

Another example of using biomass for liquid fuel is the production of biodiesel from vegetable oil or animal fat. The basic chemical structures of vegetable oil and animal fat molecules are identical: it is a triglyceride formed from a single molecule of glycerol, and three molecules of fatty acid, see Fig. 1.15. A fatty acid is a carboxylic acid (characterized by a -COOH group) with a long unbranched carbonhydride chain. With different types of fatty acids, different types of triglycerides are formed. Although vegetable oil can be used in diesel engines directly, the large molecule size and the resulting high viscosity as well as the tendency of incomplete combustion could damage the engine. Commercial biodiesel is made from reacting triglyceride with alcohol, typically methanol or ethanol. Using sodium hydroxide or potassium hydroxide as catalyst, the triglyceride is transesterified to form three small esters and a free glycerin, see Fig. 1.15. The ester is immiscible with glycerin, and its specific gravity (typically 0.86 to 0.9 g/cm^3) is much lower than that of glycerin (1.15 g/cm^3). Therefore, the biodiesel can be easily separated from the mixture of glycerin and residuals.

The biodiesel thus produced has a much smaller molecule size than the triglycerides, which provides better lubrication to the engine parts. It was reported that the property of biodiesel is even better than the petroleum-derived diesel oil in terms of lubricating properties and cetane ratings, although the calorific value is about 9% lower. Another advantage of biodiesel is the absence of sulfur, an severe environmental hazard of petroleum-

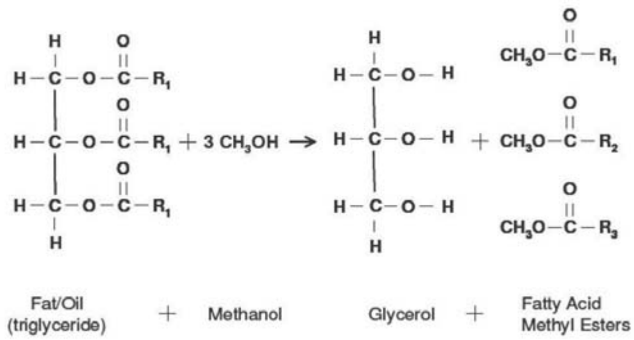

Fig. 1.15. The production process of biodiesel. By mixing triglyceride with alcohol, using a catalyst, the triglyceride is transesterified to form three esters and a free glycerin. The esters, or the biodiesel, has a much smaller molecule size, which provides better lubrication to the engine parts.

derived diesel oil.

The cost and productivity of biodiesel depends critically on the yield and cost of the feedstock. Recycled grease, for example the used oil for making French fries and the grease recovered from restaurant waste, is a primary source of the raw materials. Byproducts of food industry, such as lard and chicken fat, often considered unhealthy for humans, are also frequently used. However, the availability of those handy resources is limited. Virgin oil is thus the bulk of the feedstock of biodiesel. The yield and cost of virgin oil vary considerably from crop to crop, see Table 1.5.

In Table 1.5, several crops for producing biofuels are listed, including those for producing alcohol. Two of them are sugar-rich roots (sugar beet and sweet sorghum). The harvesting of those roots are much more energy and labor intensive than sugarcane. Therefore, the energy balance (the ration of energy produced versus the energy required to produce it) is often around 2, much lower than the case of sugarcane, which is higher than 8. The energy balance of corn is also lower (around 2), because the first step

Table 1.5: Yield of biofuel from different crops.

For Alcohol	m^3/hectare	For Biodiesel	m^3/hectare
Sugar beet (France)	6.67	Palm oil	4.75
Sugarcane (Brazil)	6.19	Coconut	2.15
Sweet sorghum (India)	3.50	Rapeseed	0.95
Corn (U.S.)	3.31	Peanut	0.84

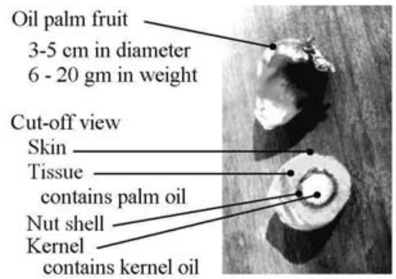

Fig. 1.16. Oil palm fruit. The size and structure of oil palm fruit are similar to a peach or a plum. However, the soft tissue of the fruit contains about 50% of palm oil. The yield of palm oil per unit plantation area is much higher than any other source of edible oil. The kernel is also rich in oil, but of a different type. The oil palm kernel oil is a critical ingredient of soap.

is to convert corn starch into sugar, which requires energy and labor. The oil that has the highest yield per unit area of land is palm oil, from the oil palm originally from Africa. A photograph of the oil palm fruit is shown in Fig. 1.16. The size of that fruit is typically 3 - 5 cm in diameter. The soft tissue of that fruit contains about 50% of palm oil. The kernel contains another type of oil, the palm kernel oil, a critical ingredient for soap. Under favorable conditions, the yield of palm oil could easily reach 5 tonnes per hectare per year, far outstrips any other source of edible oil. Because it contains no cholesterol, it is also a healthy food oil. Currently, palm oil is the number one vegetable oil on the world market (48 million tonnes, 30% world market share), where Malaysia and Indonesia are the largest producers. Unlike other types of oil-producing plants (such as soybean and rapeseeds) which are annual, oil palms are huge trees, see Fig. 1.17. Once planted, an oil palm can produce oil for several decades.

Fig. 1.17. Wild oil palms in Africa. Oil palms are native trees in Africa, which have supplied palm oil for centuries. Showing here is a photo of wild oil palms, taken by Marco Schmidt on the slopes of Mt. Cameroon, Cameroon, Africa.

1.3.4 Shallow geothermal energy

By definition, geothermal energy is the extraction of energy stored in the Earth. However, there are two distinct types of geothermal energy depending on its origin: the shallow geothermal energy, and the deep geothermal energy. Shallow geothermal energy is the solar energy stored in the Earth, the origin of which will be described in Section 5.4. The temperature is typically some 10 degrees centigrade off that of the surface. The major application of shallow geothermal energy is to enhance the efficiency of electrical heater and cooler (air conditioner) by using a vapor-compression heat pump. Deep geothermal energy is the heat stored in the core and the mantel of the Earth. The temperature could be hundreds of degree Celsius. It can be used for generating electricity and large-scale space heating. In this section, we will concentrate on shallow geothermal energy. Deep geothermal energy is presented in the following section.

The general behavior of underground temperature distribution is shown in Fig. 1.18. At a great depth, for example, at 20 to 30 meters underground, the temperature is the annual average temperature of the surface, for example, $\bar{T} = 10°\text{C}$. At the surface, the temperature varies over the seasons. In January, the temperature is the lowest, for example, $\bar{T} - \Delta T = 0°\text{C}$. In July, the temperature is the highest, for example, $\bar{T} + \Delta T = 20°\text{C}$. There are diurnal variations, but the penetration depth is very small. Because of the finite speed of heat conduction, at certain depth, typically -5 to -10 meters below the surface, the temperature profile is *inverted*. In other words, in the Summer, the temperature several meters underground is *lower* than the annual average; and in the Winter, the temperature several meters underground is *higher* than the annual average.

The solar energy stored in the Earth is universal and of very large quan-

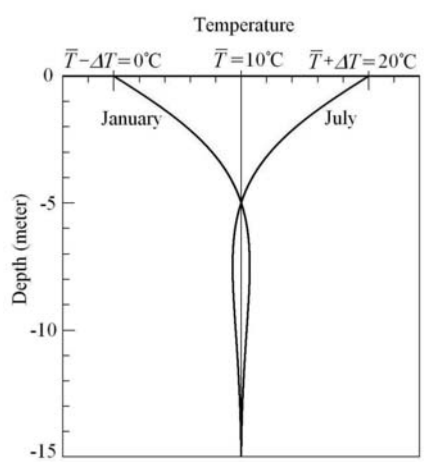

Fig. 1.18. Shallow geothermal energy. Seasonal variation of underground temperature. On the surface, the Summer temperature is much higher than the Winter temperature. Deeply underground, e.g., -50 meters, the temperature is the annual average temperature of the surface. in the Summer, the temperature several meters underground is *lower* than the annual average; and in the Winter, the temperature several meters underground is *higher* than the annual average. The energy stored in the Earth can be used for space heating and cooling, to make substantial energy savings.

tity. In much of the temperate zone, it can be used directly for space cooling. By placing heat exchange structures underground and guide the cool air through ducts to the living space, a virtually free air conditioning system can be built. In areas with average temperature close to or slightly below 0°C, underground caves can be used as refrigerators, also virtually free of energy cost.

The major application of the shallow geothermal energy is the space heating and cooling systems using a heat pump or a vapor-compression refrigerator, taking the underground mass as a heat reservoir. Details will be presented in Chapter 6.

1.3.5 Deep geothermal energy

The various types of renewable energies presented in the previous sections are derivations of solar energy. Deep geothermal energy, on the other hand, is the only major energy source not derived from solar energy. At the time the Earth was formed from hot gas, the original heat and the gravitational energy made the core of the Earth red hot. After the Earth is formed, the radioactive elements continuously supply energy to keep the core of the earth hot. Figure 1.19 is a schematic cross section of the Earth. The crest of the Earth, a relatively cold layer of rocks with a relatively low density (2 - 3 g/cm^3), is divided into several *tectonic plates*. The thickness varies from place to place, from 0 to some 30 km. Underneath the crest is the *mantle*, a relatively hot layer of partially molten rocks with relatively high density (3 - 5.5 g/cm^3). It is the reservoir of magna for volcanic activities. From about 3000 km and down is the core of Earth, which is believed to be molten iron and nickel, with highest density (10 - 13 g/cm^3).

The heat content of the mantle and the core is enormous. In principle, by drilling a deep well to the hot part of the Earth, injecting water, superheated steam can be produced to drive turbines to generate electricity. In general, such operation is prohibitively expensive and difficult.

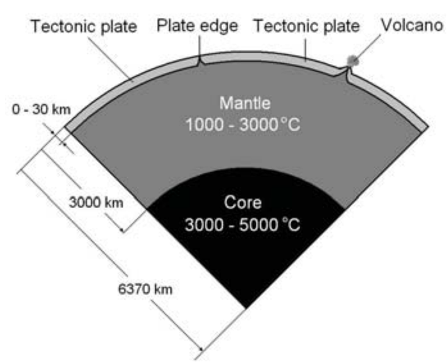

Fig. 1.19. Deep geothermal energy. Thr origin of deep geothermal energy is the core of the Earth. First, dusing the time of the formation of Earth, gravitational contraction generated heat. Then, nuclear reactions in the Earth continuously supply energy. Because the thickness of the tectonic plates, deep geothermal energy is economical only at the edges of the plate or near the volcanos.

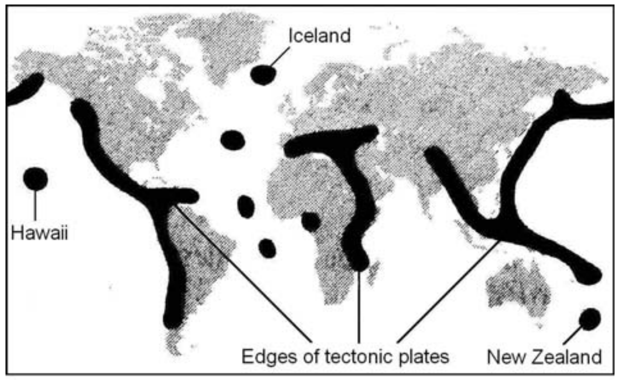

Fig. 1.20. Regions for deep geothermal energy extraction. At the edges of tectonic plates and regions with active volcanoes, deep geothermal energy can be extracted with economical sense.

Most of the current geothermal power stations are located either in the vicinity of edges of tectonic plates, or in regions with active volcanoes, where the thickness of the earth crest is less than a few kilometers, and drilling to hot rocks is practical. Figure 1.20 shows the regions on the Earth where deep geothermal energy can be extracted.

Being rich in active volcanoes, Iceland has an unusual advantage in utilization of deep geothermal energy. In 2008, about 24% of Iceland's electricity is geothermal, and 87% of the buildings are heated by geothermal energy. Figure 1.21 is a photograph of Nesjavellir Geothermal Power Station, the second largest in Iceland, with capacity of 120 MW.

Fig. 1.21. Nesjavellir geothermal power station, Iceland. Due the high concentration of volcanoes, Iceland has an unusual advantage of utilizing geothermal energy. Showing here is Nesjavellir Geothermal Power Station, with capacity of 120 MW.

1.4 A solar photovoltaics primer

It is clear that in the first half of the 21st century, fossil fuel will be depleted to an extent that it could not support the energy demand of human society. There are various types of renewable energy resources. Many of them have limitations, including hydropower, wind energy, and geothermal energy. Solar thermal applications, such solar water heater, can only serve a small part of the total energy demand. Solar photovoltaics is the single most promising substitute to fossil energy. In this section, we will present an elementary conceptual overview of photovoltaics. Details will be presented in Chapters 2, 3, 4, 7, 8, 9, and 10.

1.4.1 Birth of modern solar cells

In 1953, Bell Labs set up a research project for devices to provide energy sources for remote part of the world where no grid power is available. The leading scientist, Darryl Chapin, suggested to use solar cells, and his proposal was approved by his supervisors.

At that time, the photovoltaic effect in selenium, discovered in the 1870s, was already commercialized as a device for the measurement of light intensity for photographers. Figure 1.22(a) is a schematics. A layer of Se is applied on a copper substrate, then covered by a semitransparent film of gold. When the device is illuminated by visible light, a voltage is generated, which in turn generates a current. The intensity of electric current depends on the intensity of light. It has been a standard instrument in the first half of the 20th century for photographers to measure the light conditions. That device is much more rugged and convenient than photoresistors, because there is no moving parts and no battery is required.

Chapin started his experiment with selenium photocells. He found that the efficiency, 0.5%, is too low to generate sufficient power for telephony

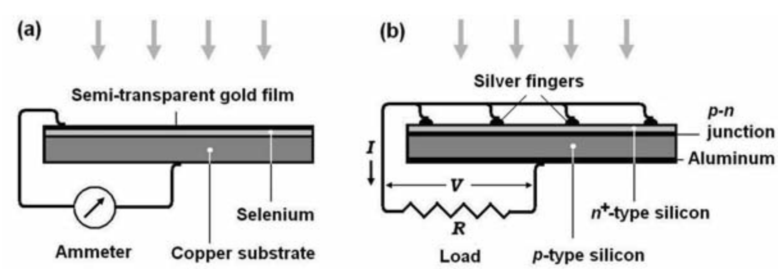

Fig. 1.22. Selenium solar cell and silicon solar cell. (a) Selenium photovoltaic cell was discovered in the middle of 19th century, and were used as a device for measuring light intensity for photographers. (b) Silicon photovoltaic cell was invented in Bell Labs in 1954 using the technology for silicon transistors.

Fig. 1.23. Inventors of silicon solar cells. Left to right: Gerald Pearson (1905-1987), Darryl Chapin (1906 - 1995), and Calvin Fuller (1902 - 1994). In 1953 Bell Labs set up a research project to provide energy sources for remote part of the world where no grid power is available. By utilizing the nascent technology to make silicon transistors, in 1954, they designed and demonstrated the first silicon solar cells. The efficiency they achieved, 5.7%, makes the solar cell a useful power source. Since then, the efficiency of silicon solar cells has been improved to over 20%, but the basic structure stays unchanged.

applications. Then there was an unbelievable luck. Two Bell Lab scientists involving in that pioneering effort to develop silicon transistors, Calvin Fuller and Gerald Pearson, joined Chapin to use the nascent silicon technology for solar cells, see Fig 1.23. In 1954, a solar cell of 5.7% efficiency was demonstrated. A schematics is shown in Fig. 1.22(b).

The silicon solar cell was made from a single crystal of silicon. By judicially control the doping profile, a *p*-*n* junction is formed. The *n*-side of the junction is very thin, and highly doped, to allow light to come to the *p*-*n* junction with very little attenuation, but the lateral electric conduction

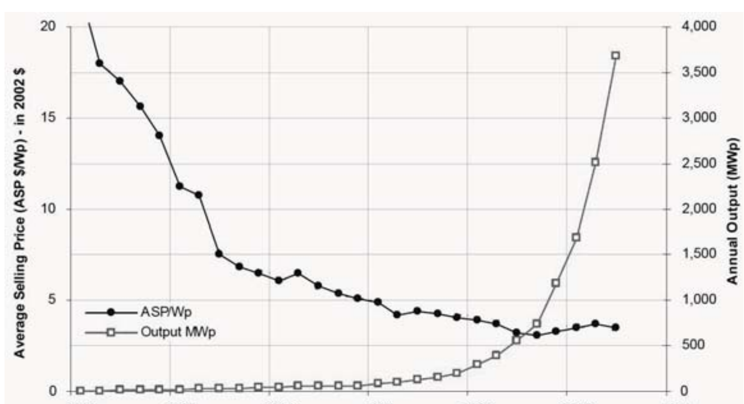

Fig. 1.24. Averager price and installation of solar cells: 1980 to 2007. The average price of solar cells dropped three folds from more than $20 per peak watt in 1980 to $6.5 per peak watt in 1990. The installation of solar cells has been steadily increased in that period of time. After *Solar Photovoltaic Industry, 2008 global outlook*, Deutsch Bank.

is high enough to collect the current to the front contact through an array of silver fingers. The back side of the silicon is covered with a metal film, typically aluminum. The basic structure of the silicon solar cell keeps almost unchanged until now.

The press conference and the initial demonstration of the solar cell to the public in New York City was a fanfare. However, the cost of building such solar cells was very high. From the mid 1950s to the early 1970s, photovoltaics research and development was directed primarily toward space applications and satellite power. In 1976, the U.S. Department of Energy (DOE) was established. A Photovoltaics Program was created. US DOE, as well as many other international organizations, began funding research in photovoltaics at appreciable levels. A terrestrial solar cell industry quickly established. Economy of scale and progress in technology brought down the price of solar cells dramatically. Figure 1.24 shows the evolution of price and annual PV installation from 1980 to 2007.

1.4.2 Some concepts on solar cells

Following are a list of key terms and concepts regarding solar cells:

Standard illumination conditions

The efficiency an power output of a solar module (or a solar cell) is tested under the following standard conditions: 1,000 W/m^2 intensity, 25°C ambient temperature, and a spectrum that relates to sunlight that has passed through the atmosphere when the sun is at a 42° elevation from the horizon (defined as air mass [or AM] 1.5, see Plate 1).

Fill factor

The *open circuit voltage* V_{op} is the voltage between the terminals of a solar cell under standard illumination conditions when the load has a infinite resistance, that is open. In this situation, the current is zero. The *short circuit current* $I_{\rm sc}$ is the current of a solar cell under standard illumination conditions when the load has zero resistance. In this case, the voltage is zero. By using a resistive load R, the voltage V will be smaller than V_{op}, and the current I is smaller than $I_{\rm sc}$. The power is $P = IV$. The maximum power output is determined by the condition

$$dP = d(IV) = IdV + VdI = 0. \tag{1.27}$$

Figure 1.25 shows the relation among those quantities. Denoting the point of maximum power by $I_{\rm mp}$ and $V_{\rm mp}$, we have $P_{\rm max} = I_{\rm mp}V_{\rm mp}$.

A fill factor of a solar cell FF is defined as

$$FF = \frac{P_{\rm max}}{I_{\rm sc}V_{\rm oc}} = \frac{I_{\rm mp}V_{\rm mp}}{I_{\rm sc}V_{\rm oc}}. \tag{1.28}$$

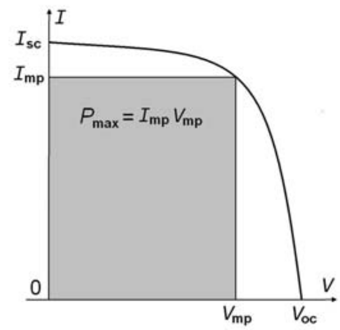

Fig. 1.25. Maximum power and fill factor. By connecting a load resistor to the two terminals of a solar cell, the solar cell supplies power to the load. The maximum power point occurs when $P = IV$ reaches maximum. At that point, $P_{\mathrm{max}} = I_{\mathrm{mp}}V_{\mathrm{mp}}$. Obviously, there is always $I_{\mathrm{mp}} < I_{\mathrm{sc}}$ and $V_{\mathrm{mp}} < V_{\mathrm{oc}}$. The fill factor of a solar cell is defined as $FF = P_{\mathrm{max}}/I_{\mathrm{sc}}V_{\mathrm{oc}} = I_{\mathrm{mp}}V_{\mathrm{mp}}/I_{\mathrm{sc}}V_{\mathrm{oc}}$.

The typical value of fill factor is between 0.8 and 0.9.

Efficiency

The efficiency of a solar cell is defined a the ratio of the output electric power over the input solar radiation power under standard illumination conditions at the maximum power point. A collection of efficiency values for various solar cells are shown in Plate 5.

Peak watt

The "peak watt" (Wp) rating of a solar module is the power (in watts) produced by the solar module under standard illumination conditions at the maximum power point. The actual power output of a solar cell obviously depends on the actual illumination conditions. For a discussion of the actual solar illuminations, see Chapter 4.

1.4.3 Types of solar cells

The crystalline silicon solar cell was the first practical solar cell invented in 1954. The efficiency of such solar cells as mass produced is 14% to 20%, which is still the highest in single-junction solar cells. It also has a long life, and the readiness for mass production. To date, it still accounts for more than 80% of the solar cell market. There are two versions of the crystalline silicon solar cell: monocrystalline and polycrystalline. Amorphous silicon thin film silicon solar cells is much less expensive than the crystalline ones. But the efficiency is only 6% to 10%. In between are CIGS (copper indium gallium selenide) and CdTe-CdS thin film solar cells, with a typical efficiency of around 10%, accounts for about 15% of the market. Because of the very high absorption coefficient, the amount of materials required is small, and the production process is simpler, thus the unit price per peak watt is lower than crystalline silicon solar cells. Table 1.6 summarizes various types of solar cells.

Table 1.6: Types of solar cells

Type	Efficiency	Cost	Market share
Monocrystalline Si	17% - 20%	\$3.0/Wp	30%
Polycrystalline Si	15% - 18%	\$2.0/Wp	40%
Amouphous Si	5% - 10%	\$1.0/Wp	5%
CIGS	11% - 13%	\$1.5/Wp	5%
CdTe-CdS	9% - 11%	\$1.5/Wp	10%

1.4.4 Energy balance

It takes energy to produce solar cells. Therefore, a study of the energy return over energy invested (EROI) is important. Here we discuss the energy balance for the most expensive case, crystalline silicon solar cells. The energy investment includes that for producing silicon feedstock, ingot and wafers, cell production, module assembly, and installation. A standard benchmark number to evaluate the energy balance of photovoltaics is *payback time*. By setting the solar cells in a given solar illumination condition, the solar cells will generate energy in the form of electricity. Payback time is the number of years the electricity generated by the solar cell to compensate the energy invested in the production and installation process.

Figure 1.26 represents a conservative estimate of payback time for crystalline silicon solar cells based on European insolation conditions. Even for Central Europe, with annual insolation of 1000 W/m^2, the payback time is 3.6 years. Its lifetime is typically 25 years, which means a EROI of 7. In Southern Europe and most places in the US, the EROI is above 10. The EROI for thin film solar cells is even better. However, because of lower efficiency, it requires more space to generate the same power.

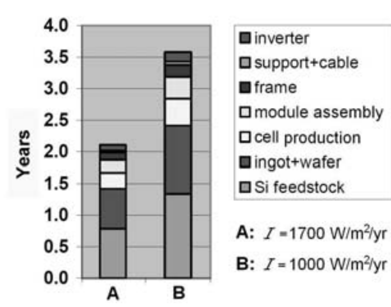

Fig. 1.26. Payback time for crystalline silicon solar cells. The energy invested for a solar cell includes the energy for producing silicon feedstock, ingot and wafers, cell production, and installation. Even under unfavorable insolation conditions, such as central Europe, the payback time is less than 15% of its lifetime, which means a EROI of 7.

1.5 Above physics

Good physics does not always lead to successful industrial implementation, and to confer a great benefit on mankind. Solar energy is no exception. Economics and politics play a significant role. In this section, we will review some important historical lessens, and to analyze the economical and political context for which the utilization of solar energy can become a success and thus to benefit the mankind.

1.5.1 Economics of solar energy

The early history of solar water heaters in the United States vividly illustrates the interplay of physics, engineering and economics.[1] In the 19th century, before the invention of modern running hot water systems, making hot water for a bath was expensive and difficult. Water has to be heated in a large pot with fire then scooped into the bathtub. It was especially expensive in California, where fuels such as coal must be imported from elsewhere, and wood was precious. Artificial gas and electricity were very expensive. However, sunlight is plenty, and the weather is mild.

In 1891, Clarence Kemp patented an effective and usable solar water heater, named Climax (US Patent 451,384). First marketed in Maryland, the business was not very successful. Then he sold the exclusive right to two Pasadena businessmen and made a great commercial success in California. By 1900, six hundred units were sold in southern California alone. However, the Climax water heater has a drawback that it takes a few hours of sunlight to heat up the water; and after sunset, the water temperature drops quickly. Therefore, it can only be used in the afternoon of a sunny day.

In 1910, William J. Bailey invented and patented the Day-and-Night solar water heater (US Patent 966,070), which resolved the major problems and became the prototype of later solar water heaters, see Fig. 1.27. First, the heat collector A is made of a parallel grid of copper pipes welded on a flat piece of copper plate. Second, it uses an water tank C placed above the heat

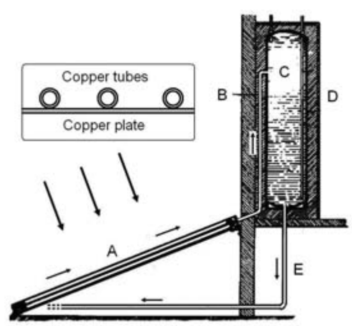

Fig. 1.27. The Day-and-Night solar water heater. A schematic of the Day-and-Night solar water heater. The inset shows the copper tubes and copper plate of solar heat collector A. The entire system works under natural convection: the water heated by sunlight in collector A rises to the insulated tank C. The cold water flows down from the tank C through pipe E back to the solar heat collector A.

collector, heavily insulated by cork, D. Such an arrangement enables water circulation by *natural convection* and effective *energy storage*. When water is heated by sunlight, the specific gravity decreases. It flows automatically upwards through pipe B into the water tank C. The colder water then flows automatically downwards through pipe D back into the heat collector A. If the insulation is sufficient, the water can stay hot overnight. Therefore, it works in the day as well as in the night. Although a Day-and-Night system cost about $180 at that time, much higher than a Climax system, it quickly conquered the consumers. Climax was forced out of business. By the end of World War I, 4000 Day-and-Night solar water heaters were sold. In 1920 alone, more than people bought 1000 Bailey's systems.

In early 1920's, abundant natural gas was discovered in Los Angeles basin. The price of natural gas in 1927 was only a quarter of that in 1900 for town gas. The gas-operated water heater, much cheaper in initial investment than the solar heater, and more convenient to use, gradually replaced the once popular solar water heaters. Bailey's company, being quite experienced in water heater systems, quickly adapted into gas heater business. Day-and-Night became even more accurate. It soon became one of the largest producers of gas water heaters in the nation.

The downfall of the solar water heater business in California was not the end of it. Florida, with a real estate boom in the 1920's through the 1940's, and no natural gas available, became the sweet spot of solar water heaters. It is estimated that from 25,000 to 60,000 solar water heaters were installed in Miami during 1920 and 1941. During the War, price of copper skyrocketed. After the war, the price of electricity plummeted. The joint

Fig. 1.28. A Day-and-Night solar water heater in Florida. From 1920 to 1941, more than 25,000 solar water heaters were manufactured and installed in Florida. After 70 to 80 years, thousends of them are still working. The photo, taken by the Author in Miami in August 2010, is a solar water heater installed in 1937. The insulated water tank is disguised as a chimney. Even with a broken glass, it is still working properly.

result is the gradual replacement of solar water heaters by electric water heaters. In the United States, solar water heater lost its glory.

However, after World War II, on other places of the World, solar water heaters gained momentum, especially in Israel. A desert area without energy resources, similar to California in late 19th century, solar water heaters could bring sizeable economical benefit. A significant advance in solar thermal technology, the selective absorption coating, was invented in Israel in the 1950's, which greatly improved the efficiency of solar water heaters. Later on, Israel became the first country to require that all new building must have solar water heaters.

1.5.2 Moral equivalence of war

Government policies on energy have a major effect on renewable energy development. In the United States, the new energy policies during the Carter administration in the 1970s created a golden period for renewable energy research and development.

After World War II, the United States has enjoyed cheap crude oil, staying below $20 per barrel (inflation adjusted on January 2008 dollar) for three decades. In 1973, an oil embargo triggered the first energy crisis. The price of crude oil on the world jumped dramatically, see Fig. 1.29.

Coincidentally, the time of energy crisis matches the prediction of M. King Hubbert in 1956 that shortly after 1970, the production of crude oil in the United States would peak and start to decline, see Section 1.2. The coincidence is not accidental. As the crude oil production in the United States starts to decline, the consumption is still growing. In 1971, the United

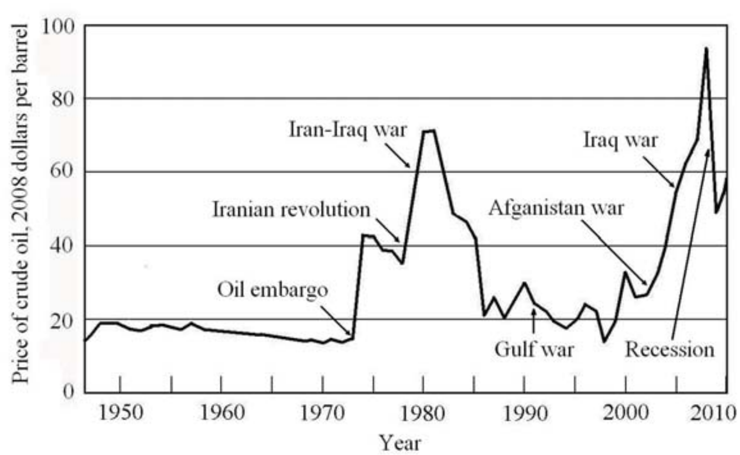

Fig. 1.29. History of crude-oil price, in 2008 dollars. Source: United States Energy Information Administration.

States paid \$3.7 billion for importing crude oil; but in 1977, it was increased ten fold to \$37 billion (in 1977 dollar). Obviously, excessive dependence on foreign oil poses severe economic and security threats.

On April 18, 1977, then President Jimmy Carter delivered a televised speech about his new energy policy. He called the struggle for greater energy independence the *moral equivalence of war*, – one that "will test the character of the American people." He said,

> Tonight I want to have an unpleasant talk with you about a problem unprecedented in our history. With the exception of preventing war, this is the greatest challenge our country will face during our lifetimes. The energy crisis has not yet overwhelmed us, but it will if we do not act quickly.
>
> It is a problem we will not solve in the next few years, and it is likely to get progressively worse through the rest of this century.
>
> We must not be selfish or timid if we hope to have a decent world for our children and grandchildren.
>
> We simply must balance our demand for energy with our rapidly shrinking resources. By acting now, we can control our future instead of letting the future control us.

The major points of Carter's energy policy include energy conservation, increasing domestic traditional energy exploration, and to development renewable energy resources. In his words, "we must start now to develop the new, unconventional sources of energy we will rely on in the next century." A few days later, Jimmy Carter signed a legislation Department of Energy Organization Act, and formed the United States Department of Energy on August 4, 1997. Then, an National Energy Act (NEA) was established in 1978 with tax incentives to renewable energy projects, especially solar energy. The legislation initiated a significant boost to the research, development and installations of solar water heaters, solar cells, and solar-operated buildings.

To lead the public by example, on June 20, 1979, Carter installed a solar water heater with 32 panels on the roof of the White House, see Fig. 1.30. At the ceremony, Jimmy Carter reflected upon his own idealism:

> A generation from now, this solar heater can either be a curiosity, a museum piece, an example of a road not taken, or it can be a small part of one of the greatest and most exciting adventures ever undertaken by the American people, ... to harness the power of the sun to enrich our lives as we move away from our crippling dependence on foreign oil.

In 1978, the Carter administration enacted the first National Energy Act to promote fuel efficiency and renewable energy. The research and

Fig. 1.30. Jimmy Carter dedicates the solar water heater atop the White House. On June 20, 1979, Jimmy Carter at a dedication ceremony for a solar water heater on the roof of the White House. He hoped that this would be "a small part of one of the greatest and most exciting adventures ever undertaken by the American people, ... to harness the power of the sun to enrich our lives as we move away from our crippling dependence on foreign oil". Courtesy of Jimmy Carter Library, Atlanta, GA.

development funding for renewable energy is greatly increased. Part of the 1978 National Energy Act is an Energy Tax Act to gave an income tax credit to private residents who use solar, wind, or geothermal sources of energy. The 1978 Energy Tax Act in the US was expired in 1986. However, many other countries followed the example of the United States to provide government financial support for renewable energy utilization.

As anticipated by Jimmy Carter, during the rest of the 20th century, several factors made the energy problem "progressively worse": Due to a steady decline and an increasing consumption, the crude oil import to the United States has increased from 1.8 billion barrels in 1980 to 5.0 billion barrels in 2000s. The price of crude oil (in 2008 dollar) has increased from about $20 to more than $100 a barrel in late 2000s, see Fig. 1.29. The petroleum crisis in the 1970s reappeared, but with an even more gruesome context: According to Hubbert, in early 2000s, the world's crude oil production peaked and started to decline, see Section 1.2. The world's two most populous countries, India and China, are experiencing rapid economical development, which consume a growing proportion of the dwindling production of the world's crude oil. Both India and China have very limited crude oil resource, which have an even more severe energy problem.

1.5.3 Solar water heaters in other countries

As we have presented, solar water heater was invented in the United States and it was quite popular in the first half of the twentieth century. However, despite the energy crisis and strong government incentive in 1970s, the installation volume in the United States is still very low. Nevertheless, in recent decades, solar water heater has enjoyed an explosive growth globally, especially in China. As shown in Fig. 1.31, in 2007, China installs 80% of new solar water heaters, with 16 GW capacity; and the total installation capacity of solar water heaters is 84 GW, accounting for two third of the world's total. There is a good lesson to learn from.

A huge virgin market

The market of water heaters in China is quite similar to that in California in late nineteenth century. Up to the 1980s, nearly one billion people in China have no running hot water. The improving living standard has made hot water a necessity of life. However, natural gas and heating oil are expensive and not generally available. Electricity is very expensive. The cost of equipment for making hot water using fossil fuel is comparable with that using sunlight. It is a perfect soil for solar water heaters to grow.

Advances in technology and economy of scale

Until recently, most of the solar water heaters in the Western world use flat-plate heat collectors, similar to the Day-and-Night system, Fig 1.28, and the White House solar panels, Fig 1.30. The structure is rather inconvenient for mass production. It uses a lot of copper, a major factor of its demise during and after World War II. The heat loss due to conduction through the glass

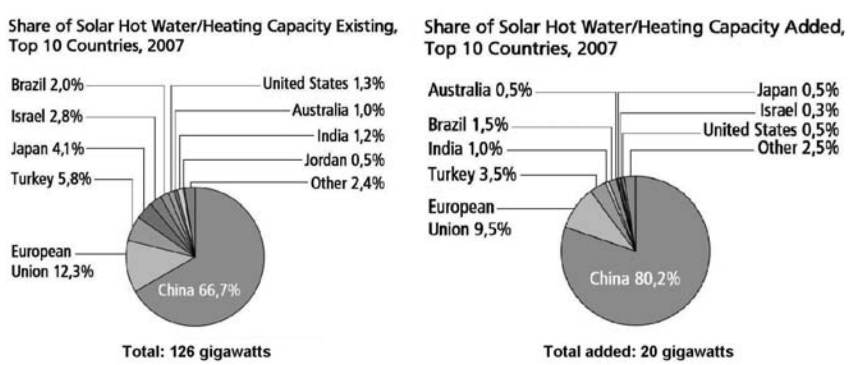

Fig. 1.31. Global installations of solar water heater. Globally, solar water heater installation is increasing rapidly. The most growth is in China. Source: Renewables Global Status Report, 2009 Update (see http://www.ren21.net).

window and the back plate is significant. A lot of metal parts exposed to the elements limit its lifetime. The vacuum-tube heat collectors, invented by a distinguished American engineer William L. R. Emmet in 1911 (US Patent 980,505) has superb properties. However, for several decades, it has been expensive and complicated. In early 1980s, vacuum-tube solar heat collectors were improved. An extremely simple and effective solar water heater was invented and perfected, see Fig 1.32.

Figure 1.32(a) shows the design of evacuated-tube solar water heater. Each heat collector is a double-walled glass tube. The space between the outer tube and the inner tube is evacuated to a high vacuum, similar to a Dewar flask. On the outer surface of the inner tube, a *selective absorption film* is applied. For sunlight, which is mostly visible and near-infrared, the absorption coefficient is around 95%. For far-infrared radiation from the hot water (80 to 100°C), the emission coefficient is around 5%. The vacuum sleeve perfectly blocks thermal conduction. The entire system works automatically under the principle of natural convection. The water heated by sunlight, having a lower specific gravity, flows upwards to the insulated tank. Similarly, the cold water flows downwards from the tank into the heat collector tubes. A photo is shown in Fig 1.32(b). Typically, 10 to 40 evacuated tubes are used in one system. The water tank is insulated by foam polyurethane. The temperature only drops a few degrees overnight. Therefore, it can provide hot water day and night.

The design also facilitates shipping and storage. The tubes, the tank, and the parts of the frame are shipped in three separate rectangular cardboard boxes. The system is then assembled at the installation site.

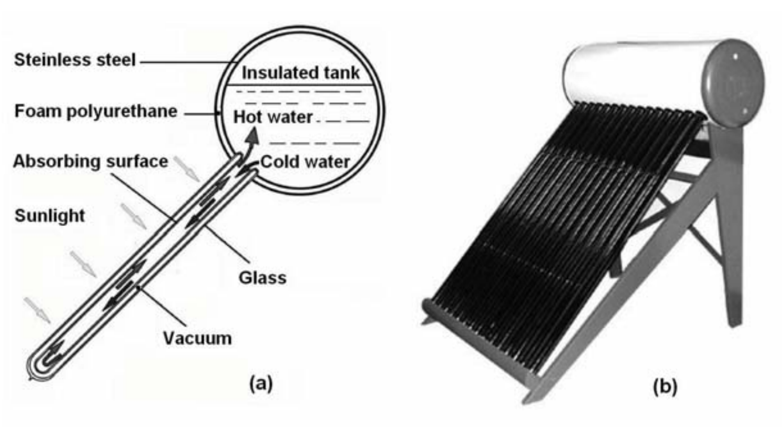

Fig. 1.32. The evacuated-tube solar water heater. (a) A schematic of the evacuated-tube solar water heater. Each heat collector is a double-walled glass tube. The system works automatically under the principle of natural convection. (b) A photograph of such a system.

Because the evacuated tubes are made of borosilicon glass (Pyrex), the selective absorption film is under high vacuum, and the tank is usually made of high-grade stainless steel, unless being broken by brute force, the system could work for decades. Those parts are perfectly suitable for automatic mass-production. Currently, some 200 million evacuated tubes and some 10 million insulated water tanks are being manufactured every year.

The huge market enables cost advantages by the economies of scale. The producer's average cost per unit fall as scale is increased. Due to relentless effort of automation, the manufacturing cost of evacuated tubes is reduced to a few dollar per piece, unimaginable a few decades ago. The reduced price of solar water heaters further increases the size of the market. The expansion of the market further provides grounds to improve the manufacturing process. As a result, the solar water heater business in China is sustaining *without government financial incentives*.

Himin model of solar energy business

It is instructive to learn how the colossal solar water heater industry could grow from nowhere during such a short period of time. For that purpose, I visited the world's largest manufacturer of solar water heaters, Himin Solar Energy Group, and meet the founder and CEO, Mr. Huang Ming in Beijing, when he attended the Plenary Meeting of People's Congress. A number of internal documents of this company were then collected.

In 1978, when Huang Ming was a student at East China Petroleum Institute, he learned that the crude oil reserve in the world will be depleted in 50 years. China's crude oil will be depleted even sooner. Several years after graduation, he became a highly regarded research engineer specialized in oil-well drilling. However, his personal experience reinforced his pessimism about the future of petroleum.

In 1987, by chance, he found Duffie and Beckman's book "Solar Energy Thermal Processes". By reading it from cover to cover, and doing hands-on experiments using funds from selling of a patent, he was convinced that sunlight is an ultimate solution to the energy problem. Solar energy became his lifetime passion. Since then, he spend 8 hours in the Petroleum Institute, 8 hours working home on solar energy projects, and 8 hours for sleeping and eating. He gave his hand-made solar water heaters to friends and relatives as gifts, installed a system at a children's entertainment center, and received overwhelming welcome.

In 1995, he quited his job in petroleum industry, and started his own business. He chose the Chinese name of the company, Huangming, as a homophone of his personal name, to symbolize his dedication. Within ten years, his company has grown into one of the largest solar water heater manufacturers on the world without government subsidy. In 2009, Himin produced more than two million square meters of solar heat collectors, equivalent to 2 GW of peak solar energy utilization. In May 2006, Huang Ming was invited by United Nations to present Himin's business mode at the 14th Meeting of United Nations Commission on Sustainable Development, 2006. It was later known as the "Himin model of solar energy business".

Figure 1.33 is a sketch of the Himin model of solar-energy business. A central point is to create new market through popular science enlightenment and education. In 1996, right after the birth of Himin, a weekly newsletter "Popular Solar Energy" was established. It became Himin's continuing marketing tool, with accumulated distribution of 300 million copies in 2010. Himin organized numerous popular science tours, traveled 80 million kilometers over China. Because for an average Chinese family, a solar water heater is still a major capital investment, a decision to purchase a set must be based on careful thinking. The educated people were that first group of customers, then become volunteer marketers for the product. The Himin model is represented by three loops, see Fig. 1.33.

Loop 1 is the main production cycle. Himin's strategy is to pursue the highest standard of excellence. The retail price of their product is among the most expensive on the market. However, because of their extensive research and quality control, the products have less trouble and last a long time. The quality ensures their reputaion in the market.

Loop 2 emphasizes the importance of popular science enlightenment and education. In addition to the corporate investment, a substantial portion of profit is invested in science education, to ensure the customers understand how the system works and how to choose a good product or part.

Loop 3 emphasizes the importance of pushing for energy policy legislation and to raise the public attention to renewable energy. This is also a significant factor of its success. In 2003, local city folks, especially Himin em-

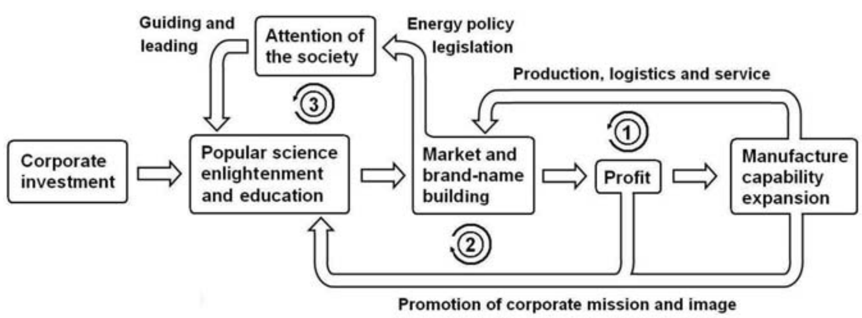

Fig. 1.33. Himin model of solar-energy business. The Himin modelll consists of three loops. Loop 1 is similar to a conventional business cycle. Strict quality control and good after-sale service build up the brand name. Large scale mass production reduces unit cost. Loop 2 is to invest heavily in popular science education as the major marketing method. Loop 3 is to push energy policy legislation to favor renewable enegy and to promote public awareness. Source: Minutes of the 14th Conference of United Nations Commission on Sustainable Development, 2006, New York.

ployees, elected Huang Ming to become a member of the People's Congress. He then mobilized 60 fellow congressmen to propose a Renewable Energy Act, which was passed in Spring 2005. The legislation has motivated central and logal governments to set up renewable-energy projects, and raises public support to solar energy technology and products.

In 2008, the International Solar Energy Society (ISES) decided that Dezhou, the location of Himin, to host the 2010 International Solar City Congress. Around that time, Huang Ming was elected as the Vice President of ISES for industry. The venue of the congress, the Dezhou Apollo Temple, a 800,000 square foot museum, ballroom and hotel building with 65% of energy supplied by solar, was completed in 2009, see Plate 17.

1.5.4 Photovoltaics: towards grid parity

Because hot water heaters only consumes less than 10% of total energy, the bulk of energy needed, especially electricity, can only be supplied through photovoltaics or other means of solar electricity generation. By comparing with the installation of solar water heaters, the total installation of solar PV over the world is much smaller. In 2008, 6.08 GWp of photovoltaics was installed on the world. The accumulative installation in 2008 is 15 GWp. Figure 1.34 shows the yearly installation and growth rate of the entire world from 1990 to 2008.

As shown, the installation in terms of peak watts of PV is only about one tenth of solar water heaters. The limiting factor is simply economics. As shown in Section 1.4.1, although practically usable solar cells were invented in 1954, the manufacturing cost was very high. The major applications were space and military fields. In the late 1970s and early 1980s, stimulated by the National Energy Act, dramatic improvement of efficiency and reduction

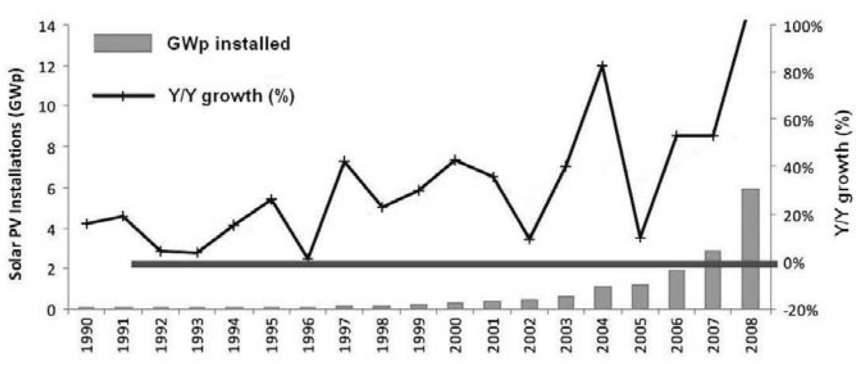

Fig. 1.34. Installation of solar photovoltaics: 1990 to 2008. Bar graph: the annual installation of solar photovoltaic panels over the world. Solid curve: Growth rate year by year. After *Solar Photovoltaic Industry, 2008 global outlook*, Deutsch Bank.

Table 1.7: Cost of solar electricity for various cases

Insolation	Cost of installed PV per peak watt				
Cost per kWh ↘	\$ 2	\$ 4	\$ 6	\$ 8	\$ 10
3 kWh/m^2/day	\$ 0.073	\$ 0.146	\$ 0.219	\$ 0.292	\$ 0.365
4 kWh/m^2/day	\$ 0.054	\$ 0.109	\$ 0.164	\$ 0.219	\$ 0.273
5 kWh/m^2/day	\$ 0.043	\$ 0.087	\$ 0.131	\$ 0.175	\$ 0.219
6 kWh/m^2/day	\$ 0.036	\$ 0.073	\$ 0.109	\$ 0.146	\$ 0.182

of cost have achieved, see Fig. 1.24. The gradual reduction of the manufacturing cost of solar cells continues in the 1990s and early 2000s. In 2003, the price of solar cell per peak watt has dropped to \$6.5. However, the solar electricity is still much more expensive than the electricity generated by the traditional energy resources, especially by coal and hydropower, which is \$0.05 to \$0.10 per kWh. Including supporting structure, invertors and necessary instruments, the cost of installed solar panel per peak watt in 2003 was about \$10. Table 1.7 shows the cost of generating 1 kWh of electric energy by solar cells in regions with different insolation.

To jump-start the utilization of solar energy, in 1990s, many European countries established *feed-in tariff law* (FIT), which guarantees a solar photovoltaic system access to the grid, with a purchase price of thus generated electricity based on cost. The purchase guarantees could be extended to 20 or 25 years, but the rate could decline based on expected cost reductions. The law significantly expended the market for solar photovoltaics. However, it also causes certain gyrations. For example, in 2007, Spain raised the date for large PV systems from €0.18/kWp to €0.42/kWp. Immediately, the installation surged from 61 mWp in 2006 to 591 mWp in 2007, then to 2700 mWp in 2008. The Spanish government suddenly found that the rate is not sustainable, and reduced it to €0.32/kWp, to take effect in 2009. In 2009, the installation is reduced to less than 200 MWp. See Figure 1.35.

The dramatic increase of demand in 2007-2008 nevertheless gave a thrust to an unprecedented boom of solar cell industry, especially in the United States and Asia. The economy of scale, in the form of vertical integration, again works. First Solar in the US is vertically integrated in a sense that they design and manufacture equipment for solar-cell production by themselves, thus its production capability is quickly expended. Yingli Solar in Baoding, China and Renewable Energy Corporation in Norway, both are manufacturer of polycrystalline silicon solar cells, are so vertically integrated that they start with producing pure silicon from silica mine and end up with solar panel installation. In 2009, 49% of the world's solar cells were produced in China and Taiwan, mostly crystalline silicon solar cell with

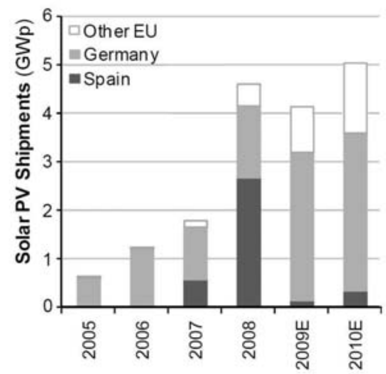

Fig. 1.35. Installation of solar cells in Europe. Due to an excessive feed-in tariff in Spain during 2007 and 2008, PV installation in Spain exploded in 2008. After the feed-in tariff was reduced in 2009, the trend was reversed rapidly. The feed-in tariff in Germany was relatively stable, which maintains a sustainable growth. The explosive growth of demand in 2008 has stimulated a rapid growth of solar-cell manufacturing, especially in the United States and Asia.

high efficiency. Figure 1.36 shows the statistics from two manufacturers. As shown, in 2009, the manufacturing cost of First Solar's CdTe thin-film solar cells has dropped to \$0.8 per peak watt, and the retail price is \$1.5 per peak watt. Yingli's polycrystalline silicon solar cells, with an efficiency close to 20%, is manufactured with \$1.5 per peak watt, and a and the retail price of \$2 per peak watt. The cost and price is expected to decrease continuously in the years to come. (Recently, Yingli announced selling price of polycrystalline silicon solar panels of less then \$1 per peak watt).

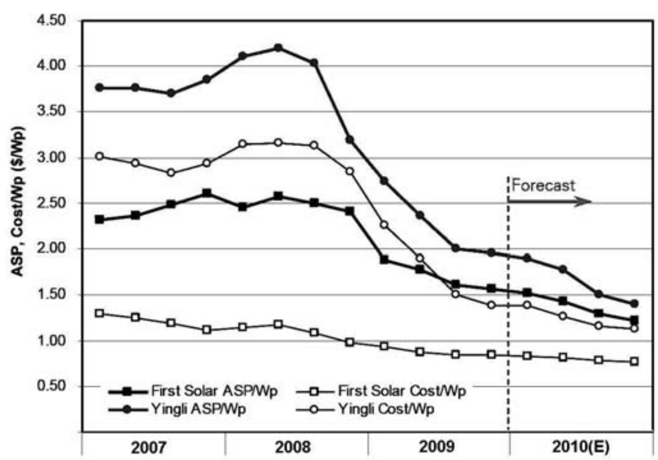

Fig. 1.36. Price of solar cells from two major suppliers: 2007 to 2010. Existing data and forcast for two representative solar cell manufacturers. First Solar is the world's largest manufacturer of CdTe-CdS thin film solar cells. Yingli is the world's largest manufacturer of polycrystalline solar cells, which is also one of the world's most vertically integrated solar cell manufacturers. After *Solar Photovoltaic Industry, 2008 global outlook*, Deutsch Bank.

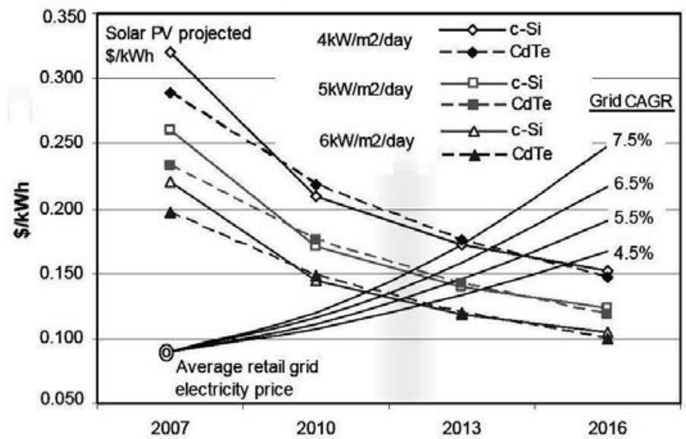

Fig. 1.37. Prediction of grid parity. According to the forecast of Deutsch Bank, two most promising solar cell technology, crystalline silicon solar cells and CdTe thin film solar cells, will arrive at grid parity around year 2013. Beyond 2013, the cost of solar electricity could be lower than that of traditional source of electricity for many places of the world. After *Solar Photovoltaic Industry, 2008 global outlook*, Deutsch Bank.

According to the statistics and analysis by Deutsch Bank, because of the combined effect of explosive expansion of solar-cell production capability and the recession, in 2009, the price of solar cells on the international market dropped significantly. A brutal shake-up of the industry, both the suppliers of pure silicon and the solar cells, takes place. After a brief period of oversupply, the price of solar cells will be reduced to a level that the cost of solar electricity will be comparable to electricity generated by, for example, coal-burning power stations, that is to say, reaches *grid parity*, see Fig. 1.37. The pace of grid parity depends on the local situation, thus varies from place to place. For places with high electricity cost, such as Hawaii, Connecticut, California and New York, especially those places with high insolation, grid parity will take place earlier. For areas with low electricity price, for example, West Virginia and central-west China, especially for places with low insolation, grid parity will be reached later. However, the trend that the cost of fossil fuel electricity will increase and the cost of solar electricity will decrease is inevitable. Solar electricity will gradually replace fossil-fuel electricity as time goes on.

Figure 1.38 shows the average annual growth rates of renewables from 2002 to 2006, as reported by REN21[3]. As shown, the average growth rate for grid-connected solar photovoltaics, more than 60%, far exceeds other energy resources. In 2006, the percentage of solar photovoltaics is only a miserable 0.07%. However, if in the future, the rate of growth of photovoltaics could maintain 40%, in 20 years, or 2030, solar photovoltaics would supply more than 50% of the energy consumption.

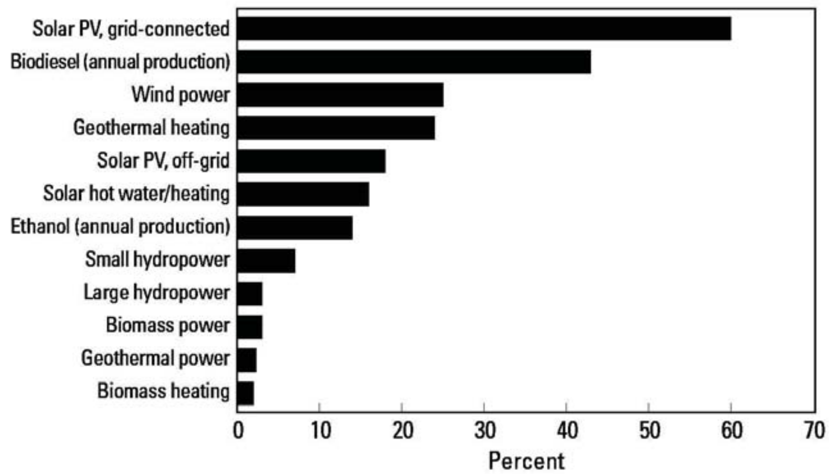

Fig. 1.38. Average annual growth rates of renewables: 2002 to 2006. The average growth rate for grid-connected solar photovoltaics far exceeds other renewable energy capacities, and even more to the traditional energy resources. If in the future, the rate of growth of photovoltaics could maintain 40%, in 20 years, or 2030, solar photovoltaics would count for 50% of the energy supply and become the dominant energy source. After *Renewables 2007 Global Status Report*, REN21[3].

Problems

Problem 1.1. In the United States, the British thermal unit, abbreviated as Btu, is defined as the energy to raise the temperature of one pound water by one degree Fahrenheit. Show that to a good approximation, one Btu equals one kJ.

Problem 1.2. Approximately (to $\pm5\%$), how much energy is in one billion barrel of petroleum, in GJ and TWh?

Problem 1.3. Approximately (to $\pm5\%$), how much energy is in one billion barrel of petroleum, in GJ and TWh?

Problem 1.4. The area of New Mexico is 121,666 square miles. The average annual insolation (hours of equivalent full sunlight on a horizontal surface) is 2200 hours. If one half of the area of New Mexico is covered with solar panels of 10% efficiency, how much electricity can be generated per year? How much percentage of US energy need can be satisfied? (The total energy consumption of the United States in 2007 is 100 EJ).

Problem 1.5. The area of Tibet is 1,230,000 square kilometers. The average annual insolation (hours of equivalent full sunlight on a horizontal surface) is 3000 hours. If one half of the area of Tibet is covered with solar panels of 10% efficiency, how much electricity per year can be generated? How much percentage of the world's energy need can be satisfied? (The total energy consumption of the world in 2007 is 500 EJ).

Problem 1.6. A solar oven has a concentration mirror of one square meter with a solar tracking mechanism. If the efficiency is 75%, on a sunny day, how long it takes to melt one kilogram of ice at 0°C into water at the same temperature? How long it takes to heat it up to the boiling point? How long it takes to evaporate it at 100°C?

Problem 1.7. For wind speeds 20 mph, 40 mph etc. up to 160 mph, calculate the wind power density (in watts per square meter).

Problem 1.8. By definition, the distance from the equator of the Earth to the North Pole along the surface of the Earth is 1.00×10^7 meters. If the average solar radiation power density on the earth is one sun, how much energy is falling on the Earth annually? If the annual energy consumption of the entire world in 2040 is 800 EJ, how much percentage of solar energy is required to supply the entire world's energy need in 2040? (Hint: a day is $24\times60\times60=86400$ seconds.)

Problem 1.9. Using a solar photovoltaic field of one square mile (2.59 square kilometers) with efficiency of 15%, how many kilowatt-hours this field can generate annually at locations of average daily insolation (on flat ground) of 3 hrs (Alaska), 4 hrs (New York), 5 hrs (Georgia) and 6 hrs (Arizona)? An average household consumes 1,000 kWh per month. How many households can this field support in the four states, respectively?