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Alpha Science

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Alpha Science International Ltd.
Oxford, U.K.

**Solar Electricity Generation**
146 pgs. | 85 figs. | 14 tbls.

**Subhadeep Bhattacharjee**
Department of Electrical Engineering
National Institute of Technology (NIT) Agartala
Tripura



ALPHA SCIENCE INTERNATIONAL LTD.
7200 The Quorum, Oxford Business Park North
Garsington Road, Oxford OX4 2JZ, U.K.

**www.alphasci.com**

ISBN 978-1-84265-928-1

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# Preface

***I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait till oil and coal run out before we tackle that. I wish I had more years left.***

***- Thomas Alva Edison***

Electricity is a key infrastructure for development of any nation. But burning fossil fuel to generate electricity is not benign for the environment. Moreover, fossil fuels are finite in nature and millions of years are required to form fossil fuels in the earth. Fossil fuels like coal, oil, natural gas etc. are depleted at a rate 100,000 times faster than they are being formed. Under this backdrop, there is a pressing need to accelerate the development of renewable energy technologies in order to address the global challenges of energy security, climate change and sustainable development. Renewable energy sources derived principally from solar energy have been gaining ground over the last few years and are now beginning to contribute to the global energy mix. Solar power and solar energy resources on earth are enormous, nonpolluting, and virtually inexhaustible and has proven to be an economical source of energy in many applications. As the conventional fossil fuel is depleting at a faster rate while the cost of electrical energy is increasing due to growing consumer demand, solar electricity generation has become a promising alternate.

Two main types of solar technology exist for the conversion of solar energy into electricity: active and passive. The first is related to the transformation of solar light directly into electricity by using a photovoltaic (PV) semiconductor material called solar cell. The second technology type is adapted more for large-scale applications using solar radiation directly to heat liquid or gas.

The main objective of this book is to enable the students and stakeholders to quickly understand the concepts of solar electricity generation techniques. The book is organized through seven chapters. Chapter 1 is intended as an introduction to energy and power. It discusses various issues and current status of renewable solar electricity generation.

Chapter 2 focuses on solar fundamentals. Solar energy principle and solar geometry are explained.

Chapter 3 is devoted to PV electricity generation. Solar cells' fundamentals, modules, arrays, PV effect, modelling and characteristics of solar cells, power conditioning equipments, various types of PV systems etc. have been described.

Chapter 4 presents the PV systems' design aspects. Typical size and ratings of various components along with practical designing of the PV systems are illustrated.

In Chapter 5, performance assessment of PV power plant in terms of various performance parameters such as normalized performance index, solar fraction, performance ratio, capacity factor, efficiency, losses, energy flow pattern etc. have been discussed.

Thermo solar electricity generation technologies are outlined in chapter 6. Passive hot water solar system, parabolic trough, parabolic dish, solar power tower and solar pond are explicated.

Chapter 7 illuminates on various simulation tools for design and analysis of solar energy systems. Distinguishing features of the simulation tools are presented.

Author has tried to fashion the vast amount of material available from primary and secondary sources into coherent body of description and analysis. Materials from the works of various eminent authors have been found useful for writing this book, for which the author in all modesty wishes to express his gratitude.

He would like to express his gratefulness to Mr. N.K. Mehra, Managing Director, Narosa Publishing House for taking responsibility of publishing this book and also thank all those who were in any way related to this work for their co-operation and help.

Errors might have crept in despite utmost care to circumvent them. Author shall be obliged of these are pointed out along with other suggestions for improvement of the book.

**Subhadeep Bhattacharjee**

# Contents

CHAPTER

# 1

# Energy and Power

## 1.1 ELECTRICITY FUNDAMENTALS

### 1.1.1 Electrical Concepts

The purpose of this section is to understand enough about electricity in the context of photovoltaics (PV). When talking about electricity, terms like **power** and **energy**, which we often use interchangeably in daily speech, as well as **current**, **potential**, **charge**, **electrons**, and even **photons** are frequently used. Though we might have learned about all of these, but usage in daily life may have confused their meaning. Here some important electrical concepts are discussed.

**Power:** The *rate at which work is performed* or energy is supplied, or the amount of energy required or expended for a given unit of time. It is measured in **watts (W)**.

**Energy:** The actual *work* done, for example, by solar panels, in other words, *power over a period of time*. It is typically measured in **joules** or (in the electric business) **watt-hours (Wh)**.

**Potential:** The *capacity* of an electric field *to do work* (*provide energy*), like the height of water behind a dam (the higher the water, the more energy available). It is measured in **volts (V)**.

**Current:** A movement or *flow of electrically charged particles*, like the speed of water flow in a river. It is measured in **amperes (A).**

**Resistance:** The property of a material, object or circuit to resist the flow of electricity. Materials that allow electricity to flow easily (with low resistance) are called **conductors**; materials that resist the flow of electricity are called **insulators**. It is measured in **ohms (R)**.

**Charge:** A property of some subatomic particles, which determines how they interact. Electrically charged matter is influenced by, and produces, electromagnetic fields. Charges are **negative** (as for electrons) or **positive** and have measurable strength.

**Field:** An *effect produced by an electric charge* that exerts a force on charged objects in its vicinity.

**Electron:** A negatively charged subatomic particle. The current is caused by the movement of electrons.

**Photon:** An elementary particle that is the carrier of electromagnetic radiation of all wavelengths. The photon is different from many other elementary particles, such as the electron, because it has no mass. That means that it travels (in vacuum) at the speed of light.

**Note:** *Light has both wave and particle properties.*

- *As a **wave**, light is distributed over space and can be refracted by a lens; reflected waves can cancel each other out (called 'destructive interference').*
- *As a **photon particle**, it interacts with matter by transferring energy.*

### 1.1.2 Units to Measure Electricity

**Watt:** The basic unit to measure power with electricity, just like horsepower is used to measure the power of cars. (1 hp is about ¾ kW). A watt can be defined with this equation: watts = volts × amps (W = V × I).

**Volt:** The unit of 'potential difference' or 'electromotive force' (or pressure.) volts = amps × ohms (V = I × R).

**Ampere (amp):** The unit of electric current. amps = volts/ohms (I = V/R).

**Ohm:** The unit of electrical resistance. ohms = volts/amps (R = V/I).

**Kilowatt:** Solar electric systems are sized and referred to in kilowatts (kW), which is a measure of the power available in the system, in other words, how much energy can be produced by the system at any given instance under optimal circumstances.

**Kilowatt hours:** To measure energy (which is also known as work, or output), a timeframe is needed together with the amount of power available. Utility companies use hours as the time factor and kW as the unit of power. So they bill customers in kilowatt-hours (kWh). Likewise, a 1 kW solar array in direct sun for one hour will produce 1 kWh energy to do work, like lighting a 100 W lightbulb for 10 hours.

### 1.1.3 Electricity Water Analogy

If electricity is compared with water running through a pipe

- Watts (power) measures the amount of water at the end of the pipe at any single point in time.
- Volts (force) measures the water pressure.
- Amperes (current/rate of flow) measures the volume of water flowing by a point.

So if it is taken the rate of water flow (amps) times the pressure (volts), the amount of water (watts) at the end of the pipe at any given instant would be available. The comparison with a measure of energy would be the quantity of water to, say, fills a bucket. This is equivalent to the *amount* at the end of the pipe times the *time* it takes to fill the bucket. So a kWh is like a bucket full of water (*watts*) filled *in a given time period (hours)* using enough water flow (amps) with enough pressure (volts).

### 1.1.4 Larger Power Units

Watts are really small and are used to describe the potential energy production of a single solar cell (around 3 watts) or single solar module (around 100-200 watts). Utility companies measure residential power consumption in kWh and residential solar arrays are measured in kW, for the power they can produce. These conversions might be helpful when you are talking about very large installations.

- One kilowatt (kW) is one thousand watts ($10^3$ watt)
- One megawatt (MW) is a million watts ($10^6$ watt)
- One gigawatt (GW) is a billion watts ($10^9$ watt)
- One terawatt (TW) is a trillion watts ($10^{12}$ watt)

## 1.2 ENERGY UNITS AND THEIR CONVERSION

Energy has many forms, viz., chemical, mechanical, electrical etc. During application of energy, it converts from one form to another but total energy always remains conserved. An energy quantity can be represented in several units. Table 1.1 gives the equivalence between different energy units.

**Table 1.1** Energy units and equivalent conversion

| Unit | Joule | | kWh (kilowatt-hour) | BTU (British thermal unit) |
|---|---|---|---|---|
| 1 joule | 1 | 0.239 | $2.78 \times 10^{-7}$ | $9.47 \times 10^{-4}$ |
| 1 calorie | 4.19 | 1 | $1.16 \times 10^{-6}$ | $3.96 \times 10^{-3}$ |
| 1 kWh | $3.6 \times 10^{6}$ | $8.59 \times 10^{5}$ | 1 | $2.93 \times 10^{-4}$ |
| 1 BTU | 1055.06 | 251.99 | $2.93 \times 10^{-4}$ | 1 |
| 1 joule = 1 N–m (newton-meter) | | | | |
| 1 TOE (ton of oil equivalent) = 11634 kWh | | | | |

## 1.3 RENEWABLES

Figure 1.1 depicts the classification of major renewable power generation sources. Renewable sources of electricity take many forms, e.g., the

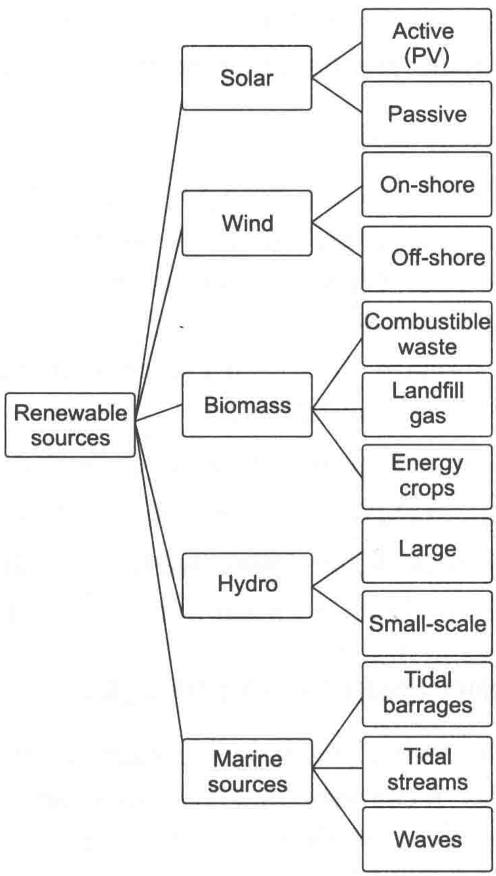


**Fig. 1.1** Classification of renewable energy sources

marine sources – tidal barrages, tidal streams and waves – wind both on-shore and off-shore, biomass – combustible waste, landfill gas and energy crops – hydro – both large and small-scale – and solar – both active (PV) and passive. Among these stochastic (fluctuating) renewable energy sources are wind and tide. The various forms of renewable energy depend primarily on incoming solar radiation (discussed in Chapter 2).

## 1.4 BENEFITS OF RENEWABLE POWER GENERATION

- Fuel sources are free, abundant and inexhaustible.
- Eco-friendly.
- Operation and Maintenance (O & M) costs are low.
- As the technology is maturing, the cost of the devices is declining. In last two decades cost of photovoltaic (PV) has gone down by more than 10 times.
- A coal mine and power plant requires more than 5 times the amount of land to comparable wind farm, to produce the same amount of electricity during a 20 year period.
- Saving of fossil fuel.

## 1.5 MYTHS OF SOLAR ELECTRICITY GENERATION

- There is not enough sunlight in many parts of the world.
- Solar electric technology is not efficient in a cold climate.
- Solar electricity generation is not a proven technology.
- Solar photovoltaic systems are too expensive.
- Suitable for only small scale generation.

### *Reply*

- Solar radiation is available in every part of the world (Fig. 1.2). Average solar radiation across the world varies in the range of 3-7 $kWh/m^2/day$ which is quite admirable for solar electricity generation. Germany ranks first in the world in terms of PV installed capacity in spite of cold and cloudy climatic condition there.

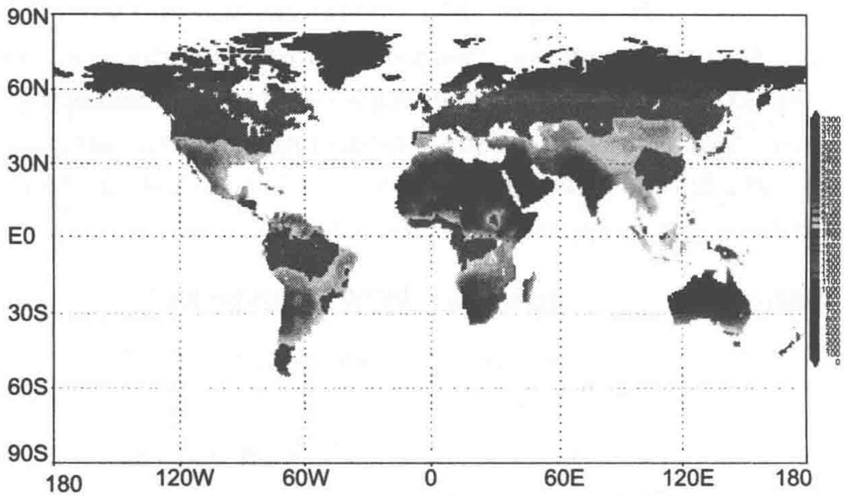


**Fig. 1.2** Annual mean solar radiation

- Temperature is a large factor in the performance of a solar cell. The maximum allowable voltage across a solar cell is equal to the bandgap voltage, this occurs when the temperature of the cell is at 0 K. As temperature increases, the bandgap and voltage across the cell decreases. Since the bandgap has decreased, it takes less light energy to free electrons from the solar cell and there will be a slight increase in the output current. There is drastic decrease in the output voltage with increasing temperature and the overall output power of the solar cell decreases. A solar cell's output power increases as irradiance increases and temperature decreases. Therefore ideal locations for solar PV panels are in cold climates that receive lots of sunlight.
- Users of PV power systems appreciate their quiet, low maintenance, pollution-free, safe and reliable operation, as well as the degree of independence they provide. The use of photovoltaic (PV) technology is increasing rapidly in developed and developing countries. Thousands of PV systems in myriad applications throughout the world today have debunked the myths of 'not a proven technology'. Solar PV power supply is till now most reliable source of power for space applications.
- The worldwide market for PV has grown exponentially over the last ten years as PV costs decreased significantly (Fig. 1.3). The cost of PV is likely to decrease further over the next ten years; if