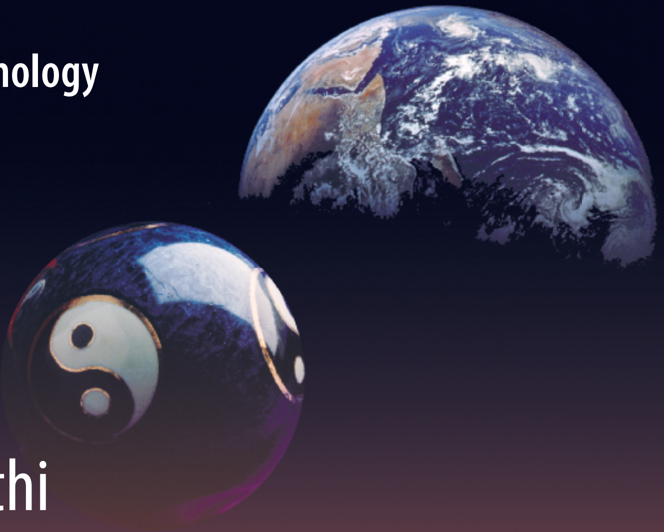
Green Energy and Technology



Malti Goel
V. S. Verma
Neha Goel Tripathi

Solar Energy

Made Simple for a Sustainable Future

Climate Change
Research Institute

Springer

Green Energy and Technology

Climate change, environmental impact and the limited natural resources urge scientific research and novel technical solutions. The monograph series Green Energy and Technology serves as a publishing platform for scientific and technological approaches to “green”—i.e. environmentally friendly and sustainable—technologies. While a focus lies on energy and power supply, it also covers “green” solutions in industrial engineering and engineering design. Green Energy and Technology addresses researchers, advanced students, technical consultants as well as decision makers in industries and politics. Hence, the level of presentation spans from instructional to highly technical.

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Dedicated to SuryaDeva (Hindi name for Sun God)

Om Adityaya Vidmahe Sahasra Kiranaya
Dhimahi Tanno Surya Prachodayaat //

—I meditate on the Sun God, the one with thousands of rays. Let the Sun God (Surya Deva) illuminate my intellect.

Preface

> *…We should be using Nature's inexhaustible sources of energy—sun, wind, and tide… I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that.*
>
> *—Thomas Edison in 1931in conversation with Henry Ford*[1]

Solar energy is people's energy. The book *Solar Energy: Made Simple for a Sustainable Future* provides glimpses of vast application areas of solar energy. Its 14 chapters aim to create public awareness about solar energy, educate the youth about the fundamental principles of its conversion, and create understanding among the masses about its large-scale applications. Since ancient times, many world regions have harnessed Sun's energy for human comfort. Solar as an alternative for electricity generation became known in the last seventy years. The book explores new ways of harnessing solar energy as chemical energy, in addition to solar heat and light, and covers large-scale applications in buildings and cities. Fundamentals of solar collectors, and various other devices, being used in households and industry for power production, process heating, and cooling are described.

Progress in solar energy is helping us to meet our national commitments for international agreements and protocols such as Paris Agreement on climate change and achieving sustainable development goals. The book has a particular chapter on International Solar Alliance, an Indian initiative with a vision to realize "One Sun, One World, One Grid". India being a tropical country, there is plenty of sunshine throughout the year, and "solar hotspots" are many. India has set a laudable target to achieve the installed capacity of 175 GW from renewable energy sources by 2022, out of which 100 GW is to be met from solar energy. A total of 48 GW has been achieved as of December 2021.

Dr. A. P. J. Abdul Kalam, late President of India, greatly appreciated the first author's book on Energy Sources and Global Warming published by Allied Publishers

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[1] 1987, Uncommon Friends: Life with Thomas Edison, Henry Ford, Harvey Firestone, Alexis Carrel, & Charles Lindbergh by James D. Newton (James Draper Newton), Quote Page ix, Harcourt Brace Jovanovich, San Diego, California.

in 2005. The author covered all renewable and non-renewable sources, and its two chapters discussed solar energy. The original idea for writing a new book came after the Paris Agreement 2015. The need was felt for revising, and the current book incorporates recent advancements in solar energy covered in the 14 chapters. It includes discrete chapters on solar resource assessment and utilization, solar PV plants, solar thermal energy, solar chemical energy, green hydrogen, solar cooling, solar buildings, solar rooftops, and solar cities.

The book is a quick reading for experts, researchers, and an inclusive knowledge resource to students and policymakers to expose them to solar energy's scientific and technological breakthroughs. It delves into the understanding of Sun's energy potential from idea to several applications and examples in practical use. The reader will learn how science has provided tools for harnessing solar energy, why you should pursue solar science and technology, and how it helps in clean energy transition contributing to the improvement in the environment toward net zero.

Acknowledgements For their inspiration, we convey our thanks to Shri. K. S. Popli, Ex-CMD, IREDA, Shri. P. S. Bami, Ex-CMD, NTPC Ltd., and Shri. R. V. Shahi, Ex-Secretary, Ministry of Power. Our thanks are due to Prof. D. P. Agrawal, Ex-Chairman, Union Public Service Commission, for his encouragement. The second author is thankful to Prof. P. S. N. Rao, Director, School of Planning and Architecture, for the motivation.

Many of our near and dear ones were taken away by pandemic COVID-19. May their souls be blessed and rest in peace! Authors remember late Pankaj Gupta, a close relative, as a great motivator, who was always very encouraging and inspiring all to learn and advance in their area of work and become a better person to do something for the country. By writing this book, we continue his legacy of knowledge sharing.

Lastly, the book aims to empower youth, city leaders, policymakers, students, and communities to understand the potential for solar energy and comprehend how its enhanced deployment could benefit sustainability and a move toward net zero.

New Delhi, India
December 2021

Malti Goel
V. S. Verma
Neha Goel Tripathi

Contents

Part I Solar Radiation and Its Conversion

Part II Solar Heat Energy and Chemical Energy Devices

Part III Large-Scale Solar: Local and Global

About the Authors

Dr. Malti Goel received her Ph.D. (Physics) and D.I.I.T. (Solid State Physics) degrees from Indian Institute of Technology, Delhi. She did M.Sc. (Physics) from Birla Institute of Technology and Science, Pilani in first rank receiving a Gold Medal. Her original research work has citations in handbooks, patents and international journals. Dr. Malti Goel has 26 years of distinguished service in the Department of Science and Technology, Government of India working in various hierarchal positions. She has been heading Inter-sectoral Science and Technology Advisory Committee Division (1998–2008) as Scientist 'G' and Adviser. Her contribution to steering physical sciences thrust area research and spearheading India's national programme on carbon sequestration research is well known. She was affiliated with the Indian National Science Academy and Jawaharlal Nehru University as Emeritus Scientist in the center for science policy studies. She has been adjunct Professor/guest faculty at Jamia Hamdard University, Centre for Southeast Asian and Pacific Studies, S. V. University, Tirupati and School of Planning and Architecture, New Delhi. She headed/convened working groups on HRD for Mineral Exploration and Development and S&T in Socio-Economic Ministries for XI five year plan, many high level scientific committees and nominated expert member on Science and Technology Advisory Committees in various socio-economic ministries. Dr. Malti Goel has won many prestigious awards and honors for her contributions to academics. She was conferred the Pearl Foundation *Life Time Achievement Award 2016* in recognition of her outstanding contributions and achievements in the field of Climate Change Research in India. Dr. Malti is author and editor of 13 scientific books and published nearly three hundred scientific papers in international reputed journals and conferences. She became a fellow of National Environment Science Academy in 2008. Currently as President, Climate Change Research Institute she is devoted to public engagement in science after being an active scientist and science policy maker for 40 years.

Shri. V. S. Verma obtained his BE (Mech) and ME (App. Thermo science) degree from IIT (Roorkee) and has been an adjunct professor in IIT (Kanpur) and distinguished professor in CPRI (Bangalore). Shri. Verma has been Member of Central Electricity Regulatory Commission (CERC) and officiated as Chairman CERC also for a brief period. Prior to that Shri. Verma was Member (Planning) CEA responsible for planning of electricity availability for the country. He has been Director General of Bureau of Energy Efficiency (BEE). His initiatives were responsible for improved availability of generating stations and transmission networks and preparation of CO_2 baseline data for power sector. He chaired Expert committee to set up Geothermal Project in Ladakh, J&K, and National Electricity Plan for XI plan; and the 16th Electric Power Survey was prepared under his guidance and leadership. He has also played a lead role in implementation of Energy efficiency and energy conservations programmes in various Indian industries and the power sector in the country. Shri. Verma was awarded life time achievement awards by CBI&P, Rajeev Gandhi Institute of Technology (Bhopal) and Council of Power Utilities. He is a distinguished alumnus of IIT (Roorkee). He has visited large no of foreign countries on official assignments, published more than 50 Tech papers in the national and International workshops and conferences.

Dr. Neha Goel Tripathi received her Ph.D. degree in Environmental Planning from School of Planning and Architecture, Delhi. She did her post-graduation (Master of Planning) also from School of Planning and Architecture, New Delhi with specialization in Environmental Planning (2003) and was awarded the Gold medal for overall performance. She did her B.Tech. (Architecture) from TVB School of Architecture. She is having experience of 17 years in the field of environmental planning and architecture and has worked on projects like Zonal Development Plan for Eco sensitive Area, Mount Abu, Indian Institute of Management, Indore, etc. Dr. Neha has published research papers on field of Ecological foot print, Solar Zoning, Climate change etc. Awarded the first prize for paper presentation, Climate Change and Indian Cities Perspectives presented for World Habitat Day 2011 organized by HUDCO, New Delhi. She is Assistant Professor in School of Planning and Architecture, New Delhi. She is Associate member, Institute of Town Planners, New Delhi, Member, Council of Architecture, New Delhi and Member, Indian Building Council, New Delhi and National Environmental Science Academy.

Abbreviations

A-h	Ampere hour
a-Si	Amorphous silicon
A.U.	Astronomical Units
AC	Alternating current
ACRE	Australian Cooperative Research Centre for Renewable Energy
AFD	Agence Francaise de Développement
BIPV	Building-integrated photovoltaic
BPDS	Big parabolic dish system
CLFR	Compact Linear Fresnel Reflector
CASE	Commission of Alternate Sources of Energy
CCAC	Climate and Clean Air Coalition
CDM	Clean Development Mechanism
CdSe	Cadmium selenide
CdTe	Cadmium telluride
CERC	Central Electricity Regulatory Commission
CH_4	Methane
CIAL	Cochin International Airport Limited
CIGS	Copper Indium Gallium Diselenide
CIS	Copper indium diselenide (CuInS2)
CO_2	Carbon dioxide
COP	Coefficient of performance
COPs	Conference of Parties
CRMM	Common risk mitigation mechanism
CRTS	Central receiver tower system
CSP	Concentrated solar power
DC	Direct current
DDG	Decentralized Distributed Generation
DHI	Diffuse Horizontal Irradiance
DISCOM	Distribution Companies
DNES	Department of New Energy Sources
DNI	Direct normal irradiation

DST	Department of Science and Technology
EIB	European Investment Bank
EMC	Equilibrium Moisture Content
EXIM	Export Import Bank of India
FF	Fill factor
FICCI	Federation of Indian Chambers of Commerce and Industry
GBI	Generation Based Incentive
GDAS	Global Data Assimilation System
GHGs	Greenhouse gases
GHI	Global Horizontal Irradiance
GIS	Geographic Information System
GIZ	The Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GNI	Global Normal Irradiance
GW	Gigawatt
GWP	Global warming potential
H	Hydrogen
He	Helium
HFCs	Hydrofluorocarbons
HTST	High-temperature solar system
IGCC	Indo-German Chamber of Commerce
IMD	India Meteorological Department
ISA	International Solar Alliance
IR	Infrared
IREDA	Indian Renewable Energy Development Agency
KJ	Kilo Joules
kWh	Kilowatt hour
L	liter
LCOE	Levelized cost of electricity
LCZ	Lower convective zone
LSTM	Long Short-Term Memory networks
m2	square meter
mc-Si	Monocrystalline silicon
MIT	Massachusetts Institute of Technology
MNRE	Ministry of New and Renewable Energy
MPPT	Maximum Power Point Tracker
MW	Megawatt
N_2O	Nitrous oxide
NCZ	Non-convective zone
NDCS	Nationally Determined Commitments
NISE	National Institute of Solar Energy
NIWE	National Institute of Wind Energy
NWP	Numerical Weather Forecasting
NZEB	Net zero emission building
OMC	Operation and Maintenance (O&M) cost

OPV	Organic photovoltaic
OSC	Organic solar cell
OSOWOG	One Sun One World One Grid
pc-Si	Polycrystalline silicon
PCM	Phase Change Materials
PFCs	Perfluorocarbons
PR	Performance ratio
PM-KUSUM	Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan
PTC	Parabolic trough collector
REC	Renewable Energy Certificate
RESCO	Renewable Energy Service Company
RTPV	Roof Top PV
SEGS	Solar energy generating systems
SGSP	Salt gradient solar pond
SPV	Solar Photovoltaic
SRISTI	Sustainable Rooftop Implementation for Solar Transfiguration of India
SF_6	Sulfur hexafluoride
SDG	Sustainable Development Goal
SRMI	Solar Risk Mitigation Initiative
SRRA	Solar Radiance Resource Assessment
STFI	Solar Thermal Federation of India
STPP	Solar thermal power plant
STARC	Solar Technology Application Resource Centre
SWH	Solar water heater
TES	Thermal energy storage
TWy	Terawatt year
UCZ	Upper convective zone
UV	Ultraviolet
VAM	Vapor absorption machine
VCM	Vapor compression machine
UNFCCC	United Nations Framework Convention on Climate Change
UNCED	United Nations Conference on Environment and Development
WB	World Bank
WSTS	World Solar Technology Summit

Chapter 1
Solar Energy—Then and Now

1.1 Solar Breakthrough

A Solar Breakthrough*—In 2016, Solar Impulse 2 landed back after a 25,000-mile trek worldwide. It was a feat in which a two-pilot team demonstrated the solar energy potential to take a round-the-world trip without using any fossil fuel and relying only upon the Sun as a fuel source.*

The Solar Impulse was a commendable achievement since the first solar Aircraft demo by Paul Macready, who took a historic flight in 1981 from France to England, comprising of 1600 solar cells. Solar Impulse 2: in 2016, a solar-powered aircraft created excitement "*Solar Plane makes history after completing round-the-world trip*" as reported in The Guardian on 26 July 2016. After a 40,000 km journey with zero fuel, Piccard Bertrand and André Borschberg completed 118 h of flying. Using solar energy the plane reached its starting point in Abu Dhabi after nearly 17 months [1]. The navigation, which began on 9 March 2015, was made possible by using 2.3 tones solar battery. Sunlight constantly charged the 17,248 solar cells on board.

The Solar Impulse feat made possible what looked impossible; thus giving hope to mankind that solar energy is the energy of the future. As expected, solar energy technology is revolutionizing the energy scene. In the transportation sector viz.; solar cars, solar space crafts, solar two-wheelers, solar trains, solar buildings, and solar cities are the incorporating large-scale applications. Solar energy storage and solar hydrogen production is expected to accelerate the global clean energy transitions beyond our imagination.

1.2 Solar Energy in Ancient Times

Sun has been a source of energy on earth from time immemorial. Almost all of the ancient civilizations worshipped Sun as God. The deities or Gods of Sun, as manifested in their place of worship, are *Helios* in Greece, *Surya* in India, *Apollo* in

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Rome, and *Amaterasu* in Japan. North and South American natives also worshipped Sun. The Great Pyramid of Egypt, the last remaining construction from the list of the seven wonders of the ancient world, was built as a stairway to the Sun.

The relationship of Indians with the Sun is one of the oldest in history. The Sun has played a massive role in Indian art, culture, and spirituality. Indian culture embraces Sun worship. Konark temple in Odisha (known as the Black Pagoda) is a famous *Surya* Temple. *Gayatri Mantra* from Rig Veda is dedicated to Vedic Sun Deity *Savitar*. *Surya Namaskar* in Yoga Asanas and Rituals like *Chhath Puja*[1] are symbolic expressions of the immense faith of Indian culture in Sun God.

Documented evidence has shown that knowledge about the Sun as the center of the earth and the planetary system existed since the fifteenth to tenth century B.C. It is reflected in the following verse of ancient Rig Veda written sometimes during fifteen to tenth century B.C. translated as; "*The sun has tied Earth and other planets through attraction and moves them around itself as if a trainer moves newly trained horses around itself holding their reins*" (Rig Veda 10.149.1). According to Hindu Vedas, the *A„va* is symbolic of the Sun, which is the biggest source of energy in the Universe. *A„vamedha YÈga* is a process of harnessing solar energy. Sun, who is the king, accompanied by four queens, performed the *A„vamedha yÈga* [2]. Here four queens of the king are symbolic of four directions. The scripture says—"*SÊrya ÈtmÈ jagatas thu„a„ ca*". It translates into "it should be possible for anyone to acquire from Sun physical, mental, social, intellectual and spiritual boons" suggesting the Sun is the soul of this world.

One of the earliest direct solar heating applications was building greenhouses for plant growth. Before glass was invented, a thin mineral sheet of mica was used to construct greenhouses. Such a greenhouse was built for Tiberius, who wanted to eat cucumbers throughout the year. Solar greenhouses helped in maintaining the desired temperature inside the chamber for growing cucumber. Since then, many improvements have been made to increase the variety of crops that can be grown suiting the varied climates.

Ruins of Indus Valley and Harappa suggest that solar energy was effectively utilized in 4000 BC through positioning and orientations of buildings. In early societies, solar architecture evolved by placing buildings to face south to gather heat and light, heating and cooling with added open courtyards in the middle. Hence progressively fundamentals of solar architecture in building houses were adopted in Chinese, Roman, Greek, and Egyptian civilizations.

Box 1: SUNDIAL Solar Observatory, Jaipur, Rajasthan

Maharaja Jai Singh of Jaipur in India built a SUNDIAL in the early eighteenth century AD, depicting his advanced knowledge of planetary system and celestial position of the Sun. The unique location specific observatory made of stone comprises of nineteen astronomical instruments of great precision and

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[1] Worship devoted to Sun soon after the Diwali festival of crackers.

uses solar energy for the study of the sky operating in each of the three main classical celestial coordinate systems: (i) the horizon-zenith local system, (ii) the equatorial system, and (iii) the ecliptic system. The information about time of the day from the shadow and tracks solar movement in the sky with seasonal changes could be obtained. It has 14 structures built in a large courtyard, or gnomons of fascinating variety: some serve to measure time; others to study stars and constellations and predict eclipses or position the planets. *Samrat Yantra* is a Sundial 27 m high, that points to the North Pole and is the largest in the world. Many examples of early solar use in buildings exist in other parts of the world (Fig. 1.1).

Fig. 1.1 Solar Observatories, Jaipur

National Large Solar Telescope, Merak, Jammu & Kashmir

The Sun is a unique astrophysical observatory. India has proposed to setup the National Large Solar Telescope (NLST) in Merak with a scope to support and substantiate the multitude of solar atmospheric observations from space-based and ground based MAST telescope at Udaipur [3]. The NLST's innovative design and backend instruments will enable observations with an unprecedented high spatial resolution that will provide crucial information on the nature of magnetic fields in the solar atmosphere and reveal details one can never hope to see in distant stars.

The Gwalior Fort in India is an example of solar passive architectural marvel. It has extensively used scientific concepts of light bending principles, which have lighted basements two floors below with solar light. It was built during the sixth century AD or later (exact date not known, but the Fort existed in the ninth century

AD). In the twelfth–fourteenth century AD, uses of solar energy and wind energy had picked up in Europe. The “Age of Discovery”, also known as the “Age of Exploration” (fifteenth–eighteenth century), made use of technological advancements and fructified the use of the Sun’s thermal energy in many ways. It adopted carefully designed solar passive building systems with insulation, south-facing glass, and naturally assisting heating, cooling, and lighting. In the late 1800s, solar-heated collective Roman baths demonstrated effective use of solar thermal energy.

SUNDIAL was built by Maharaja Jai Singh of Jaipur in the early eighteenth century AD (please see Box 1). In more recent times, *Umaid Bhawan* Palace is the last royal palace in Jodhpur, a hot city in Rajasthan, India. The castle was built by Maharaja Umaid Singh in the early twentieth century before the Independence of India as a mitigation strategy for fighting drought and providing jobs to the helpless farmers. The Fort is an example of solar cooling with judicious local sandstone material with Indian architectural features. It gives a feeling of air-conditioning in the hot summer of Jodhpur.

1.3 Solar Energy in Modern Times

The energy resources are differentiated as, renewable and non-renewable. The renewable resources of energy are those which cannot be exhausted and can be used again and again. For example: Sun, wind, biomass, ocean tides and hydro, etc. The examples of non-renewable energy sources are; coal, oil, natural gas, uranium. The Sun is an abundant resource and provides much more energy than we can ever possibly use. More power from Sun reaches the earth in one hour (4.3×10^{17} kJ) than all the energy consumed globally in one year (4.1×10^{17} kJ) [4]. Humans have used solar energy in different forms enriched by ancient knowledge about Sun. Technology breakthroughs are taking place in harnessing solar energy directly and indirectly as source of energy for meeting ever increasing demand on the planet.

Science and technology has demonstrated ways to extract energy from the Sun in modern devices. Solar passive applications have transitioned to active devices with the knowledge of science. The breakthrough flight around-the-world using solar energy in 2016 was a spectacular feat in this direction. The technology of solar photovoltaic cells technology was developed in the 1950s. One of its first uses was in space satellite launched in 1958. Since then, the development of innovative solar energy technologies has continued. These developments and new inventions have led to a significant fall in the price of solar energy. Direct utilization of solar resources as heat, light, and chemical energy is possible in various applications. Technology has made the conversion of limitless solar energy into solar photovoltaic, solar thermal, solar chemical, and concentrating solar. Among these, direct photovoltaic conversion is still one of the most advanced solar energy applications. Innovations in others will continue to drive new solar energy technologies to help power a cleaner world. For indirect uses of solar energy, please see Box 2.

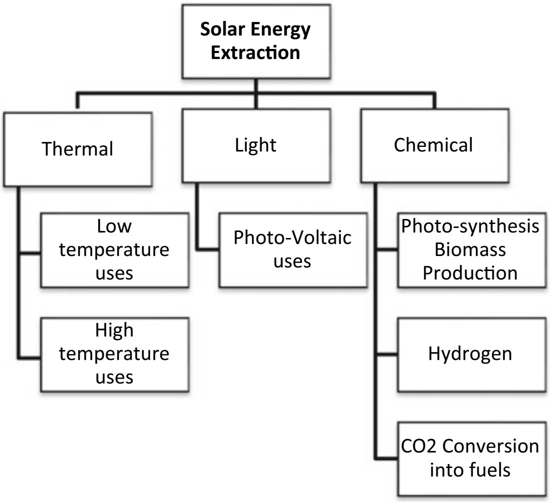

Fig. 1.2 Solar energy extraction methods

Leading technologies for solar energy direct use are solar heat and solar light. The applications range from low temperature uses in heating water or air, high temperature uses with concentrators to run the turbine for electricity production and conversion of light using photovoltaic cells. Solar chemical energy conversion to fuels like biomass and hydrogen are other technologies advancing rapidly (Fig. 1.2).

(1) *Solar Thermal*—Solar heat applications range from hot water baths to space heating and electricity production. Solar heat can be used directly for water heating, space heating in households, and low-temperature industrial applications. It can maintain a building infrastructure for human comfort by adopting passive heating or cooling techniques. We can also use it to make greenhouses, generate electricity, and process metals/alloys at high temperatures. Different solar collectors are used to optimize the utilization of solar heat at low temperatures in homes and industries. To get high-temperature beyond 300 °C, concentrating collectors in parabolic or spherical shapes are used. The mirrors focus the Sun's energy towards a receiver. When the temperature is high enough, we can use the heat from the receiver to run a dynamo and generate electricity. The largest concentrating solar thermal power plant globally has been built in California of 377 MW capacity [5].

Box 2: Indirect Forms of Solar Energy

Different forms of renewable energy are indirect conversions of solar energy. These are discussed as below.

Wind Energy—Earth is in constant motion orbiting around the Sun and also rotating along its axis. These motions result in uneven heating of the earth surface and cause variable air currents in the atmosphere. The energy possessed by air is the kinetic energy, resulting from the temperature differences as well as pressure differences on the earth's surface. A wind machine is used to convert the kinetic energy of the wind into electrical energy. Whenever wind blows electricity can be produced.

Hydro-Energy—The hydrological cycle on earth is maintained by the solar energy. Water in rivers and ocean gets evaporated by solar heat, it goes up to create clouds and falls back as rain on the earth, collects in rivers and catchments. The potential energy of water falling from a certain height can be used to run a turbine for generation of electrical energy. The dams are constructed on river fronts to increase the height of falling water for generating hydroelectric power. Energy from natural falls can also be extracted in microhydel plants.

Ocean Energy—The oceans store enormous solar energy in the form of thermal and wave energy. These ocean energies are useful to mankind as they are and can also be converted to electrical energy. For thermal energy, the temperature difference of ocean water from surface to a depth of about 1 km provides energy to run a turbine. For generating electricity from ocean waves, a wave energy converter is used. In addition to these two ways of exploring ocean energy, Sun and moon gravitational forces cause tides formation on a regular time scale, the height of tide depends on position of sun, moon and earth. Tidal power is being used to generate power at in many countries certain locations across the globe.

Biomass Energy—Sun is the source for all forms of biomass on earth produced by chemical conversion. Energy from the plants, plant wastes and agro-wastes can be generated by combustion or biochemical conversion. Burning of wood also produces biomass energy. It is not completely free from pollution.

Geothermal Energy—Geothermal heat can be utilized when the temperature difference between the surface of the earth and at a certain depth is sufficiently large. The geothermal heat works as heat pump for utilization as energy. Alternatively, it is converted to electricity in a Rankine cycle. Geothermal electricity has a lower efficiency and is also not completely pollution free.

(2) *Solar Light*—Solar light energy can be directly converted into electricity using a solid-state electronic device known as a photovoltaic (PV) cell. The cell is made of silicon, absorbs solar light and emits electrons to produce electricity. The earliest uses of solar PV energy were in high-end applications such as a space satellite or to charge a battery. From these specialized or micro applications, large-scale solar electricity in homes is seen as a solution to

climate change. Through direct conversion from solar cells, solar electricity has become the most convenient and cost-effective way to install solar cells on a larger scale as Solar Parks. As Solar Rooftops generate electricity, they are seen as a solution to energy security, which the owners can utilize and supply excess production to the electric grid.

(3) *Solar Chemical*—Solar chemical energy conversion aims to achieve fuel from solar radiation such as biomass or hydrogen. Solar light plays a vital role in photosynthesis, leading to plant growth by producing chemical energy. In the presence of chlorophyll, the plants convert the Sun's energy into sugars, providing food for growth and life. Solar energy is trapped and stored in chemical bonds and is essential for agriculture—cultivating land and producing crops and forests. Biomass energy can be recovered through the burning of wood or using thermo chemical or biochemical conversion processes. Another critical and direct emerging application of solar chemical energy is the electrolysis of water to produce hydrogen, which is again the clean energy source. This hydrogen can be used in automobiles as an energy carrier in fuel cells. Hydrogen and its isotopes are fuels in a Fusion Nuclear reactor. Solar chemical energy helps in the conversion of waste carbon dioxide into fuels.

Increasing solar energy use combats climate change by reducing greenhouse gas emissions during electricity production. With this in view, solar passive and active devices are being used and becoming cost-effective while reducing dependence on fossil fuels. Innovations in materials development in solar technology lead to floating solar plants on lakes and seawater and provide greater efficiency. A vast panorama of solar energy applications exists in various sectors of the economy that are explained in the book.

1.4 Solar Energy and Sustainable Energy Future

Energy is a vital resource for the growth of an economy and has the largest share in global warming. Current energy systems are unsustainable and, therefore, face the most significant challenges;

(i) Resource constraints for meeting the growing energy demand
(ii) Increased pollution, global warming and severe threats to human health.

Since the first industrial revolution, which took place in the eighteenth century, our energy demands have been met mainly from fossil fuel resources, coal, oil, and natural gas. The extensive use of fossil fuel resources in the past 250 years has resulted in substantial solid, liquid and gaseous wastes, causing environmental degradation. While solid and liquid wastes give rise to local and regional pollution, gaseous waste from energy generation results in global environmental pollution. It was estimated in 2019 that about 15 billion metric tons of fossil fuels were consumed in one year and added to almost two billion tons of carbon dioxide in the atmosphere

[6]. The increasing accumulation of carbon dioxide emissions in the atmosphere from the growing use of fossil fuels in power plants, industry, and automobiles for over two hundred years is the prime cause of global warming and climate change. The increasing combustion of fossil fuels is also leading to the depletion of the earth's resources.

Increased pollution is threatening life on the earth. The Intergovernmental Panel on Climate Change (IPCC) projections for earth warming using different models suggest that the world temperature could rise by 2.7–3.1 °C by the end of the century [7]. The global population will be primarily affected by extreme heat, water scarcity, and infectious diseases in the coming years. Recurring floods, sea-level rise, coastal migration, ocean acidification and ecosystem restoration are becoming critical challenges for humanity to tackle. The Avalanche of COVID-19, a major disaster in 2020 and its second wave in 2021, led to more than 4 million deaths, of which 2 million have happened in the first five months of 2021.

Climate change, depleting energy resources, and the increasing levels of pollution are driving the global economies towards adopting renewable energy (RE) sources. Solar energy would have the highest share among the various RE resources, as evidenced by the current growth trends. In 2019, solar technology had the largest share of 58% in total RE capacity addition, while wind energy share was 30%, and the remaining was from other sources. Three significant commitments that solar energy can fulfill towards sustainability are; International protocol on Paris Agreement on Climate Change, Transition towards Clean Energy and Implementation of UN Sustainable Development Goals.

1.4.1 Paris Agreement on Climate Change

Under the UN Framework Convention on Climate Change, the Paris Accord on Climate Change as International Protocol was agreed in the 21st session of the Conference of Parties (COPs) held in Paris in 2015. The agreement aimed to strengthen the global response to the threat of climate change by keeping the temperature rise well below 2 °C above the pre-industrial level and making efforts to limit the increase to 1.5 °C. Energy sector is the primary source of greenhouse gas emissions and global warming. According to BP Energy Survey, energy-related emissions would need to decrease by 3.5% per year to meet the Paris Agreement on Climate Change target. According to the sixth Assessment Report of IPCC,[2] climate change is already affecting every region on earth, is intensifying and stabilizing the climate will require intense, rapid, and sustained reductions in greenhouse gas emissions [8].

Recognizing that RE and energy efficiency improvement will significantly reduce the carbon dioxide (CO_2) emissions in the atmosphere, more than 50 countries and 200 cities are targeting 100% electricity generation from RE by 2050 towards net-zero

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[2] Released on 9th August 2021.

emission targets for compliance of the agreement. Globally there is a leapfrogging towards the use of solar technology in all sectors of the economy.

1.4.2 Clean Energy Transition

The world needs energy for development. Decarbonization of energy systems has become primary goal for reducing emissions in a step towards sustainability. Solar electricity is the emerging most favourable clean energy option. With no air pollution or liquid effluents, solar energy aims at a sustainable energy future. According to the World Energy Outlook 2020 of the International Energy Agency (IEA), Sun becomes the new king of electricity by 2040 [9]. After adhering to a constant price for several decades, solar modules have shown a price drop from 2008 onwards. The cost of solar PV electricity is becoming compatible with coal, as solar has grown fastest in the past decade. Combining this with technology flexibility, sunlight resource is undoubtedly the largest of all carbon–neutral energy sources.

According to International Renewable Energy Agency (IRENA), global RE capacity must reach 18 times the current levels, or become more than 8000 GW by 2050, to reduce 21% of CO_2 emissions while giving jobs to 18 million people [10]. In the Paris meeting, India has taken the lead to launch the International Solar Alliance (ISA) initiative for solar resource-rich countries to enhance climate-compatible development and to make a transition towards low carbon solar energy technology. Undoubtedly, solar energy technology development would help achieve primary targets of clean energy transition for the world.

1.4.3 Sustainable Development Goals

Solar photovoltaic technology (PV) has emerged as a source of cost-competitive clean energy and has a central role in achieving Sustainable Development Goals (SDGs) sub-targets. Solar energy has impacted all walks of life and provides several benefits other than climates, such as job creation, household savings, less pollution, improved quality of life and others. It directly addresses SDG 7 (Affordable and Clean Energy) to ensure universal access to affordable, reliable and modern energy services to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030. It also addresses SDG 13 (Climate Action) to combat climate change by reducing greenhouse gas emissions in the atmosphere. The health of the global population at risk due to air pollution improves, and it would add to SDG 3 (Good Health and Well-Being). By increasing the share of solar energy, millions of new jobs are being created, and it, therefore, would achieve SDG 8 (Decent Work and Economic Growth). Having 30% of the workforce as women would address SDG 5 (Gender Equality). Sun can reach areas where the grid cannot go, and solar energy provides electricity to rural and remote populations. By lighting primary schools, millions of children get schooling and SDG 4 (Quality Education) ensures that all girls and boys receive accessible, equitable, and quality primary and secondary education becomes strengthened. Educating the poor children would contribute to SDG 1 (No Poverty) and SDG 10 (Reduced Inequalities).

1.5 The Scope of the Book

Solar energy is people's energy. The book on 'Solar Energy: Made Simple for a Sustainable Energy Future' provides glimpses of vast application areas of solar energy. Its 14 chapters have a goal to create public awareness about solar energy, educate the youth about the fundamental principles of its conversion, and create understanding among the masses about its large-scale applications. As we go along, you will learn how science has provided tools for harnessing solar energy, why you should pursue solar science and technology and importance of solar energy for sustaining life on the planet.

The book's introductory chapter emphasizes on the importance of solar energy as a life-giver from primordial times to the present and towards sustainability in the future. The book has three parts. After the introductory chapter, Part 1 is dealing with the **Solar Radiation and Its Conversion**. Chapter 2 explains the unlimited solar resource, describes the composition of the Sun and earth and their atmospheres. Chapter 3 is on Solar Resource: Assessment and Utilization. It describes the fundamentals of the conversion of solar radiation into electricity, heat and fuels. The following Chap. 4 is about solar power plants, solar parks, decentralized systems, and micro grids. Chapter 5 explains what is a solar PV cell and the advancements in second and third-generation devices for improved efficiency that rely on development in materials sciences.

Part 2 covers **Solar Heat and Chemical Energy Systems**. Chapters 6 and 7 detail various appliances of solar low-temperature devices for homes and industries. Chapter 8 elaborates on solar concentrator high-temperature systems for electricity generation and industrial use. Chapter 9 describes solar cooling technology, an area expected to grow fast in the coming years. Chapter 10 is about solar as chemical fuel and the production of hydrogen.

Part 3 focuses on **Large Scale Solar: Local and Global**. Solar is playing an essential role in decarbonizing the industry and transport sectors and is contributing to zero-emission building and cities. Chapter 11 describes advancements made in building integration of solar power with examples. Chapter 12 gives current advancement's in solar rooftops in India. Chapter 13 describes solar cities to highlight solar energy potential in the towns towards a sustainable energy future. Chapter 14 is devoted to International Solar Alliance, an initiative to address global climate change that puts Sun in the limelight in foreign diplomacy.

1.6 Outlook

Solar energy can be a game-changer in the twenty-first century. The current book is dealing with direct solar energies. Indirect technologies are not covered. To summarize, the book aims at:

- Analyzing solar technology developments, with emphasis on their applications in urban and rural environments.
- Empower youth, city leaders, policymakers, students and communities to gain a greater understanding of the potential for solar energy and comprehend how its enhanced deployment could benefit local and global levels.
- Helping to meet national and international objectives relating to energy use and reduction of carbon footprints.

The book is a comprehensive knowledge resource to expose the reader to solar energy's scientific and technological breakthroughs. It delves into the understanding of solar systems, from theory to several applications and methods in practical use.

References

1. The Guardian (2021) Solar plane makes history after completing round-the-world trip. [Online]. Available at https://www.theguardian.com/environment/2016/jul/26/solar-impulse-plane-makes-history-completing-round-the-world-trip
2. https://ancientindianscience.in/v4/energy%20generation/solarenergy.html
3. https://www.iiap.res.in/nlst/?q=home
4. Report of the basic energy sciences workshop for solar energy utilization, 18–21 Apr 2005. http://www.sc.doe.gov/bes/reports/files/SEU_rpt.pdf
5. Buck R, Schwarzbözl P (ed) (2018) Solar tower systems. In: Comprehensive energy systems, 1st edn. Elsevier
6. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data
7. IPCC (2014) Climate change 2014: synthesis report. In: Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, 151 pp
8. IPCC (2021) AR6 climate change 2021: the physical science basis. In: Working group I
9. https://www.iea.org/reports/world-energy-outlook-2020
10. IRENA (2019) Renewable capacity statistics 2019. International Renewable Energy Agency (IRENA), Abu Dhabi

Part I
Solar Radiation and Its Conversion

Chapter 2
Sun: Unlimited Energy Resource on Earth

2.1 The Sun

The Sun, a hot ball of glowing gases, is one among the 100 billion or more stars in the Universe. The Sun at a surface temperature of 5778 K radiates energy equivalent to 3.846×10^{26} W. The average distance between Sun and Earth is 149,597,870 km or 1496 A.U. (approx.) (10^8 m = 1 Astronomical Unit or A.U.). The diameter of the Sun is 13.9 A.U. (approx.). The solar system comprises the Sun as star, and the planets Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune and dwarf Pluto; dozens of moons; and millions of asteroids, comets, and meteoroids. The entire solar system is orbiting at the center of the galaxy. It takes 225 million years to complete one revolution around the Milky Way.

The Sun is the closest star to the planet earth. The Sun is 99.8% of the solar system's mass and is nearly 109 times the earth's diameter. Earth continuously orbits around the Sun in an elliptical orbit, and therefore, the distance between Sun and Earth constantly changes. For heliocentric model of earth, please see Box 1. Around January 3, at Perihelion, the distance between earth and Sun is at a minimum, i.e., 1.471×10^{11} m. Around July 3, at Aphelion, the distance is at a maximum, i.e., 1.521×10^{11} m. Sun orbits in its galaxy and completes one revolution in about 250 million years. Some basic facts about the Sun are depicted in Table 2.1.

Earth's magnetosphere acts as a shield against cosmic particle radiation and protects it from solar winds. Sun has a magnetic field that is twice that of the earth's magnetic field. There is a solar activity cycle of 11 years, a subject of intense study for understanding its impact on the planet earth.

M. Goel et al., *Solar Energy*, Green Energy and Technology,
https://doi.org/10.1007/978-981-19-2099-8_2

Table 2.1 Basic facts about the Sun [1]

Mean distance from the Earth	149,600,000 km (1496 AU)
Diameter	1,392,000 km (109 times that of Earth)
Volume	1,300,000 times that of Earth
Mass	1.993×10^{27} kg (332,000 times that of Earth)
Density (at its center)	Over 100 times that of the Earth
Pressure (at its center)	Over 1 billion atmospheres
Temperature (at its center)	About 15,000,000 K
Temperature (at the surface)	5778 K
Energy radiated	3.846×10^{26} W

Box 1: The Heliocentric Model for the Solar System

Greek astronomer, geographer, and mathematician Ptolemy considered the Earth the center of the universe believed that Sun revolves around the earth and suggested a *geocentric* model. This hypothesis was contradicted by Nicolaus Copernicus only after 1700 years in 1543 AD. Copernicus gave a *heliocentric*, sun-centered model of the solar system suggesting that it is earth that is rotating around the Sun. However, the religious authority of the Roman Catholic Church had condemned his theory and the findings of Copernicus were not allowed to be published at that time. Later in 1642, Galileo Galilei discovered planet Jupiter and its moons, and also that Venus went through phases like that of Moon. Galileo got convinced that Copernicus was right and supported the *heliocentric model*. The Heliocentric model was later universally accepted. Today we know that Copernicus was right, Galileo was acclaimed. Knowledge about the planetary system continues to grow. Discovery of ninth planet and new moons of existing planets continues.

2.1.1 Internal Structure of the Sun

The Sun is a celestial body and a planetary energy source. Its structure has three zones. It has a *Core*, extending up to about 20–25% of the Sun's total radius. The Core attracts all gases toward the center. The temperature in this region exceeds 15 million degrees in Kelvins. The pressure is 250 billion times that of the earth's atmosphere. It is the source of unlimited energy produced by the fusion of hydrogen (H) nuclei to form helium (He)[1] by a process known as nuclear fusion.[2]

In a series of reactions, four hydrogen atoms combine to form one helium atom. As the lightest nucleus in the Periodic Table, the hydrogen atom has one proton and one electron. In contrast, the helium nucleus has two protons and two neutrons, and atom has two electrons. The mass of the helium atom is 0.7% less than that of four hydrogen atoms. The mass difference between one helium atom and four hydrogen atoms gets converted into energy. The energy released is about 3.6×10^{11} kJ of energy per mole of helium produced [2].

The fusion is explained by following reaction,

$$4^1\mathrm{H}_1 = 4\mathrm{He}_2 + 2\mathrm{p} + 2\mathrm{n} + \mathrm{energy}$$

In the above equation, p and n represent positron and neutrino, respectively.

The fusion of two nuclei results in an unlimited energy resource in the Sun. The mass difference gets converted into enormous energy. In comparison to nuclear fission of uranium, the energy produced by nuclear fusion is more. It is a million times more than the energy of chemical combustion. The reaction, however, is not so straightforward; it undergoes many steps. On earth, we have been trying to mimic the fusion by using two heavy isotopes of hydrogen, i.e., a deuteron—^{2}H and a triton—^{3}H. Deuteron and Triton undergo fusion reactions at extremely high temperatures and can form a helium atom and a neutron.[3]

The Core radiates the energy in all directions and transfers it to the *Radiative* zone of the Sun. The Radiative zone extends up to 70% of the radius from the center. The temperature at the top of this zone reduces from 15 million degrees to nearly 2 million degrees. Above the radiative zone, there is a *Convective* zone, which occupies the remaining space inside the Sun. This zone occupies almost 66% of the sun's volume. The energy from the radiative zone is transferred to the surface through convective currents in the convection zone. The temperature falls to around 6000 °C at the top of convective zone. It is estimated that it takes almost 10,000 years for the energy inside Sun to get transferred to the surface, while it takes only 8 min for the solar energy to cross the solar atmosphere and the earth's atmosphere and reach the ground.

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[1] When four protons (hydrogen nuclei) combine, they form one alpha particle identical to the nuclei of helium.

[2] German Physicist Hans Bethe gave the theory of nuclear fusion as a source of stellar energy in planetary stars.

[3] A huge International Thermonuclear Energy Reactor (ITER) of 500 MW capacity to demonstrate nuclear fusion, is under construction in France.

2.1.2 Sun's Atmosphere

Outside the sun's surface, its atmosphere comprises of Photosphere, Chromosphere, a Transition region, and the Corona. From the solar surface, radiation propagates out into space through the Photosphere.

The *Photosphere* is the visible surface of the sun that extends up to 400 km. Its temperature varies in the range of 6125 °C at the bottom to 4125 °C at the top. It emits the light we receive on earth.

The *Chromosphere* extends up to 10,000 km in height from the Sun and is made up of spiky structures known as spicules of 1000 km across at a temperature of 19,725 °C.

The *Transition region* is between Chromosphere and Corona. It extends up to a few thousand kilometers and sheds most of its light as ultraviolet rays. It gets heated by the Corona above it.

The Corona is a vital region made of structures such as loops and streams of ionized gas. When solar flares occur, the corona temperature rises as high as 500,000 °C to 10 million °C. The solar flares create solar wind streams of plasma and particles from the Sun out into space. The solar wind and solar flares are detected on the planets, including earth.

2.2 Energy Received from Sun to Earth

Earth is one of the eight planets revolving around the Sun in the solar system. Like Sun, the earth also has different names in different civilizations. According to Greeks, Earth is *Gaia*, a living system, and Roman called it *Tellus*—the fertile soil. In Hindi, it is called '*Dharti*' or '*Bhum*i'. Earth is an English/German name, which means 'the ground'. Earth is the only planet in the solar system known to have an atmosphere containing oxygen and water, the two essential sources of life. The Sun's energy received on the earth passes through its atmosphere.

2.2.1 About Earth and Its Atmosphere

Earth formed 4.5 billion years ago is nearly spherical. It has an equatorial radius of 6371 km and a polar radius of 6356 km. The surface area of the earth is 510 million square kilometres. Earth has the highest density of all the planets in the solar system, i.e., 5.51 g/cm^3. The gravitational force of the earth is 9.807 m/s^2 which is equivalent to 1 'g'. Earth orbits around the Sun once every 365.25 days. As one calendar year has 365 days, there is a leap year with an extra leap day every four years. Earth completes one rotation around its axis in 23.9 h. The earth's axis has a tilt of 23.44° away from the plane of the earth's orbit around the Sun. The tilt is called obliquity, and it changes with time on the scale of centuries. The tilt is responsible for the seasons and daily temperature variations. The earth travels in an elliptical orbit in space at a speed of 107,826 km per hour.

Around 71% of the Earth's surface is covered by water and the remaining 29% by land. Inside the earth, there are four main layers: an Inner Core at the center, an Outer Core enveloping it, a Mantle, and a Crust. The Inner Core is a solid made of iron and nickel, about 1221 km in radius. The temperature in the core is 5400 °C, almost the same as that on the surface of the Sun. The Outer Core of the earth is a viscous mixture of molten rocks about 2900 km thick.

Currents flowing inside the earth in its Outer Core generate a magnetic field. In the Mantle, convection currents flow, and the warmer material rises toward the Crust. The Crust thickness varies from 10 to 30 km thick on the land with a maximum at the equator. Inside the oceans, its extent is only 5 km from the seafloor up to the Mantle. The Crust is divided into seven tectonic plates, which are in constant motion. The slow movements give rise to change in the surface geology of the Earth over millions of years. It takes about 50,000–60,000 years for a blob to move a single kilometer.

2.2.2 Energy Received on the Earth

The Sun emits energy in all directions. The global solar radiation received on the earth passes through its atmosphere. The earth's atmosphere is varying in its composition with height. It has six layers; the nearest layer to the planet is Troposphere; followed by Stratosphere, Mesosphere, Thermosphere, Exosphere, and Ionosphere. The vertical structure of the atmosphere up to 100 km is shown in Fig. 2.1.

The atmosphere near the ground comprises roughly 78% nitrogen, 21% oxygen, 0.95% argon, and the remaining 0.05% has several trace gases in minute quantities. The mixture of gases is commonly known as air. The height of the troposphere is 8 km near the pole and 16 km near the equator. Almost 75% of the atmospheric mass lies up to the Tropopause. With increasing height, the gases in the atmosphere become rarer. Nearly 99% of the atmospheric mass is within 30 km. Some gases in the atmosphere act as greenhouse gases and help maintain an average temperature of around ~14.5 °C. Carbon dioxide, the leading global warming gas, is about 0.03% as a trace gas in the lower atmosphere.

The Sun's surface emits 63 million watts of energy per square meter [3]. The total energy emitted from the Sun in the form of electromagnetic radiation is 3.846×10^{26} W. The wavelength range of entire electromagnetic radiation varies from several thousand meters for *long radio waves* (10^{8} m) on one end to as small as a billionth of a meter for *gamma rays* (10^{-16} m) on the other. To determine the average energy radiated from the Sun, we apply the principle of black body radiation (please see Box 2).

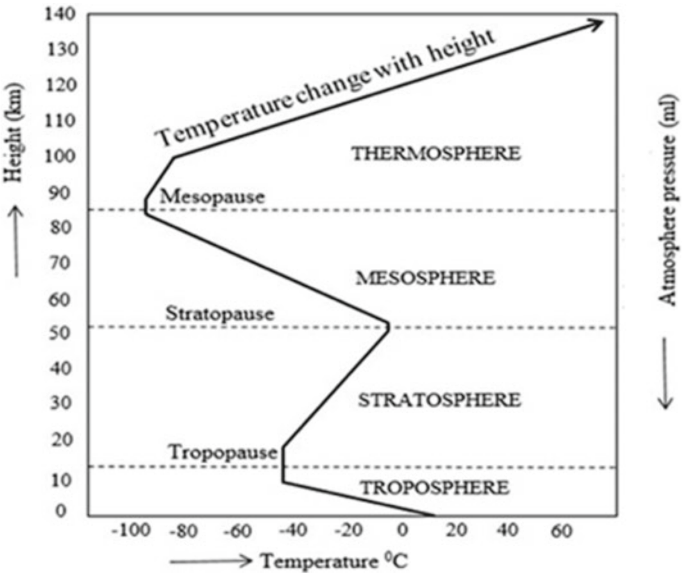

Fig. 2.1 Structure of Earth's atmosphere

Box 2: Principle of Black Body Radiation

A Black Body is an ideal body that absorbs all the radiation falling on it [4]. Since absorption is a property of black color, so it is called a black body. The spectral distribution of the thermal energy emissions from the black body depends on its temperature. It is stated by 'Stefan–Boltzman law', as 'Energy radiated from a black body is a function of its temperature'. The energy Es emitted from solar radiation can therefore be written as

$$\mathrm{Es} = \sigma \mathrm{Ts}^4 \tag{2.1}$$

Here, Ts is the surface temperature of the Sun

σ is known as Stephan–Boltzman constant, it has a value of 5.67×10^{-8} W/m^2.

All bodies at temperatures above 0 °C emit electromagnetic radiation. The wavelength distribution has a maximum at a particular wavelength depending on the temperature. From the peak in the spectrum, we can determine the surface temperature of the body. The Sun spectrum has a peak at 5778 °C. The solar radiation, when it strikes the earth, part of it is absorbed, and part of it is reflected into the atmosphere. Assuming that earth also acts as a black body; its spectrum has a maximum wavelength that falls in the invisible infrared region. The solar and earth radiations are depicted in Fig. 2.2.

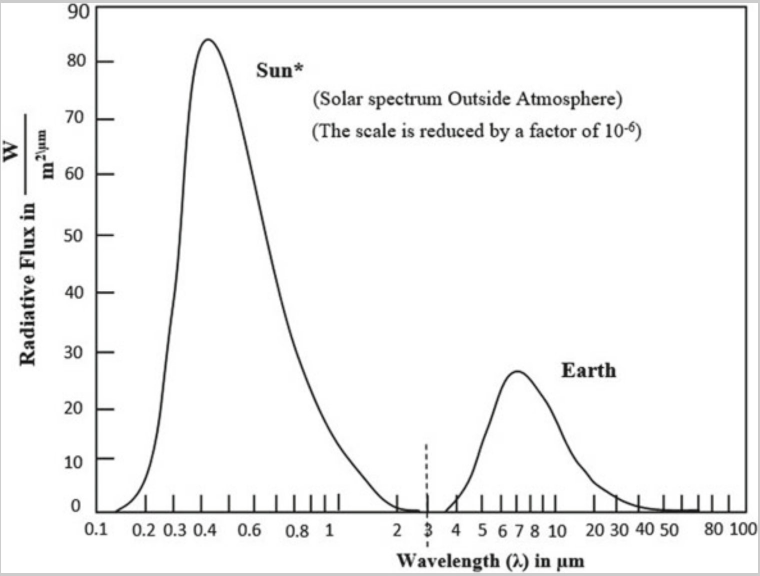

Fig. 2.2 The Sun and Earth spectrum

We use spectrum science to know the temperature of different stars in the Universe.

The average power density of solar radiation reaching the earth outside the atmosphere is 1368 W/m^2. Not all solar radiation falling on the top of the earth's atmosphere reaches the ground. It undergoes absorption, scattering, reflection, etc. Nearly 30% of solar radiation is reflected or scattered into space, and 20% is absorbed by the clouds and gaseous molecules in the air. Some part is scattered from the water surfaces. In the remaining 45%, if only 10% of total solar radiation is utilizable, the solar energy potential on the entire earth's surface in one year is 23,000 TW (terawatts). Assuming that the energy consumption on earth in 100 years is about 1600 TW, less than 0.1% of solar radiation reaching the ground can power the entire world.

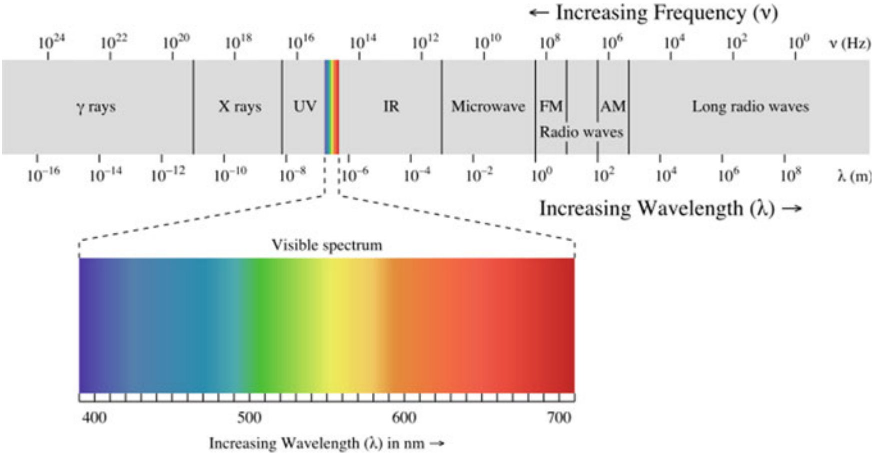

Fig. 2.3 Electromagnetic radiation and visible radiation wavelengths

2.3 Composition of Solar Radiation

The electromagnetic radiation from the Sun comprises $\surd$ rays, X-rays, ultraviolet, visible, infrared, microwave, radio wave,[4] and long radio wave radiation (Fig. 2.3). The sunlight received on earth is ultraviolet, visible, and infrared light and ranges from 100 to 5000 nm. The ultraviolet radiation (UV) (100–400 nm) comprises three wavelength bands: UV-A, UV-B, and UV-C. The shorter the wavelength, the more harmful it is. The UV-C (100–280 nm) wavelength band makes up 0.5% of all solar radiation and is the most damaging. The stratospheric ozone layer absorbs it and acts as a protective layer by preventing most of it to reach the earth. UV-B (280–320 nm) is a photo-activating radiation band, and it is only partially absorbed in the stratosphere. This radiation band is known to cause skin cancer in humans. However, UV light has a beneficial effect in retarding the growth of pesticides on farms. Recently scientists from the National Academy of Sciences America have reported the beneficial impact of UV radiation in reducing the COVID-19 growth rates [4]. It was seen that a 1 kJ m^{-2} h^{-1} increase in local UV reduces local COVID-19 growth rates by 0.09 (± 0.04, $P = 0.01$). UV-B can also penetrate the ocean up to 20 m below the surface and harm water inhabitants. The band UV-A (320–400 nm) is the safest. It can cause sunburns but has much less energy than UV-B. It undergoes scattering, leads to fluorescence, and also impacts the photosynthesis process.

The solar radiation breaks up is; infrared radiation (>700 nm), which makes up 49.4%, visible light (400–700 nm) having a share of 42.3%, and remaining as ultraviolet radiation (320–400 nm). More than 90% of the solar intensity lies in the visible and infrared regions and this energy is utilized as light or heat energy or as

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[4] Microwaves and radio waves help in the transmission of satellite signals and radio signals across the globe.

Table 2.2 Sunlight radiation and impact on the atmosphere

Type of solar radiation	Wavelength (nm)	Impact of atmosphere	Energy use
Ultraviolet (UV)-C	100–280	Absorbed in the upper atmosphere	–
UV-B	280–320	Absorbed by ozone in the stratosphere	1%
UV-A	320–400	Air molecules Rayleigh scattering and absorption	15%
Visible	400–700	Transmission, reflection scattering, and absorption by aerosols, clouds	15% up to 100%
Infrared (IR)	700–5000	Absorption by water vapor	15%
Thermal IR	5000–14,000	Absorbed in the atmosphere leading to greenhouse effect	

Compiled by authors from available data

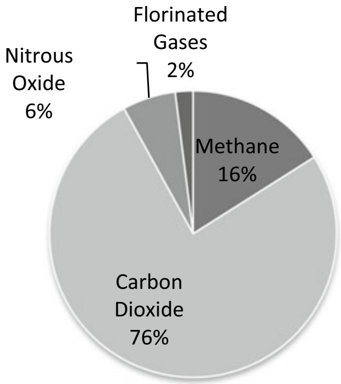
both. Table 2.2 describes the impact of the atmosphere on solar ultraviolet, visible, and infrared radiation.

2.4 About Natural and Enhanced Greenhouse Effect

In 1896, from the spectral studies of the solar and earth radiations, Svante Arrhenius (1859–1927) explained the 'natural greenhouse effect' as the earth's natural warming. Heat from the ground is radiated back into the atmosphere in invisible infrared light some of the atmospheric gases present naturally, absorb the radiation and redirect it back toward the earth. These gases thus trap the heat that would otherwise escape into space. In this manner, the natural greenhouse effect warms the planet to its comfortable average of 14.5 °C. The leading gases responsible for the greenhouse effect are carbon dioxide, methane, nitrous oxide, and water vapor, all occurring naturally in minute quantities except water vapor. Without these gases, the planet would be frozen and uninhabitable, like Mars or other planets.

The Industrial Revolution of the 1750s had resulted in the increased use of fossil fuels in coal-powered steam engines and power plants. Fossil fuel combustion generated pollution in the atmosphere. Growing emissions from energy consumption and other human economic development activities have added to the greenhouse gas volume and added new greenhouse gases into the atmosphere. These gases trap more radiation, and the temperature of the earth started increasing. It gave rise to the 'enhanced greenhouse effect', which led to Global Warming. The contribution of each

Fig. 2.4 Share of major anthropogenic greenhouse gases to the global warming. *Source* IPCC [6]



gas is known by its global warming potential (GWP).[5] According to the Intergovernmental Panel on Climate Change report, 2014, Fig. 2.4 shows how much each greenhouse gas contributes to global warming [5]. Energy generation and consumption made the highest contribution to greenhouse gases.

2.4.1 *About Global Climate Change*

Earth's dynamic system largely comprises; Atmosphere, Biosphere, Hydrosphere, Cryosphere, and Lithosphere, each changing on different time scales. These components are constantly interacting, and the atmosphere's rising temperature leads to feedback in other parameters. Such interactions have led to global climate change, manifested as ocean acidification, seasonal changes, frequent extreme weather events, and related calamities and disasters.

Globally, countries are ranked on their total GHGs and per capita GHGs (Figs. 2.5 and 2.6). On a carbon dioxide equivalent basis, China has the highest emissions and is responsible for 27% of all emissions. The United States is second at 15%. India is the third-highest emitter with a share of nearly 7% of the total global emissions. On a per capita basis, Saudi Arabia tops the list, the USA is fourth-highest, and India, with 1.96 tons per capita, is at the 21st position after Brazil.

The highest share of GHGs is from energy generation and consumption activities. Decarbonization of the energy systems has become the priority before the nations for reducing the emissions. The energy transition from a fossil fuel-based economy toward a clean share of renewable energy sources is expected to get accelerated in the coming decades. Solar energy leads the growth, and Sun is the topmost resource, being timeless and inexhaustible resource. With declining costs and the technology

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[5] The GWP of greenhouse gas is the cumulative radiation forcing of a unit mass of a gas relative to carbon dioxide as a reference gas over a given period.

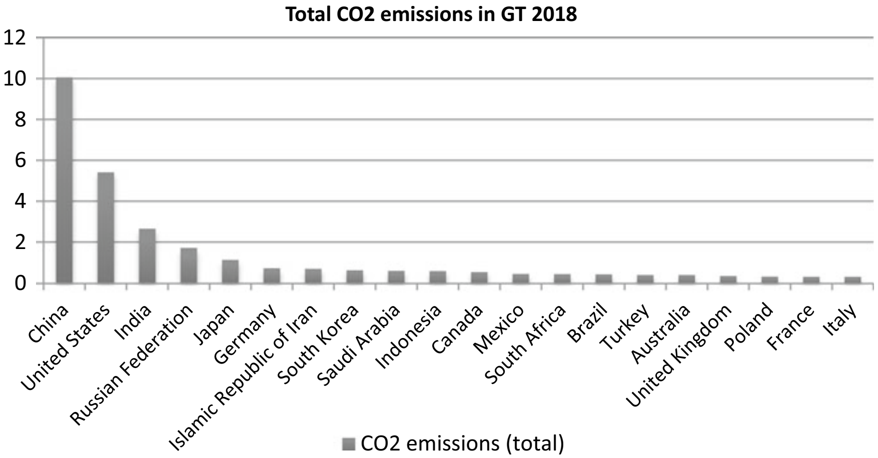

Fig. 2.5 The 20 countries that emitted the most carbon dioxide in 2018 [7]

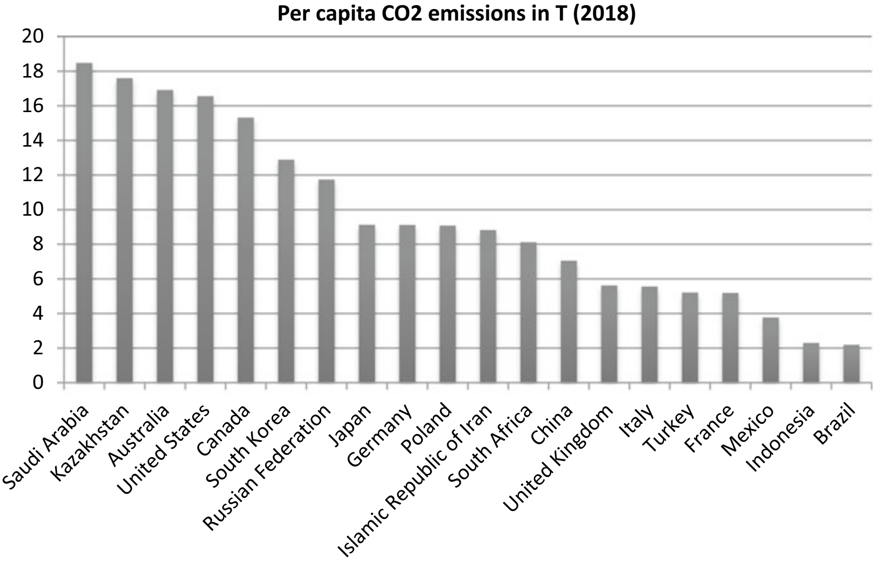

Fig. 2.6 Countries rankings by per capita greenhouse gas emissions, 2018 [8]

flexibility, solar energy has emerged as an abundant free resource to mitigate and address global climate change challenges.

References

1. https://theplanets.org/the-sun/
2. Nuclear fusion—chemistry libre texts. Available at https://chem.libretexts.org/
3. https://sciencing.com/earth-receive-heat-sun-4566644.html
4. https://astronomy.swin.edu.au/cosmos/b/blackbody+radiation
5. Carleton et al (2021) PNAS 118(1):e2012370118. https://doi.org/10.1073/pnas.2012370118
6. IPCC (2014) Climate change 2014: synthesis report. In: Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change
7. https://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions
8. https://en.wikipedia.org/wiki/List_of_countries_by_greenhouse_gas_emissions_per_person

Chapter 3
Solar Resource: Assessment and Utilization

3.1 Solar Radiation

The Sun emits 3.846 × 10^{26} W energy in one year. Sunlight is everywhere. Sun falls on every part of earth at least for a few hours in a year. A small portion of this is received on the earth. It is much higher than the total energy consumed globally in a year. We have seen that Sun is directly or indirectly at the origin of nearly all the energy resources we have on earth. However, studies have shown that solar radiation is economical for conversion into usable form of energy only when the 'solar radiation levels' at a location are high enough for most of the time in a year. The number of sunny days at a place and the number of solar hours daily are essential to know the solar potential of the location for utilization. Annual solar radiation or solar flux on earth varies from 800 to 2450 kWh/m^2. The world's regions having solar flux of at least 1750 kWh/m^2 in a year, which is equivalent to 4.5 kW/m^2 in a day, are suitable for Photovoltaic (PV) solar energy generation (Fig. 3.1).

The solar resource varies with the geographic location, time, season, weather, and the landscape. Its utilization involves capturing solar radiation, its conversion, and storage. Assessment of solar resources at a location is vital for knowing the potential for utilization. As solar plant pre-feasibility, therefore, requires; (i) What is the potential at a particular location for a specific technology? (ii) Is there enough area available for putting up the plant? (iii) Are adequate solar data available for the site? (iv) What will be the desired orientation of solar devices and shadows at the site? (v) Would it be an economically viable project for achieving grid connectivity? among others.

All these requirements are challenging to be met for solar energy production from a site. In practice, some compromises have to be made.

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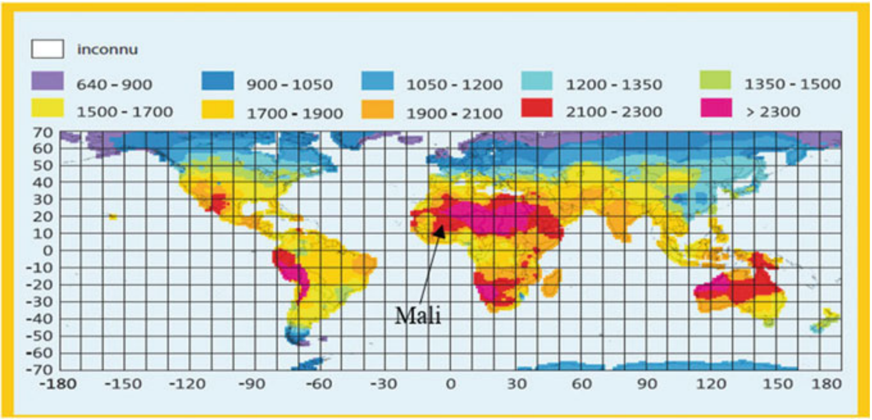

Fig. 3.1 Global distribution of annual solar radiation in kWh/m^2 [1]

3.2 Solar Resource Assessment

Solar energy strikes the earth at different angles. Polar Regions receive less radiation as compared to temperate or equatorial regions. Earth's distance from Sun varies as it revolves around the Sun in an elliptical orbit. Solar radiation reaching the earth's surface; undergoes absorption, scattering, and reflection. Three distinct physical processes operate simultaneously: (i) selective absorption by gaseous molecules like ozone, carbon dioxide, and water vapor, etc., (ii) selective scattering by atmospheric particles like dust, (iii) reflection from the clouds, the ground, and other surfaces. Solar resource measurement requires knowledge of various solar radiation parameters and a systematic collection of site-specific meteorological data and their variance in time and space. Key parameters are Solar Irradiance, Solar Constant, Insolation, and Air Mass Number to determine atmospheric attenuation of solar radiation.

3.2.1 Solar Irradiance

The intensity of solar light hitting the one square meter of the earth's surface, which is the sum of the contributions of all wavelengths within the spectrum, is called solar irradiance and is expressed in the unit of watts per m^2 (W/m^2). Irradiance gives a measure of solar energy that strikes a place. It is less when sunlight hits the earth at an angle. The earth moves around the Sun in an elliptical orbit and rotates around its axis. Its distance from the Sun and irradiance keep changing. Therefore, irradiance varies during the day and is not the same on all days throughout the year. At night solar irradiance is zero. Irradiance over a period is known as Solar Radiation (Fig. 3.2). The unit of solar radiation is watt-hour per m^2.

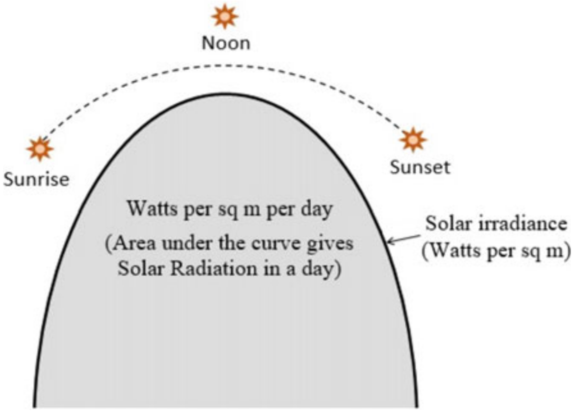

Fig. 3.2 Solar irradiance and solar radiation

3.2.2 Solar Constant

Total Sun's radiation falling on an imaginary surface at the outer edge of the earth's atmosphere in a perpendicular direction is known as 'Solar constant' and is 1.368 kW per m^2. The radiation incident on the outer edge of the atmosphere is partly absorbed, reflected, or scattered by clouds, dust particles, aerosols, the ozone layer, water vapor, and other gases, as well as industrial pollution in the atmosphere. On average, 20% of the radiation is absorbed by the cloud cover. A part of it is scattered from the particulate matter and pollutants in the atmosphere. When the particle size is much smaller than the incident wavelength, scattering occurs in all directions, known as Rayleigh scattering. When the particle size is bigger than the wavelength, Mie scattering occurs, and it is uni-directional (please see Box 1).

3.2.3 Insolation

When solar radiation reaches the earth's surface, it is reduced to a value less than the solar constant and varies from place to place. It is known as Solar **'Insolation'**. In a day, insolation varies by the timings of sunrise and sunset and several other factors. Hourly average radiation energy intercepted on a particular day at the ground can be calculated using the expression [2]

$$I_n = S\left[1 + 0.034\cos\left(2\pi\frac{n}{365.25}\right)\right] \tag{3.1}$$

where I_n is insolation on a particular day of the year with n starting from 1 for January 1st up to 365 for December 31st.

S is Solar Constant.

A part of insolation falling on the earth is reflected from the ground. This fraction is known as **Albedo**.

Box 1: Rayleigh Scattering and Mie Scattering

Two types of scattering occur from the atmospheric particle, depending on its size.

(a) *Rayleigh Scattering*—is primarily the elastic scattering of light from the atmospheric particles whose diameter is less than about one-tenth the wavelength of the incident light. Spatial redistribution of the energy of the incoming radiation takes place with predominance of shorter wavelengths and is responsible for blue of the sky. In the process, the wavelength of light does not change and the energy of scattered photons remains unchanged.

(b) *Mie Scattering*—is primarily the inelastic scattering of light from atomic and molecular particles in the air, whose diameter is equal to or larger than the wavelength of the incident light. Dust, aerosols, and water globules cause Mie scattering. Depletion in the solar radiation occurs both by redistribution of energy as well as wavelength. The scattered signal is proportional to the square of the particle diameter and it varies according to the angle of scattered light. A part of the radiant energy is transformed into heat. This type of scattering also leads to a fraction of the solar radiation converted as diffuse radiation.

3.2.4 *Solar Declination*

Solar declination angle is an important parameter to understanding the solar resource at a place. Solar declination is the ratio between the lengths of the atmosphere traversed by the solar beam to the distance traveled when the Sun is perpendicular to the earth. We can compute declination angle [3] from

$$\theta = 23.44 \sin \frac{360}{365}(n - 81) \tag{3.2}$$

where θ is the angle of Solar declination and n is the day of the year.

It fluctuates seasonally. The earth is tilted by 23.44° on its axis of rotation and the solar declination angle varies from +23.44° (on June 21) to −23.45° (on December 22). The declination angle becomes 0° during Spring (March 23) and Fall (September 23). Declination angle[1] variations define Solstice—occurs when Sun reaches the

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[1] If the earth was not tilted on its axis of rotation, the declination would always be 0°.

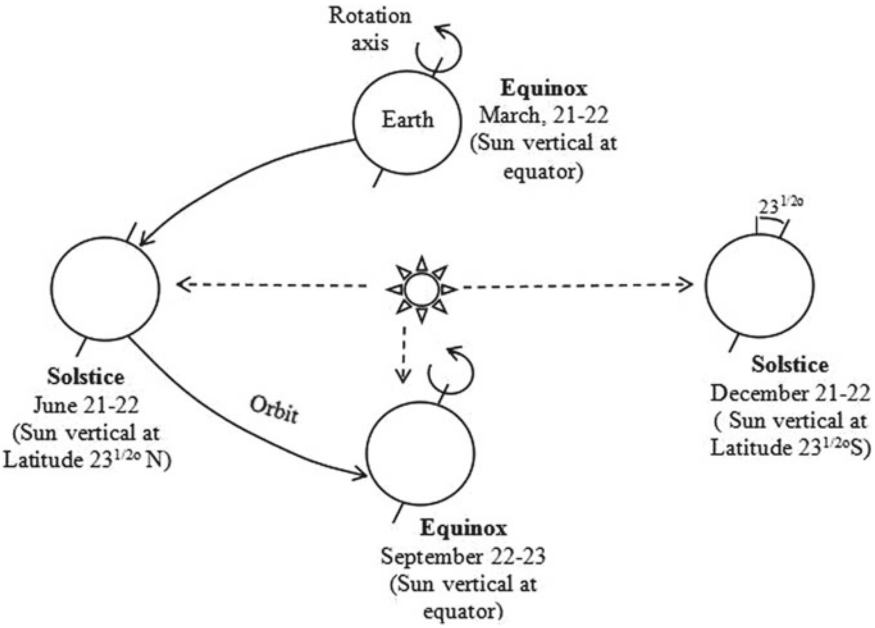

Fig. 3.3 Characteristics of the Earth's orbit Solstice and Equinox

farthest or highest point from the Earth equator, and Equinox—the time when declination is zero. The summer solstice occurs when Sun comes to the highest point in the Northern hemisphere, and the Winter solstice occurs when it is farthest in the Southern hemisphere. We experience different seasonal changes in the two hemispheres because of these variations (Fig. 3.3).

3.2.5 Air Mass Number

'Air mass Number' (A_m) measures the total attenuation of radiation in the atmosphere. Atmospheric attenuation of energy intercepted by earth depends on the distance traveled in the atmosphere, cloud cover, atmospheric pollutants, and other obstacles that scatter light. Both intensities of solar radiation and its spectral content on the earth's surface impact Air mass number. It also depends on the solar declination at a place. The Air mass number (A_m) is given by,

$$A_m = 1/\cos\theta \tag{3.3}$$

cos θ for $\theta = 0$–90° varies from 1 to 0. When the Sun is directly overhead, and θ is zero, cos θ becomes one, and $A_m = 1$. When it is 90°, cos θ becomes 0, and this would mean $A_{\mathrm{m}} = \infty$. The air mass number is therefore always greater than or equal to one, at the earth's surface. The larger the air mass number more is the attenuation.

3.2.6 Global, Direct, and Diffuse Solar Radiation

Solar Resource determination at a place and its utilization potential require global, direct, and diffused radiation data. Total solar radiation received on earth is global solar irradiation. It comprises both 'direct' and 'diffuse' radiations. Direct radiation is measured as Direct Normal Irradiation (DNI) and is a function of the altitude and solar declination, as given by the equation,

$$\mathrm{DNI} = A \sin \theta \tag{3.4}$$

where A is the altitude of the place and θ is the declination.

Solar energy potential at a place includes direct radiation as well as diffuse radiation. Diffused solar radiation is indirect diffused radiation scattered from clouds, dust particles, and other gases. Global Horizontal Irradiance (GHI) data provides a measure of diffuse radiation. Both DNI and GHI are essential for flat plate collectors, such as PV and low-temperature devices. The DNI data are significant in devices having concentrating collectors such as high-temperature devices. The DNI and GHI data tables are essential at potential locations for solar resource assessment.

3.2.7 Tilt Angle

The tilt angle is a critical parameter for mounting solar panels. The angle between the solar array or collector and the horizontal surface that gives a maximum incidence of solar radiation on the panel is called the tilt angle. The panel should face southwards when in the Northern hemisphere and northwards when in the Southern hemisphere to optimize solar radiation. At a particular latitude tilt angle of latitude $+15°$ in winter and $-15°$ in summer is recommended. Adjoining areas' geography affects the actual orientation. The moving panels track the Sun, and they can capture more energy than the fixed panels.

3.3 Solar Resource Utilization

Accurate solar assessment of a site helps in making the investment decisions for putting a solar energy plant. Effective solar resource utilization needs a vast amount of data. Satellite-based, ground-based, and a combination of these measurements give a reasonable accuracy. From seven to ten years' measurements, we determine long-term averages—other databases such as land cover, land use, and terrain help model the solar resource. Solar power variability forecasting is carried out to assess the potential of the location for a particular application.

3.3.1 Solar Power Variability Forecasting

In solar power variability forecasting, the following data sets are considered necessary.

(1) Satellite-based measurement data
(2) Ground-based measurement data
(3) Numerical weather forecasting data.

(1) *Satellite-Based Measurements*

Weather satellites in a geostationary orbit provide essential information about various solar parameters on the earth. Visible and infrared radiations scan the ground, line-by-line in space and time using sensors onboard. Monthly meteorological data sets have 1° × 1° grid (111 km × 111 km) using observations from over 200 satellites and thousands of ground stations [4]. Besides the weather parameters, satellites have other sensors to measure basic solar parameters, including irradiance, aerosols optical depth, water vapor, ozone, etc. The spatial resolution of 3–5 km and time resolution of 15–30 min is required to generate solar atlas. It provides the information about temporal characteristics of the resource. Satellites provide instantaneous spatial averages, from which hourly data is computed by extrapolation. Satellite-based measurements provide data with a lower frequency but represent long histories over larger territories.

(2) *Ground-Based Measurements*

After a potential site for a solar plant is identified using satellite data, the ground-based measurements of solar parameters usually are carried out as part of the investigations. The data from such ground-mounted instruments provide ground truth and provide data in time and space at several grid points. They provide validation for the satellite data, remove uncertainties' and help in improving the efficiency of resource utilization on selected sites. The meteorological data at the site are collected simultaneously, and data tables are made. Ground base measurement data are precious because they are simple, cost-effective, and more accurate than satellite-based measurement data.

A **Pyranometer** provides for the measurement of solar parameters. It gives high-quality data for global solar irradiance. Pyranometer has a dish-like structure for a 180° view and acts as a black body absorber from inside. It is best suited for Global Horizontal Irradiance (GHI) measurements. It can receive direct and diffuse radiation and has a sensor to measure the voltage generated due to solar heat. **Pyro-heliometer** measures direct irradiance. It is used for measurement of Direct Normal Irradiance (DNI). It tracks the Sun by aiming the instrument directly on Sun. By obstructing the direct radiation with a sun-tracking disk, DHI can be measured. Another device, **Lux meter** is used to measure the intensity of light falling on a specific area.

In practice, satellite and ground-based measurements data are combined and corrections are made to develop GHI and DNI maps at selected locations. Data sets include historical data, real-time data, and regularly updated data. Solar GIS has been validated for nearly 200 potential sites across the world. These provide a reasonable estimate of resources with an accuracy of 5%.

(3) *Numerical Weather Forecasting Models*

Numerical Weather Forecasting models use the Global Data Assimilation System (GDAS). It comprises global meteorological data, appropriate models, and neural networks. Solar resource, which is variable during the day, is affected by weather conditions like clouds, particles, wind, etc. It makes solar energy output intermittent. Weather forecast determines conditions of the atmosphere at a given location and time of the day. Several weather parameters from temperature and precipitation to lightning and wind parameters, rain, and relative humidity assimilate to provide short-term and long-term forecasts for the meteorological services.

3.3.2 Importance of Weather Forecasting in Solar Resource Utilization

Weather forecasting has an important role in solar resource utilization. An accurate weather forecast helps in achieving the full potential of the resource. Therefore, forecast capabilities are becoming the most important component of solar resource utilization for optimum generation and grid integration. Actual scheduling for RE in the grid also requires an accurate weather forecast. In forecasting, we use different terminology. Seasonal forecast is also a *medium-term* forecast. Better forecasting in the *short-term*, which is one day in advance, is critical for grid operators to accommodate changes in solar generation more efficiently. *Day-ahead* forecast supports unit commitment decisions; scheduling of solar power improves operational efficiency and cost-saving. Several existing short-term solar variability forecasting methods make use of cloud images as input. A *very short-term* forecast is 6 h in advance; it helps determine the need for a quick startup generator, better demand response and supports reliable operation of the electricity grid (Table 3.1).

There is an urgent need to upgrade predictive analysis modeling methods to achieve the resource's full potential; current research focuses on forecasting up to 6 h in advance.

Table 3.1 Solar resource forecast categories

S. No.	Time in advance	Nature of forecast	Benefits
1	Up to 1 h	Near-term	Relative dispatch decisions
2	Up to 6 h	Very short-term	Near term unit commitment (startup generator)
3	I day or more	Short-term	Unit commitment and scheduling, market trading
4	Seasonal up to a year	Medium-term	Resource planning
5	Up to 20 years	Long-term	Project sitting long-term planning

3.4 Solar Project Pre-feasibility Assessment

Besides solar variability forecasting, a project feasibility assessment is required for its optimum utilization. It considers the solar theoretical potential and data tables created for variations with the time of the day, prevalent weather, clouds, atmospheric pollution, particulate matter, etc. Furthermore, weather dependency the location dependency and time dependency need to be addressed. After knowing the theoretical potential at the site, we determine the technical potential of the site by information about the settlements, hydrology, geomorphology in the vicinity, and land-use pattern. Plant feasibility also requires an assessment of the economic potential of the site. The information about parameters such as the closeness of the plant to demand centers, available electricity infrastructure in the region, its distance from the electricity grids, and the population likely to get access is collected to know the site's final ranking. In addition, vendor information, government policy, and subsidy and incentives are essential for its success.

Big data application in an integrated solar system for optimum utilization [5] is depicted in Fig. 3.4.

3.4.1 Solar Power Forecasting Models Approach

Solar Power Forecasting Modeling Techniques provides information for different time horizons. Besides Numerical Weather Forecasting (NWP), models are used to predict the atmospheric conditions of temperature, humidity, precipitation, and wind, and the solar forecast uses satellite images to track and predict cloud formations at different time scales. The development of algorithms to forecast periodic changes improves the effectiveness of clean energy production. We can use both statistical models and a deep learning approach. Statistical models use regression methods or time series (ARIMA, GARCH, etc.) analysis.

The deep learning approach (RNN, LSTM, GRU) is explicitly designed to avoid long-term dependency [6]. For short-term forecasting and optimum utilization of PV power, its variability forecasting helps in the following system areas; (a) Unit

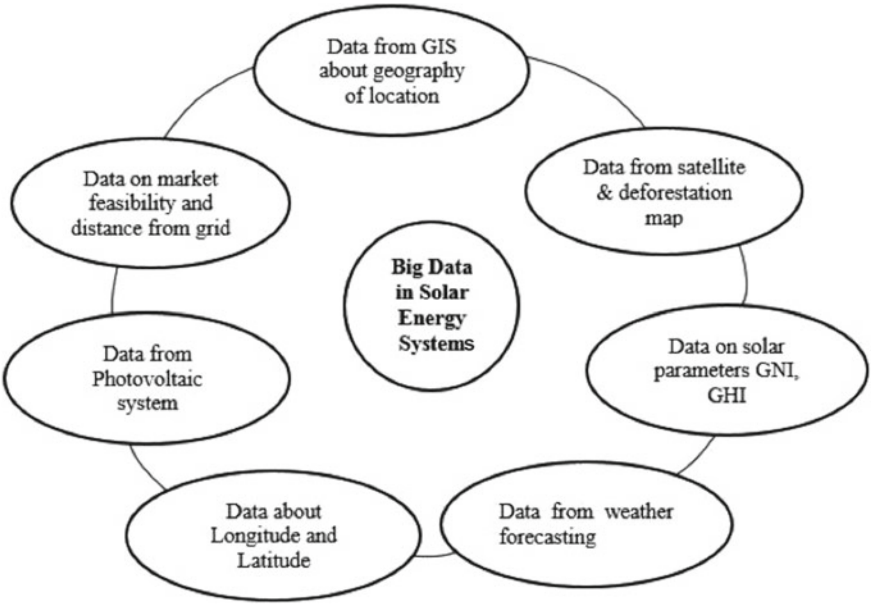

Fig. 3.4 Big data application in an integrated solar system

Commitment, (b) Scheduling of PV power in the grid, and (c) Risk analysis. The Long Short-Term Memory networks (LSTMs) have been designed and tested for different solar parks in India. It turns out to be a good model for solar forecasting under Indian conditions. Solar energy forecasting is a relatively new approach, and methodologies are rapidly evolving. With Big data, Data Analytics, Machine learning, and Deep learning, we are entering a future where solar power can reach the grid on a reliable and much more consistent basis. The latest forecasting technology and data analytics approaches would help the widespread adoption of solar energy.

Box 2: Solar Resource Assessment: India

In India, the solar resource has been assessed as 5000 trillion kWh in a year, with most parts receiving 4–7 kWh per m^2 per day. India Meteorological Department (IMD) published the first solar radiation handbooks in 1981 and 1982 based on measured data available from ground stations. First Solar Handbooks contained information on:

(i) Global and diffuse radiation data
(ii) Temperature
(iii) Other meteorological parameters for designing solar systems.

High-resolution (10-km) solar resource maps and data have been developed and incorporated into a site-time-specific solar mapping model using weather satellite data. The data output is Geographic Information System (GIS) format and as static maps.

Solar resource measurement and assessment have intensified in recent years. The Solar Radiance Resource Assessment (SRRA) stations have state-of-the-art equipment. The SRRA infrastructure comprising of a monitoring network that exists across 125 locations. It aims to develop high-quality solar radiation resource information which could help in the maximization of resource utilization. The National Institute of Solar Energy, Gurgaon, has assessed the solar resource potential as 748 GW. (This assumption is based on 3% of wasteland to be utilized for solar parks.) With the support of German GiZ SolMap, SRRA data quality checks are carried out to identify potential sites. It helps to identify high solar potential areas falling in different climatic zones.

National Institute of Wind Energy (NIWE), Chennai, produces solar and wind forecasting maps. Forecasting technology and big data can help solve another challenge, i.e., maintenance of solar farms. With hundreds or even thousands of panels spread across large regions, advances in monitoring have made checking these plants much more efficient. Other challenges in solar energy use are being addressed, such as; use of cost-effective storage batteries and disposal of large-scale panels after use.

Solar energy forecasting modeling is getting attention, and methodologies are rapidly evolving. With Big data, Data Analytics, Machine learning, and Deep learning, we are entering a future where solar power can reach the grid on a much more reliable and more consistent basis. A SWURJA mobile app provides information and a larger population can have access to it [7].

References

1. Touré AF, Addouche SA, Danioko F, Diourté B, El Mhamedi A (2019) Hybrid systems optimization: application to hybrid systems photovoltaic connected to grid. A Mali case study. Sustainability 11(8):2356. https://doi.org/10.3390/su11082356
2. Maleki SAM, Hizam H, Gomes C (2017) Estimation of hourly, daily and monthly global solar radiation on inclined surfaces. Energies 10:134. https://doi.org/10.3390/en10010134
3. Bhatia S (2014) Solar thermal energy. In: Bhatia S (ed) Advanced renewable energy systems, 1st edn. Woodhead Publishing India
4. https://gpm.nasa.gov/data
5. Briones GFE (2017) Big data & analytics to support the renewable energy integration of smart grids—case study: power solar generation. Conference paper. https://doi.org/10.5220/0006297502670275
6. Goswami S. Building LSTM-based model for solar energy forecasting. Handling some of the design issues of LSTM. https://unsplash.com/photos/mG8sgwkMhCY
7. National Institute of Wind Energy, Chennai. https://niwe.res.in/

Chapter 4
Solar Power Plants

4.1 Solar Power Plant

A solar power plant is a power-generating unit using solar energy as input for the production of electricity. It can be solar PV plant or a solar thermal plant. Either sunlight as solar cells or solar heat collectors can be used for the generation of electricity. In this chapter, we discuss solar photovoltaic (PV) power plants and their components. Independent of size, a solar PV plant can be built in a matter of days, unlike a coal-based, hydro, or nuclear plant, which involves a long construction period before it starts commissioning. Critical components of a solar PV plant are solar array, dc-ac converters, metering equipment, storage battery, charge controller, and electrical cables.

4.2 Main Components of a Solar PV Plant

The main components of a solar PV plant are [1];

i. Solar Array
ii. DC to AC Electric Inverter
iii. Power storage battery
iv. Charge controller
v. Physical infrastructure, cables, meters, sensors.

The components of a solar PV plant are discussed in Fig. 4.1.

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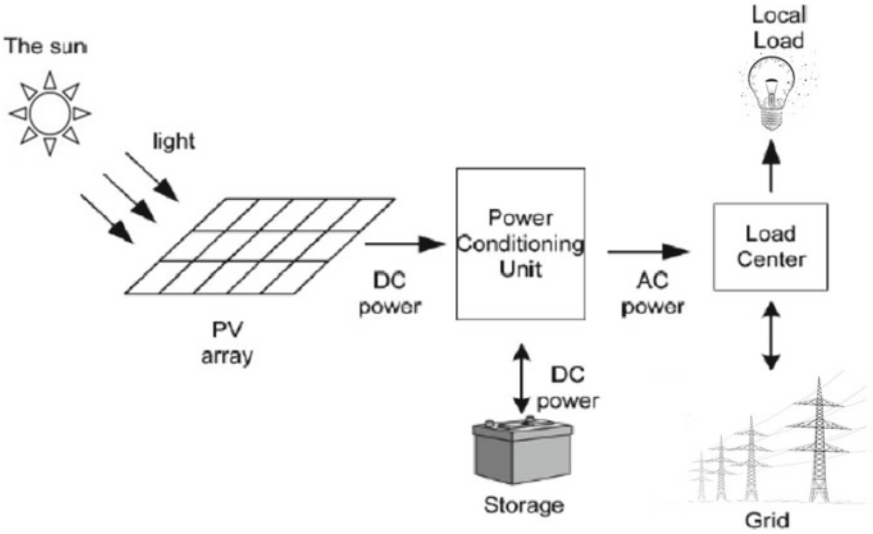

Fig. 4.1 Components of solar power plant

4.2.1 Solar Array

A large number of solar cells are combined to form a module. Solar modules are then interconnected in series or parallel combinations to get desired output and are known as Solar Array. The solar array comprises thousands to millions of solar cells. A Solar Array with an adequate solar resource is the most critical component of the solar plant. Interconnections are vital in the performance of a module, which is rated by its peak power output. The peak power output is the output at standard testing conditions. The module's normal testing conditions are specified as environment temperature of 25 °C and solar irradiance of 1000 W/m^2. For protection from environmental damage, a panel is simply encapsulated and framed. The modules or arrays should be placed in a manner to face the Sun. Optimum utilization of the SPV array depends on the site characteristics. A solar plant is a modular system, and the arrays can be added on demand (Fig. 4.2).

4.2.2 An Inverter

Inverters are an important component of a solar PV plant. When we charge the battery from a solar panel, DC from the solar panel goes directly into the battery. When a battery is charged from grid electricity, it is AC, and the inverter first converts it into DC and then connects it to the battery. It is a vital unit in the whole system. The output from a solar array is DC at low voltage of ~12 V. As most household

Fig. 4.2 Solar array for power generation

appliances work on AC which operates at a much higher voltage of ~220 V, a DC to AC Inverter is required to connect with the solar array or from the solar output from Array to the grid. In addition to converting DC to AC connected to the grid or directly supplied to household gadgets, an inverter also performs an algorithm Maximum Power Point Tracker (MPPT) control to solar output. A solar electricity system may support multiple inverters to match the power being produced. The inverters are used even when a storage battery is used along with grid connectivity. Whenever there is a grid outage, it continues to charge the battery to maintain continuity. A rectifier is the opposite of an inverter, and it converts from AC to DC. Many inverters are bidirectional and can perform in both inverting and rectifying modes, i.e., for DC-AC or AC-DC modes.

Micro-inverters—Micro-inverters are used in different designs to operate at several PV modules and have a power rating of several hundred watts and connect with each solar panel and monitor its progress. Because of the low DC output of PV modules, these inverters require two-stage power conversion. In the first stage, the PV output is boosted to a higher value and is inverted.

4.2.3 Power Storage Battery

A solar plant has intermittent electricity generation. A battery is essential for storing solar electricity for use at a later time. It gets discharged when the stored power is consumed. This forms a battery cycle. The battery cycle of charging-discharging is a most critical component of a solar plant. In an off-grid system, the battery is a must, and there may be at least one charging-discharging cycle daily. In grid-connected systems also, the use of the battery is preferred. Battery ratings are measured in A-h, which determines the current in amperes supplied by the battery and the number of hours it can be done. Batteries used in SPV plants have different A-h and a nominal voltage of the order of 12 V. To determine how much, and how long, a 50 A-h battery the battery will last for 1 h if the current flowing is 50 A. If the current drawn is only one ampere, then the battery will last for 50 h. It indirectly determines the number of hours of storage. A battery should not be allowed to discharge completely. The extent to which it is permitted to discharge is known as Depth of Discharge (DoD). Efforts are on to develop cost-effective, efficient batteries to make solar energy acceptable.

4.2.4 Charge Controller

The charge controller is an electronic subsystem that interfaces and regulates the voltage within a solar array, battery bank, and load. The controller safeguards the battery from overcharging and monitors the flow of electricity between the solar array and load. It collects data from the grid as well as the Inverter and helps in matching the load with the solar generator while controlling the battery bank. It helps to optimize performance of a solar power plant and imposes limits on the maximum current flowing through the battery. The need arises because a PV array performance is affected by ambient temperature and solar irradiance and dynamically changes. Ambient temperature also impacts battery lifespan, and the charge controller with temperature sensors helps to adjust the parameters of a battery. A multi-channel data logger can be used for better synchronization. The charge controller also supports MPPT. Improved performance offers two-fold advantages (i) extra energy produced during the day can be fed to the grid, and (ii) storage pack can be dispensed with.

4.2.5 Physical Infrastructure, Cables, Meters, Sensors

Mounting structures for solar arrays can be of different types. Stationary mounts are tilted in the direction of the Sun. Tracking facilities can be of two kinds: one-axis or two-axis. One-axis systems are typically used to track the Sun from east to west. Two-axis systems are designed in exceptional cases for use with concentrating collectors. The power from the inverter is connected to a dedicated meter through cables. It provides information about solar electricity being generated and fed to the system. The wires are used to connect with the grid. As both DC and AC currents flow, they are distinguished color codes. An additional meter is used in the case of grid-connected systems, also called ‘net meter’. The net meter measures the inflow and outflow of electricity between the plant and load and helps get the customer’s revenue on excess electricity sold. The various components comprising inverters, charge regulators, control panels, and battery banks are grouped as Balance of System (BOS).

4.3 Performance of a Solar PV Plant

A solar PV plant offers several advantages such as flexibility, short time required in the construction of a plant, and easy expansion of capacity. Other intangible benefits of a solar PV plant over the conventional one are protected from short circuits and avoidance of power outages. The critical parameters for setting up a solar plant are; (i) siting of location, (ii) solar database at the location, (iii) electricity load demand profiles over one year, (iv) distance from the electric grid, (v) selection of battery of requisite capacity.

The main consideration for constructing a solar power plant is the location with adequate solar resources and the requisite open area to put up a solar plant. The area requirement may be similar to a coal-based plant. Databases on hourly and daily Insolation at the site are mapped. These data are used to compute total solar energy requirement by considering daytime load, night time, load, and various loss factors. Site characteristics help in determining the capacity of the storage battery bank.

The performance ratio of a solar PV plant is expressed in percentages [2]. It is the ratio of its output and input, which is product of installed capacity and solar irradiation.

$$\mathrm{PR} = \frac{\text{output in kWh}}{\text{plant capacity kW} \times \text{solar irradiation kWh/m}^2} \times 100\% \tag{4.1}$$

Higher PR indicates better performance. Assessment of a grid-connected plant is carried out on a yearly basis through simulations. By quantifying solar radiation, it is understood that PR for a plant will vary from location to location. The PR falls during the lifetime of a plant because of module degradation. Environmental factors like temperature, wind, and pollution also affect the performance of a plant. In addition, annual losses occur due to factors like soiling, irradiance loss, inverter conversion loss, and reflection loss and could add up to 10% or more. Annual energy yield is dependent on actual field conditions.

4.3.1 Levelized Cost of Solar Electricity

The levelized cost of electricity (LCOE) of a source is defined as the cost per kWh of electricity produced. The concept of LCOE allocates the cost across the full lifecycle of a plant. It is the ratio of total life cycle cost and total lifetime power produced [3]. The choice of technology depends on resource availability and also the cost of technology. For this reason, for a given technology, could vary from place to place.

To determine the 'levelized cost' of a power plant in general, the following expression is used.

$$\mathrm{LCOE} = \frac{\mathrm{OC}}{\mathrm{CF} \times 8760} \times \mathrm{CRF} + \mathrm{OMC} + \mathrm{FC} \tag{4.2}$$

where OC is the overnight construction cost.

OMC is the annual Operation and Maintenance cost (O&M).

FC is the annual fuel cost which is zero for a solar plant.

CF is the capacity factor.

And CRF is the capital recovery factor, given by

$$\mathrm{CRF} = \frac{r \times (i + r)^L}{(i + r)^L - 1} \tag{4.3}$$

Here, r is the discount rate, and L is the economic life of a plant.

There is also a wide variety of solar energy technologies, and the LCOE would differ for each. The levelized cost of solar electricity from a PV plant is less than or equal to that from a solar thermal plant, i.e.,

$$\mathrm{LCOE}_{\mathrm{pv}} \leq \mathrm{LCOE}_{\mathrm{thermal}} \tag{4.4}$$

4.4 Types of Solar PV Plants

There are three main types of Solar PV systems; On-Grid, Off-Grid, and Hybrid. A plant can have many variations as distributed generation, standalone, grid-connected, microgrid, virtual plant, solar rooftop, solar agriculture pump, and a solar park.

4.4.1 Standalone

A standalone plant is off-grid system. It has an inverter connected to the charge controller and the battery bank. It charges the battery bank even when there is no sun to keep the power supply on. To design a standalone system following information is needed

(i) The electricity load at different times of the day
(ii) Solar irradiation data in daily equivalent sun hours
(iii) Optimum module size of the solar array and current requirements in the circuit
(iv) Battery size and its charging time.

A standalone solar PV is preferred for small power needs, especially at remote sites where the grid is not there. It can be a system for DC load, such as an LED connected directly to the PV panel. In DC systems an inverter is not required but has a storage battery to provide electricity at night.

In standalone systems with AC load, inverters and charge controllers have a crucial role in supplying constant AC voltage by controlling the generator output (Fig. 4.3). In applications for water pumping from the ground for irrigation, a standalone system

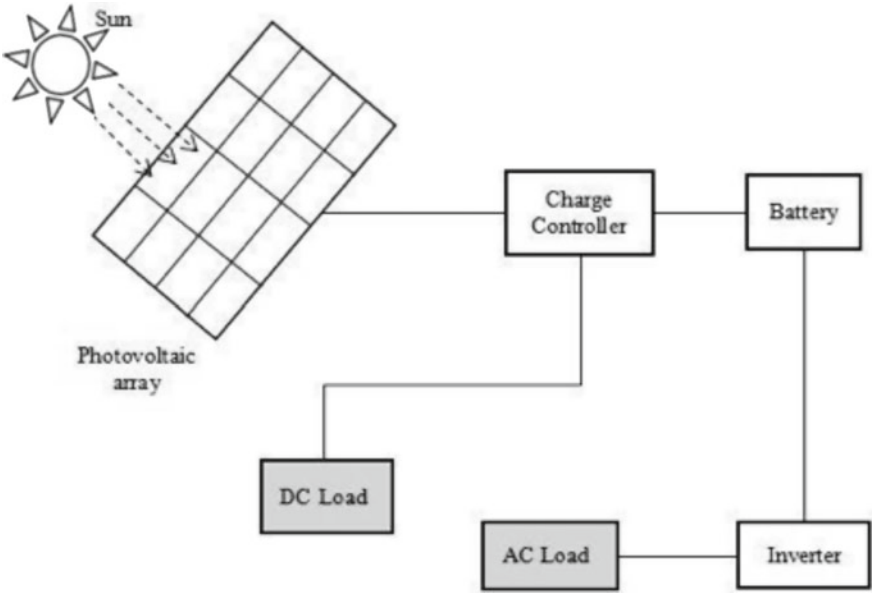

Fig. 4.3 Standalone solar PV plant

can be used. Such a system is used to generate power during the day and therefore does not need a battery.

A standalone system with battery storage for supplying AC load has an inverter and a charge controller and can be used for 24 h. It has MPPT so that the PV array operates at an optimum level. A hybrid system is also preferred to supply constant power solar array. It has another energy source such as a wind turbine or pump storage system in addition to solar. When more than one source is used, sensors are installed to optimize power system performance and to fully utilize both the sources and battery bank.

4.4.2 Decentralized Distributed Generation

A Decentralized Distributed Generation (DDG) system is somewhat similar to a standalone system. As DDG is located where the demand is, they reduce transmission and distribution costs and losses. A solar DDG offers efficient, sustainable, and cleaner power to the people. The application areas of DDGs can be rural and remote areas where grid expansion is not feasible due to geographic difficulties. The DDG application is extended to supply power to specific load points during peak periods, especially for industries. A solar DDG can substitute for grid power when used as solar rooftops. The utilities have used DDGs as base loads to support the grid by enhancing the system voltage profile and reducing the power losses. Hybrid solar and wind systems can be used as DDGs. As the costs of solar PV are falling, the potential of DDG for rural development can be immense for developing countries. Its impact in providing access to electricity can alleviate poverty (SDG 1) and help achieve energy security and clean energy (SDG 7). A 25 kW capacity plant was installed in 1996, West Bengal Renewable Energy Development Agency (WBREDA) in Sagar Island and in Chhattisgarh at Lamni in Bilaspur district in India serve the population in Sunderban delta region of West Bengal [4].

4.4.3 Grid-Connected Solar Plant

A grid-connected solar plant design is similar to standalone, but it requires some additional components and information about electricity load at site throughout the year. The annual load chart also helps determine the size of the battery. An electricity meter and utility meter are used so that generated energy and consumed energy match over the year, and the energy balance is maintained. A grid-connected inverter must ensure that there is an auto switch-off when there is a grid outage. Net metering is used to measure the excess energy supplied to the grid, which the consumer can claim later. Power conditioning is an essential function of a grid-connected plant. It is an interface between the plant and grid to help safe delivery of electricity to consumers. Inverters are used to optimize and maximize the output of the PV array into AC output.

4.4.4 Solar Microgrids

Microgrids are small, advanced electric grid self-sufficient energy systems for an entity. Specific purpose microgrids are designed with clearly defined boundaries to balance the demand and supply. Independent sources of electricity are similar to distributed energy sources and allow electricity generation closer to the user. The Department of Energy, USA offers a more formal definition for a microgrid [5] as, '*group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid*'.

Earlier, microgrids using solar energy were seen as a solution to providing access to energy in the regions of deficient power supply, such as; rural areas and remote areas. But, now, their use is proliferating in urban areas with the advancement of technology. The solar microgrids are emerging as a sustainable solution in various applications toward a clean energy transition (SDG 7). The main components of a solar microgrid are solar panels as energy generators, batteries, controllers, and local area networks. Batteries are integrated with solar panels through inverters and provide connectivity to the distributed load. A solar microgrid can have two options; it can be an independent source of electricity or connects and balances the power supply with the primary grid. Solar microgrids function better with grid connectivity, but they can be designed for rural areas with adequate battery storage to access electricity within reach for many households.

Microgrids have many applications and are becoming common in cities, especially for educational campuses, hospital complexes, residential complexes, industrial and community uses, or even a military bases. They are preferred in place of large grids as they are less costly. Globally, it is expected that the microgrid capacity could increase from 3.5 GW in 2019 to 20 GW in 2028 [6].

Microgrid demands are growing in various other fields including health care services [7]. During the pandemic COVID-19, the need to have microgrids in hospitals was amplified for dedicated patients' treatments. Microgrids help in management of electrical vehicle (EV) charging stations. As the solar and other RE technologies are becoming cost-effective, the use of hybrid microgrid systems, like using solar and wind, or solar and water is expected to grow.

A grid-connected system has an intelligent controller to manage the supply, and batteries as per consumer needs through grid communication. The system can have the flexibility to operate independently and draw power from the grid when generation becomes low, provided technical challenges in its operation to meet the demand and supply. Having intelligent or smart controllers, which can respond to weather forecasts during natural disasters or power outages, a microgrid can protect the community by switching off and switching on in time. So they are seen as disaster management options too.

As a result of growing demand [8], microgrid technologies are maturing rapidly in India. Economic modeling studies suggest that ~2 MW mini-grids in several scenarios—campuses, clusters of homes, and more with storage can be vital for energy security. Government of India facilitated loans for microgrid installations for non-farming activities. Business and social potential of a small group of 4–10 local entrepreneurs could be synthesized to form a Joint Liability Group (JLG) for loan purposes. In June 2016 the government has issued a draft 'National Policy for Renewable Energy-based Micro and Mini-Grids' [9] to encourage the use of micro and mini-grids for reaching 237 million un-served populations living in the remote areas. India has installed solar microgrids up to 2 MW at several places and targets to have 10,000 microgrids by 2026.

4.4.5 Solarization of Agriculture Pumps in India

Solar microgrids with decentralized diesel-based systems could make an ideal solution for water pumping in agricultural areas. Solar energy-water microgrids, where water infrastructure for pumping requires sufficient energy, have been designed. Microgrids are much cheaper and quicker to deploy in the range of less than 100 kW to a 1 MW system. They save on expensive electricity infrastructure and have a high potential for growth in providing energy security in India. They are a suitable replacement against existing diesel-only power generation. The Pradhan Mantri Kisan

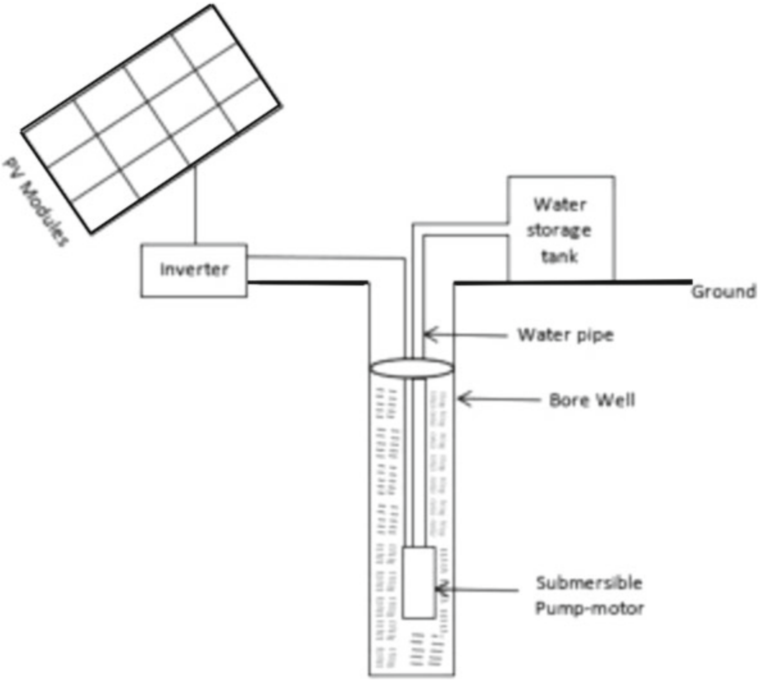

Fig. 4.4 A solar agriculture pump

Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme was launched in February 2019.[1] It aimed to include installing 2 million standalone solar-powered agriculture pumps (Fig. 4.4) and solarization of grid-connected agriculture pumps with a central and state subsidy of 30% each and a farmer's contribution of 40% [10]. India has 8.8 million agriculture pumps operated on fossil fuel or diesel.

4.4.6 *Solar Parks*

Ministry of New and Renewable Energy, Government of India has developed a scheme to set up solar parks and ultra-mega solar PV power projects across the country. A solar park is a large-scale solar plant having a capacity of several megawatts. A solar park is also called a 'utility-scale solar power plant'. It can be either a solar PV or solar thermal power plant. Solar parks are vital instruments for meeting the ambitious targets of India's solar capacity addition. Nearly 42 solar parks have come up in the last five years by facilitating land availability by the

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[1] Scheme is aimed at ensuring energy security for farmers in India, and to increase the share of installed capacity of electric power from non-fossil-fuel sources to 40% by 2030 as part of Intended Nationally Determined Contributions (INDCs).

Table 4.1 Ten world's largest solar parks of more than 1 GW capacity

S. No.	Name of solar park and country	Installed capacity
1	Bhadla Solar Park, India	2.25 GW
2	Huanghe Hydropower Hainan Solar Park, China	2.2 GW
3	Shakti Sthala Solar Power Project, India	2 GW
4	Golmukh Dessert Solar Park	1.8 GW
5	Benban Solar Park, Egypt	1.65 GW
6	Tengger Desert Solar Park, China	1.55 GW
7	Sweihan Photovoltaic Independent Power Project, UAE	1.177 GW
8	Yanchi Ningxia Solar Park, China	1.000 MW
9	Datong Solar Power Top Runner Base, China	1070 MW
10	Kurnool Ultra Mega Solar Park, India	1000 MW

Source Compiled by authors using data from various sites

government to the private investors. The world's largest solar PV power plant is in India as Bhadla Solar Park of 2.25 MW capacity. It spans 5666 ha of land. As of January 31, 2021, solar park projects for further capacity addition of 36.03 GW are under various stages of implementation, and 23.87 GW are in the tendering process. Ten world's largest solar parks are shown in Table 4.1.

References

1. Bhattachargee S (2015) Solar energy generation. Narosa Publishing House Ltd.
2. Performance ratio
3. Levelized cost
4. WBREDA: an organization under the department of non-conventional and renewable energy sources, Govt. of West Bengal. Conventional energy, renewable energy, Kolkata, India. [Online]. Available at http://www.wbreda.org
5. https://www.energy.gov/sites/prod/files/2016/06/f32/The%20US%20Department%20of%20Energy%27s%20Microgrid%20Initiative.pdf
6. Nhede N (2019) Global microgrid capacity to reach 20 GW—a 21% annual growth through 2028, 14 Nov. https://www.smart-energy.com/industry-sectors
7. Hirsch A, Parag Y, Guerrero J (2018) Microgrids: a review of technologies, key drivers, and outstanding issues. Renew Sustain Energy Rev 90:402–411
8. Aggarwal P (2020) The role of microgrids in India. [Online]. Renewable Energy World. Available at https://www.renewableenergyworld.com/solar/the-role-of-microgrids-in-india/#gref
9. Draft national policy for renewable energy based micro and mini grids (2016) MNRE. http://www.indiaenvironmentportal.org.in/
10. India.gov.in (2021) PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan) scheme. National Portal of India. [Online]. Available at https://www.india.gov.in/spotlight/pm-kusum-pradhan-mantri-kisan-urja-suraksha-evam-utthaan-mahabhiyan-scheme

Chapter 5
Solar Light Energy: A Photovoltaic Cell

5.1 Photovoltaic Effect

> If there is a dream solar technology, it is photovoltaic – solar cells … a space-age technology marvel at once the most sophisticated solar technology and the simplest, most environmentally benign source of electricity yet conceived.
>
> (Hammond 1977)

The visible radiation in solar light can be utilized directly in a photovoltaic cell to produce electricity. In Greek, 'photo' means light, and a photovoltaic device converts light (photo) energy into electrical voltage. Such conversion is achieved through a unique physical property known as photoconductivity, an essential property of solar cell materials. In a solar photovoltaic device, photons are absorbed in a 'Photoconducting cell' device, producing a voltage across its two ends.

The photovoltaic effect was first reported by French Scientist Alexandre-Edmond Becquerel in 1839 [1]. When light is incident on a material, voltage is generated, and an electric current starts flowing. Another important contribution was made by German scientist Heinrich Hertz's, who discovered in1887 that electrically charged particles are released and current flows when electromagnetic radiation falls on a metal. Einstein gave a theoretical explanation for the photovoltaic and photoelectric effects in 1905 [2], a discovery that led to Nobel Prize for him. Einstein postulated that light contains packets of energy as quanta (later came to known as photons). In 1913 William Coblentz received the first U.S. Patent (1077219) to convert sunlight into electricity [3]. It became known as a solar photovoltaic or a *solar cell.* A solar cell, therefore, directly converts sunlight into electricity in a one-step process.

The first practical solar cell device was made in 1953 by Bell Laboratories using a wafer of silicon. The first U.S. satellite, 'Vanguard I', in 1958, had incorporated a 5 kW experimental system of solar cells as a source of energy in space, where cost was not critical. Subsequently, in the 1970s, the less expensive solar cells were developed and used in micro-devices as alternative sources of electricity for meeting small-scale needs in remote areas using silicon as a semiconductor.

M. Goel et al., *Solar Energy*, Green Energy and Technology,
https://doi.org/10.1007/978-981-19-2099-8_5

5.2 A Solar Cell

A solar cell is a solid-state electronic device working on the principle of photovoltaic effect. It converts solar light into electricity by using materials with specific characteristics. A solid-state material can be classified as Conductor, Semiconductor, and Insulator (non-conductor) according to their different electronic compositions. A semiconducting material is in between a conductor and insulator. In conductors, electrons are free to move within the material and when external energy is supplied their motion increases. A conductor has a unique atomic structure, with energies of the electrons in its outer shell largely confined into two bands called ‘valance band’ and ‘conduction band’. The electrons in the conduction band are free to move. In insulators, electrons in the conduction band are not free to move or jump across a high energy bandgap between valence and conduction band.

The energy bandgap of a material is an important parameter to decide on its solar cell properties [4]. When the light of a particular frequency matches with the semiconductor’s bandgap, the atoms absorb the energy of the light beam shining on it and electrons are released.

A solar cell is made by joining two types of semiconductors, known as n-type and p-type. Silicon is a semiconductor, which has four electrons in its outer shell. These electrons are called valence electrons. When silicon is doped with another material (adding minor quantity) containing five valence electrons in the atom’s outer shell, such as phosphorous, the extra electron from it wanders freely. It settles neither in the valence band nor in the conduction band. The silicon becomes an n-type semiconductor. Suppose silicon is doped with a material containing only three valence electrons in its outer shell, such as boron. In that case, a few extra holes are created in it, and the silicon then becomes a p-type semiconductor. When these two n-type and p-type semiconductors are joined, excess electrons and holes occupy additional energy levels between the conduction and valence bands.

When light with photons having energy more than the bandgap falls, electrons in the valence band can jump to the conduction band leaving holes in the valence band, an electron-hole pair is thus created across the junction of the two semiconductors. This process leads to the generation of an electric field across the junction, producing an electric current. The structure of the solar cell is shown in Fig. 5.1.

In a practical device, a metallic grid on surface allows light to penetrate the semiconductor between the grid lines and forms electrical contact for drawing current. The electrodes are molded on p-type and n-type materials. Light absorbed at the p–n junction is converted into electrical energy. The amount of electricity generated in such a configuration depends on several factors like; the type of cell material used (silicon or other), the size of the cell (individual or a group of cells), solar radiation intensity, solar inclination, and other associated factors features.

We can write the output power P in a solar cell as

$$P = I \cdot V \tag{5.1}$$

I is the solar cell current and V is the output voltage.

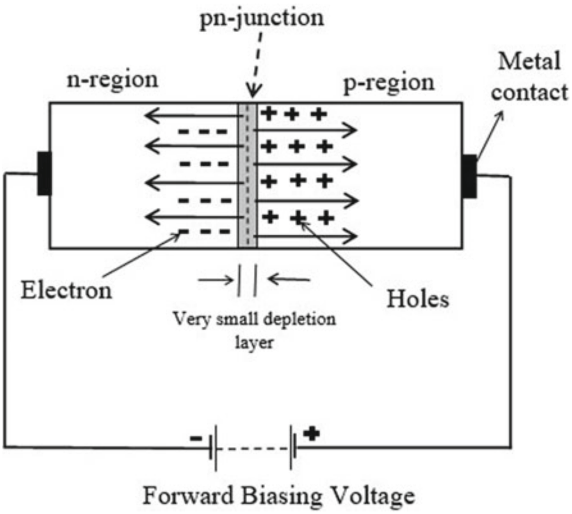

Fig. 5.1 A schematic of a solar photovoltaic cell

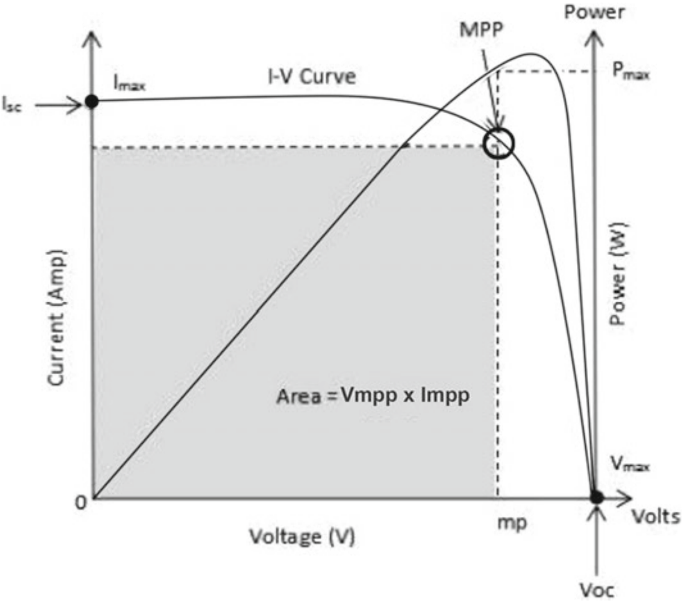

Fig. 5.2 Solar cell current-voltage characteristics

The current-voltage and power voltage characteristics of a solar cell [5] are shown in Fig. 5.2.

A solar cell can produce up to 2 W of energy. When load current is zero, its voltage becomes maximum and is known as open-circuit voltage V_{oc}. When load current increases, short circuit current I_{sc} is reached, and voltage becomes zero. Power from a solar cell shows a bell-type behavior between these two extremes of zero power. The voltage and current corresponding to maximum are V_{max} and I_{max}. The maximum power P_{max} can be written as,

$$P_{max} = I_{max} \times V_{max} \tag{5.2}$$

V_{max} and I_{max} determine the maximum power P_{max} achievable from a solar cell.

The Fill Factor (FF) of a cell is the ratio of maximum power to open-circuit voltage and short circuit current.

$$\mathrm{FF} = P_{max}/V_{oc} \cdot I_{sc} \tag{5.3}$$

The fill factor explains the efficiency and performance of the system. If FF for a cell is known, its maximum power output can be found. A fill factor of 1 is ideal.

The amount of energy a light quanta or photon carries is inversely proportional to the wavelength of light. The energy of the light beam at a particular wavelength E_λ is given by

$$E_\lambda = \frac{hc}{\lambda} \tag{5.4}$$

Here, h is Planck's constant, and c is the speed of light. λ is the wavelength of light.

A light beam consisting of photons with energy varying from 1.59 to 3.26 eV falls in the visible spectrum of solar radiation. The conversion efficiency of a solar cell is the ratio of electric power output and the energy flux of sunlight falling on the surface. We can write the maximum possible efficiency of a solar cell as,

$$\eta = \frac{P_{max}}{A \cdot R} \tag{5.5}$$

Here, A is the upper or exposed surface area of the solar cell and
R is the irradiance on the solar cell surface.

Material properties, irradiance, and spectral composition of sunlight are important considerations in the design of solar cells. The actual efficiency of a solar cell is also affected by irradiance, insolation, the temperature of surroundings and presence of clouds, etc.

5.3 Solar Cell Materials

A variety of semiconducting materials can form solar p–n junction cells. Materials having band gaps separated by an energy gap of 1.1–2.5 eV are more suited. Besides having a requisite bandgap, an ideal solar cell material should also have a high solar absorption coefficient of $>10^4$ cm and low recombination velocity of charge carriers to achieve higher efficiencies. Silicon remains the most versatile solar cell material. The bandgap between its conduction band and valence band is 1.1 eV. Silicon is also the second most abundant material on the earth. Its source is quartzite, a rock made of quartz that contains pure silica. Geological silica sand is derived from quartz for producing silica or silicon dioxide. The average requirement of silicon for 1000 MW SPV is about 15,000 Mt of silicon.

Three forms of silicon solar cells are polycrystalline, monocrystalline, and amorphous materials.

(1) *Polycrystalline silicon* (pc-Si) cells are made by pouring molten silica into molds and slicing the cooled mold into wafers. It is a proven technology that is comparatively easier to make and less costly. Using polycrystalline material that absorbs a wide range of solar spectrum, it is possible to achieve higher efficiency. The efficiency ranges from 13 to 15%. In its polycrystalline form, silicon can be produced in a ribbon form or as an ingot, from which thin slices/wafers of thickness up to 200 m are cut. The cost of silicon wafers has come down sharply in the last 20 years. It has the advantage of manufacturing in large sizes and is currently in maximum use.

(2) *Monocrystalline silicon* (mc-Si) solar cells were first to manufacture commercially. The efficiency ranged from 16 to 19%, but they are more expensive to fabricate. Fabrication of monocrystalline silicon solar cells is a high energy-consuming process. For this reason, polycrystalline cells soon took over for commercial uses. Single crystals ingots are made from pure silica. Ingots are sliced to produce ultra-thin wafers for solar cells. The highest efficiency reached for monocrystalline silicon cells in the laboratory is 26.7%.

(3) *Amorphous silicon* (a-Si) solar cell uses thin-film technology to deposit the material directly on a metal electrode. It is comparatively simpler to fabricate by deposition on low-cost substrates like glass or plastic. Thinner the cell, more sunlight can reach the junction, and hence an increase in efficiency is possible. A thin-film would not only have a larger surface area but would consume less material as well. Using both polycrystalline and amorphous materials, extremely thin films (1–20 μ) of silicon have been grown. However, the efficiency of amorphous silicon is relatively low, which further degrades with illumination and time. Hydrogenated amorphous silicon (a-Si:H) solar cells are more cost-effective but have an efficiency of less than 10%. The efforts are being made to increase their conversion efficiency further.

5.3.1 The Cell Efficiency and Collector Area

The efficiency of a solar cell depends on the material used and its collector area, besides other parameters. A single bandgap semiconducting material has a theoretical thermodynamic conversion efficiency of 32%. A Shockley–Queisser limit is an upper limit for the efficiency of a p–n junction solar cell proposed in 1961 for silicon [6].

The limit was set by the analysis of the temperature of the Sun; the temperature of the cell; and the energy bandgap of the semiconductor used. The limit in principle suggests that the efficiency could not increase beyond 45–65%. However, technology innovations using advanced material nanostructures like quantum dots, quantum wells, and multi-layer junctions can cross this limit. The efficiency can be increased by raising the temperature of the material by heating or by increasing light intensity by using concentrators or by using multi-bandgap materials.

The collector area of a solar cell is the surface exposed to sunlight. Different fabrication techniques have been tried to achieve a larger surface area; the larger the collector surface, the better the efficiency. A larger collector area achieved higher productivity at a lower cost. A bifacial [7] or hybrid solar cell can produce energy from both sides. It consists of a monocrystalline silicon wafer sandwiched between two ultra-thin amorphous silicon layers. The panel generates electricity from direct and diffuse radiation; the other side uses diffused and reflected light. The cell, in this case, produces more power.

Fabrication techniques to increase the efficiency include a larger collector area and concentrators or mirrors on the collector surface to increase the intensity of incident radiation on a solar module. The efficiency of a solar cell increases by using lenses and mirrors in the path of sunlight. The use of mirrors, however, increases the temperature of the cell, thereby reducing its efficiency. A compromise has to be made between the temperature, light intensity, efficiency, and the cost of SPV systems.

5.4 Search for New Solar Cell Materials

Several new photovoltaic materials have emerged in recent decades.

5.4.1 Second Generation of Thin-Film Solar Cells

With the advancement of thin-film technology, interest in thin-film solar cells fabrication has been growing. Films from amorphous silicon and hydrogenated amorphous silicon (a-Si:H) are prepared by the radio frequency glow discharge method. Hybrid thin-film silicon solar cells as a combination of amorphous and polycrystalline or a combination of amorphous silicon and microcrystalline solar cells have been developed and are in commercial production. Many compound materials other than silicon such as gallium arsenide, cadmium telluride, and copper sulfide are found suitable for solar cells by using thin-film fabrication techniques. Materials are classified according to their physical and chemical properties.

Cadmium Telluride (CdTe) and Cadmium Selenide (CdSe) are thin-film solar cells made of compound cadmium, tellurium, and selenium. The highest laboratory efficiency in thin-film form is 21.0% for CdTe solar cells, but the field efficiency attained is 16.5%. The CdTe has high absorption efficiency and produces high energy output across varying climatic conditions. A small amount of gallium is being added

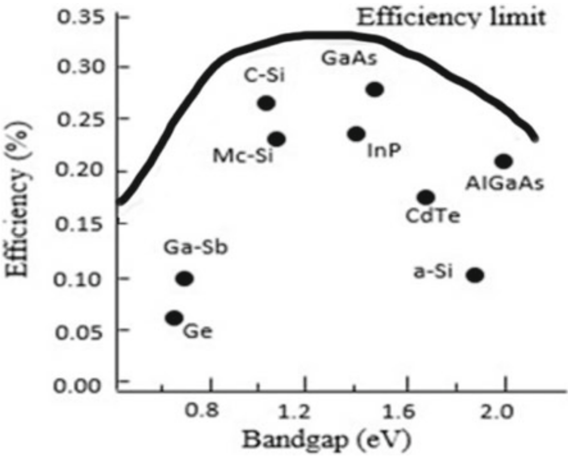

Fig. 5.3 Efficiency of semiconducting materials and their energy band gap

to improve the efficiency further. Copper indium diselenide ($CuInS_2$), commonly known as CIS and Copper Indium Gallium Diselenide or CIGS in short are promising solar cell materials. The CIS and CIGS have the advantage of getting molded into the desired shape and have an efficiency of 22.9%. Significant progress has been made in the development of Gallium arsenide (GaAs) solar cells. It has higher efficiency and very high absorptivity (bandgap as 1.42 eV) and is unaffected by heat. But gallium deposits are rare, and the cost increases. For this reason, the Gallium Arsenide solar cells have an advantage for use for strategic applications such as satellites in space technology. The relationship between efficiency and bandgap of the solar cell material is shown in Fig. 5.3. Materials with a bandgap around 1.35–1.42 eV show the highest efficiencies.

5.4.2 *Third-Generation Multi-junction Solar Cells*

The third-generation solar cells are based on multi-junction cell technology. These can be double or triple-junction cells or even quadruple junction devices. Multi-junction Tandem cells are proposed as stacks of cells. The efficiency of silicon solar cells in tandem has increased steadily from 15% for a single-junction device to 30% for a triple-junction device. Quadruple junction cells are under development at present with the hope of increasing efficiencies up to 46%. Tandem cells could cross the Shockley–Queisser limit and achieve higher efficiencies, 2–3 times of current efficiencies. Multiband cells, hot carrier cells, and multiple electron-hole pair or exciton cells are other technology innovations for converting light into voltage, intending to achieve higher efficiencies.

In the third-generation devices, hybrid technology systems of thermo-photovoltaic or thermo-photonics cells are proposed to combine the use of heat and light radiation. These are in the conceptual stage, with expected efficiency as high as 85%.

5.4.3 New Materials for Solar Cells

In addition to junction technology, new materials as higher-order compounds of inorganic materials similar to mineral 'perovskite' have shown favorable solar cell preparations. Perovskite thin-film solar cells have emerged as potential future solar cell materials. Perovskite materials, such as organic-inorganic RNH_3PbX_3 (X = Cl, Br, I; R = Me, NH = CH, etc.) emerged in 2009 and demonstrated the potential to reach higher efficiency in practical devices. Potassium hexafluorophosphate doped Formamidinium lead iodide perovskites show long-term thermal stability and have favorable bandgap leading to efficiency up to 20.4%. Because of their high efficiency, they are also being called 'Wonder Solar Cells'. National Renewable Energy Laboratory (NREL), USA study on solar cell efficiencies research by various organizations is depicted in Fig. 5.4.

The use of synthetic organic dyes sensitized material in a solar cell has attracted attention because of the reduction in fabrication costs. Solar cells of organic materials such as thin photosensitive plastic films are being developed to achieve low-cost devices. Organic dye-sensitized solar cells use electrolytes to produce ions to transfer electrons to dye molecules. Photo-electrochemical solar cells could achieve an efficiency of 12%, but the stability of materials becomes an issue. While organic solar cells and dye-sensitized solar cells are cost-effective, their efficiency is low and also decays with time and is a major drawback. Paper or wood-based solar cells outperform all other materials in optical transparency, low-cost, and high efficiency but suffer from acceptability.

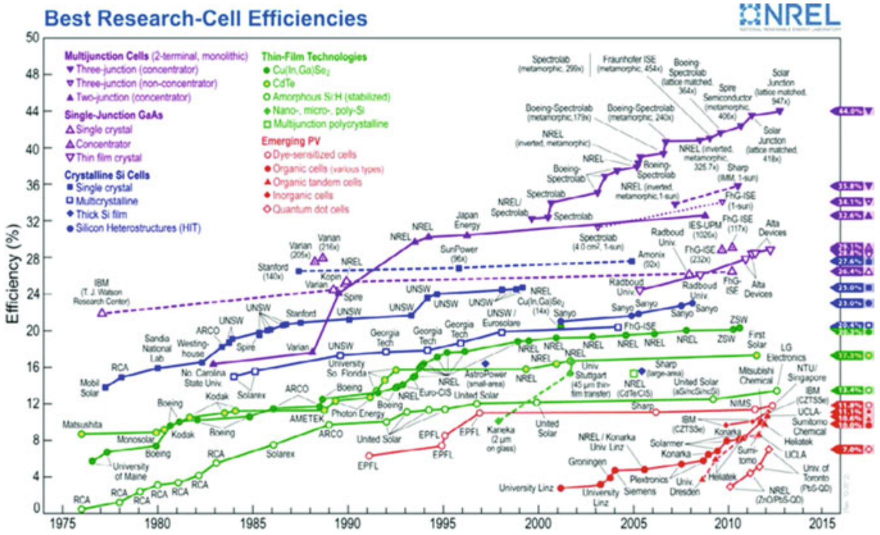

Fig. 5.4 Best research cell efficiencies starting 1975

Table 5.1 The maximum efficiencies of solar cells in 2020

Type of cells	Efficiency
Multi-junction solar cells	39.2
Tandem perovskite cells	28
Gallium arsenide cells	30
Monocrystalline cells	26.1
Unstabilized perovskite cells	25.2
Thin-film CIGS cell	23.4
Polycrystalline cells	22.8
Cadmium telluride cells	22.1
Organic solar cells	17.4
Dye-sensitized solar cells	12.3

Source Student's Portal for Renewable Energy and Sustainability information, 2021 [8]

Other materials being investigated and showing promise are carbon-based fullerenes and nano-crystals. Carbon Nanotube (CNT) based Solar PV—has the potential for a higher level of efficiency. Higher electrical conductivity and mechanical strength of CNT could improve the efficiency to the order of 35%. The CNT-based PV cells aligned with the polymer composites are expected to give very high efficiency in photovoltaic conversion. Current solar cell efficiencies for different materials are summarized in Table 5.1.

Globally, research efforts are directed toward increasing the efficiency of solar cells and simplifying the technology of fabrication by using materials other than silicon. Solar photovoltaic technologies from thin films to silicon-single crystal, silicon polycrystalline, and multi-junction new materials for large-scale deployment of solar cells have been studied. Years of intensive research have led to increase the efficiency of a solar cells. The efficiency of conversion is rising with the search for new materials. The current highest achievable efficiency of a solar cell today is 44% in the laboratory and 22% in the field. The approximate land area requirement for a solar array is about 2 ha/MW. Area is a factor of both the solar radiation intensity at a place and the efficiency of the cell. Availability of adequate land space free from obstacles at a potential location continues to be an important environmental challenge in solar energy growth. Solar energy, without doubt, has a vast scope. SPV electricity has become most sought after and favored technology in twenty-first century. For solar cell research in India and future outlook, please see Box.

Box: SPV Research in India and Future Outlook

In India, Solar Photovoltaic (SPV) R&D has received the government's attention since the 1970s in search of new materials and advanced fabrication techniques to achieve higher efficiency and cost-effectiveness. Efforts from 1985 to 1992 aimed toward single-junction amorphous silicon solar cell thin-film technology and applications in devices. Large-area multi-junction amorphous silicon solar cell development, thin-film solar cells based on cadmium telluride, copper indium diselenide, hydrogenated amorphous (a-SiH) thin films, quantum dots, and a host of other materials as III–V group compounds in the Periodic Table have been studied in the research mode for the development of solar cells. In 1988, Administrative Staff College of India, Hyderabad operated the first grid-connected 5 kW solar plant. In 1992, the government installed the SPV plant capacity of 100 kW at Kalyanpur in Uttar Pradesh. The SPV-based displays, petrol pumps, and telecommunication towers came up in remote and rural areas across the country.

In subsequent years, R&D thrust shifted to improving the materials technology of crystalline silicon cells, nanotechnology, quantum dots, and developing wafers. Dye-sensitized and organic solar cells have started emerging as potential research materials. Improvements in module efficiency and balance of system designs received attention for cost reduction.

At present solar PV use is getting accelerated with an average global growth rate as high as 50% per year. Annual production of solar cell modules has increased exponentially from 1 MW in 1990 to 700 MW in 2012 and 16 GW in 2020. The cost has come down significantly in the past few years, and the SPV system has transitioned from kW to GW sizes. Total capacity addition is nearing 40 GW. India has demonstrated capabilities for installation of more than 40 solar parks so far, having world's biggest solar park. Several solar parks adding to approximately 20GW capacity are under construction. Statewide list of sanctioned solar parks in India as on 19th March 2021 is depicted in Table 5.2 [9].

Table 5.2 State wise list of sanctioned Solar Parks

Sl.No.	State	Solar park	Capacity (MW)	Land identified at
1	Andhra Pradesh	Ananthapuramu-I Solar Park	1500	NP Kunta of Anantpuramu & Galiveedu of Kadapa Districts
2		Kurnool Solar Park	1000	Gani and Sakunala Village of Kurnool District
3		Kadapa Solar Park	1000	Vaddirala, Thalamanchi, Pannampalli,Ramachandrayapalli, Konna Ananthapuram and Dhidium villages in Mylavaram Madal,Kadapa district

(continued)

Table 5.2 (continued)

Sl.No.	State	Solar park	Capacity (MW)	Land identified at
4		Ananthapuramu-II Solar Park	500	Talaricheruvu & Aluru Villages, Tadipathri Mandal, Anathapuramu District of Andhra Pradesh
5		Hybrid Solar Wind Park	160	Kanaganapalli Mandal, Ananthapuramu District
6	Arunachal Pradesh	Lohit Solar Park	30	Tezu township in Lohit district
7	Gujarat	Radhnesada Solar Park	700	Radhnesada, Vav, Distt. Banaskantha Solar Energy Corporation of India (SECI)
8		Harsad Solar Park	500	Villages-Harsad, Madhpura, Suigam and Navapara, Taluka-Suigam, District-Banaskatha
9		Dholera Solar Park Ph-I	1000	Dholera Special Investment Region (SIR),Taluka- Dholera, District-Ahmedabad, Gujarat
10		Dholera Solar Park Ph-II	4000	Dholera Special Investment Region (SIR),Taluka- Dholera, District-Ahmedabad, Gujarat
11	Jharkhand	Floating Solar Park	150	Getalsud and Dhurwa dam, Jharkhand
12	Karnataka	Pavagada Solar Park	2000	Villages- Valluru, Rayacharlu, Balasamudra,Kyathaganacharlu, Thirumani of Pavagada Taluk, Tumkur dist.
13	Kerala	Kasargod Solar Park	105	Paivalike, Meenja, Kinanoor, Kraindalam and Ambalathara villages of Kasargode district
14	Madhya Pradesh	Rewa Solar Park	750	Gurh tehsil, District Rewa, MP
15		Neemuch-Mandsaur Solar Park	750	Neemuch site: Villages Badi, Kawai and Bardwada in Singoli Tehsil; and Mandsaur site: Runija and Gujjarkhedi villages in Suwasra Tehsil, Mandsaur district
16		Agar Solar Park	500	Susner & Agar tehsil of Agar District
17		Shajapur Solar Park	450	Moman Badodiya tehsil & Shajapur tehsil of Shajapur District
18		Morena (Chambal)Solar Park	250	Morena
19	Maharashtra	Sai Guru Solar Park (Pragat)	500	Taluka-Sakri, Dhule District
20		Patoda Solar Park (Paramount)	500	Villages Tambarajuri and Wadzari, Taluka Patoda, Dist. Beed.
21		Dondaicha Solar Park	500	Villages- Vikhran & Methi, Taluka-Dondaicha,district Dhule, Maharashtra

(continued)

Table 5.2 (continued)

Sl.No.	State	Solar park	Capacity (MW)	Land identified at
22	Manipur	Bukpi Solar Park	20	Bukpi Village, Pherzawl District in Manipur
23	Meghalaya	Solar Park in Meghalaya	20	Thamar, West Jaintia Hills & Suchen, East Jaintia Hills districts
24	Mizoram	Vankal Solar Park	20	Vankal, Khawzal RD Block Chmaphai Dist,Mizoram
25	Nagaland	Solar Park in Nagaland	23	Ganeshnagar (12 MW) of Dimapur dist. and Jalukie (11 MW) of Peren districts
26	Odisha	Solar Park by Odisha	275	Sambalpur and Boudh districts
27		Solar Park by NHPC	100	Landeihil Village, Jagannath Prasad Tehsil,Ganjam District, Odisha
28	Rajasthan	Bhadla-II Solar Park	680	Village-Bhadla, Jodhpur Dist, Rajasthan
29		Bhadla-III Solar Park	1000	Village-Bhadla, Jodhpur Dist, Rajasthan
30		Bhadla-IV Solar Park	500	Village-Bhadla, Jodhpur Dist, Rajasthan
31		Phalodi-Pokaran Solar Park	750	Villages Ugraas, Nagnechinagar & Dandhu,tehsil Phalodi, dist Jodhpur (450 MW) and villages Lavan & Purohitsar, tehsil Pokaran,dist Jaisalmer (300 MW)
32		Fatehgarh Phase-1B Solar Park	421	Fatehgarh & Pokaran, Jaisalmer, Rajasthan
33		Nokh Solar Park	980	Village-Nokh, Pokaran, Jaisalmer, Rajasthan
34	Tamil Nadu	Kadaladi Solar Park	500	Narippaiyur and nearby villages, Kadaladi Taluk in Ramanathapuram District
35	Uttar Pradesh	Solar Park in UP	440	Orai & kalpi Tehsils of Jalaun, Meja tehsil of Allahabad, Chaanbe tehsil of Mirzapur and Akbarpur tehsil in Kanpur Dehat districts
36		UP Kanpur Dehat Solar Park	50	Village Leharapur, Tehsil-Akbarpur,Dist. Kanpur Dehat
37		UP Jalaun Solar Park	50	Village-Mirzapur Jagir, Tehsil-Madhogarh, Dist.Jalaun
38		UP Kanpur Nagar Solar Park	30	Village Katar, Tehsil-Ghatampur, Dist.Kanpur Nagar
39	West Bengal	Solar park in West Bengal	125	Dadanpatrabar, Maina and Dakshin Purusottampur, Purba Medinipur, District
	TOTAL (17 States)		22,879	

Source http://164.100.47.193/lsscommittee/Energy/17_Energy_17.pdf)

Significant solar PV generation technology challenges in large-scale deployment can be identified as; low efficiency of solar cells, limited production capabilities due to material shortages, large land area requirement, maintenance of large solar parks, high degradation rate, and waste disposal after use. These concerns are being addressed through R&D in academic institutions, national laboratories, industry, and the government. The issue of solar waste recycling is also being tackled and SOFTIES India and Poseidon Solar are actively working on addressing the solar cell waste recycling after the project life ends.

References

1. Becquerel E. The man behind solar panels. Available at https://solenergy.com.ph/solar-panel-philippines-edmond-becquerel/
2. https://en.wikipedia.org/wiki/Photoelectric_effect
3. A brief history of solar panels. Available at https://www.smithsonianmag.com/sponsored/brief-history-solar-panels-180972006
4. Gray JL (2011) The physics of a solar cell. In: Luque A, Hegedus S (eds) Handbook of photovoltaic science and engineering, 2nd edn. Wiley. ISBN: 978-0-470-72169-8
5. Bhattachargee S (2015) Solar energy generation. Narosa Publishing House Ltd.
6. Shockley W, Queisser HJ (1961) Detailed balance limit of efficiency of p-n junction solar cells. J Appl Phys 32:510. https://doi.org/10.1063/1.1736034
7. https://news.energysage.com/bifacial-solar-panels-what-you-need-to-know/
8. Synergy Files (2021) Synergy files—student's portal for renewable energy and sustainability information. [Online]. Available at http://synergyfiles.com
9. Parira A (2016) Solar park: accelerating the growth of solar power in India. Akshay Urja, p 16

Part II
Solar Heat Energy and Chemical Energy Devices

Chapter 6
Solar Collectors and Low-Temperature Solar Energy for Homes

6.1 Low-Temperature Heat

Low-temperature heating devices using solar energy were among the first to develop. Low-temperature devices function around 65 °C and can go up to 250 °C in rare cases. They use flat collectors for absorbing heat. Seeing the large-scale cost-effective applications for heating water or air in India, William Adams in the 1870s; an engineer who served as deputy registrar of the High Court at Bombay in India, got so fascinated that he published a book, 'Solar Heat: A Substitute Fuel in Tropical Countries' [1]. In the book, Adams observed, '*This idea may be, and probably is, purely Utopian, but very important discoveries have been made in striving for the impossible; and if no further success is achieved than that of utilizing the rays of the sun for driving stationary steam engines, an important addition to physical science will have been made, and a great commercial revolution will have been affected*.'

In solar heating devices, low-temperature, low-cost devices are indeed a commercial revolution in many ways. Solar water heating for applications that required electricity or gas was picked up in other parts of the world in the 1950s due to electricity shortages. The solar water heating industry took shape in Israel even before Israel gained independence in 1948. In the 1950s, a fuel crisis in Israel resulted in the increased use of solar water heaters. Nearly 50,000 solar water heaters were sold in Israel during 1957–1967 for in-house use and exported to other countries [2]. Today, 85% of Israel's households use solar water heaters.

In Australia and Japan, solar water heating applications grew due to government policy support and innovative designs that could achieve cost reductions. In Japan, the soft vinyl heater proved very cost-effective and soon became popular in rural districts. In 1953, SW Hart and Co., a pioneering plumbing company based in Perth, decided that the Sun was the best energy source to heat water in Western Australian homes. Solahart, a company in Australia, nearly sold 40,000 solar water heaters in Australia. The total sales of five manufacturers of solar water heaters rose to millions by 1969 [3].

M. Goel et al., *Solar Energy*, Green Energy and Technology,
https://doi.org/10.1007/978-981-19-2099-8_6

6.2 Types of Solar Heat Collectors

Mainly two type's solar heat collectors have been built,

(i) Flat plate or non-concentrating and
(ii) Parabolic trough or concentrating.

There are several options for each type, and advanced designs like evacuated tube collectors, heliostat field collectors, etc. are built. Collectors have a vital role in collecting solar resources to a center and can act as passive or active storage devices. Each collector is specific to the application in view.

A solar thermal collector functions to store solar heat using water or air heating, for different applications [4]. We can determine the stored energy of sensible heat in a solar water collector from

$$Q_s = m \cdot s \cdot (T_2 - T_1) \tag{6.1}$$

where Q_s is the stored energy,
m is the mass of the material used for storage (it is water in this case),
s is its specific heat (which is one for water) and
T_1 and T_2 are inlet and outlet temperatures.

Water has a high specific heat and is a preferred medium for thermal storage. It can transfer heat to the user without the need for a heat exchanger. When water cannot be used for some reason,[1] fluids other than water are used and act as heat exchangers.

6.2.1 *Flat-Plate Collectors*

A flat-plate collector has a flat plate. It is coated black from the outside to absorb incident solar radiation to its maximum. The coated side of the collector facing the Sun is covered with a transparent glazing made of glass or plastic. It allows sunlight to pass but prevents cool air from flowing into this space. Solar heat is retained, and radiant heat loss is to be minimized. A normal flat-plate collector consists of an absorber, a transparent cover sheet, metal tubes welded to the absorber plate, and an insulated box. The insulation reduces heat loss from the back or the sides of the collector. The absorbed radiation transfers the heat to the liquid (water) flowing through the tubes. The collector is mounted on an inclined panel so that its maximum area faces the Sun for maximum time of the day (Fig. 6.1). The temperature attained is in the range of 30–80 °C.

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[1] Either due to its corrosive properties or in very cold climates where it can freeze.

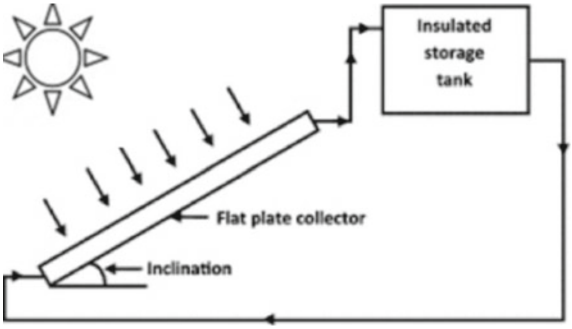

Fig. 6.1 A flat plate collector for domestic use

The collector area has an important role and the flat plate collector is designed according to the application in view and the location. For area calculation of a flat plate collector, please see Box 1.

Evacuated tube collectors have been designed to achieve greater efficiency. Such collectors help in reducing heat loss to environment and can reach temperatures up to 200 °C.

(1) *Flat Plate Evacuated Tube Collector*

An evacuated tube collector comprises an array of transparent glass tubes coated black, in place of the blackened flat plate. The glass tubes are cylindrical in shape and are mounted such that the angle of the sunlight is always perpendicular to the heat-absorbing tubes. It can be a single tube or double-walled tube, in which air is evacuated from the space between the two glass tubes [5]. In a single wall tube, a flat or curved aluminum or copper plate is attached with a metal pipe. The plate has a selective coating that transfers heat to the fluid (which can be liquid or air) circulating through the metal pipe. In a double-walled design, vacuum reduces losses in heat transfer and increases the efficiency of the collector. The outer tube is made of extremely strong transparent glass, which can be borosilicate glass. It does not get heated like a normal flat plate solar collector when in use. The tubes have a space in the center for the heat exchanger pipe. The heat transfer fluid is pumped through the absorber tube, removes heat from the absorber, and transfers to water in a storage tank (Fig. 6.2).

Evacuated tube collectors are highly efficient as they prevent heat losses from the surface. They are particularly useful in areas with cold climates and for industrial applications. There are designed according to the site requirements.

Box 1: Flat Plate Collector Area Calculator

First accurate model of flat plate solar collectors was developed by Hottel and Whillier in the 1950s. The collector efficiency determines the temperature of the water that can be reached.

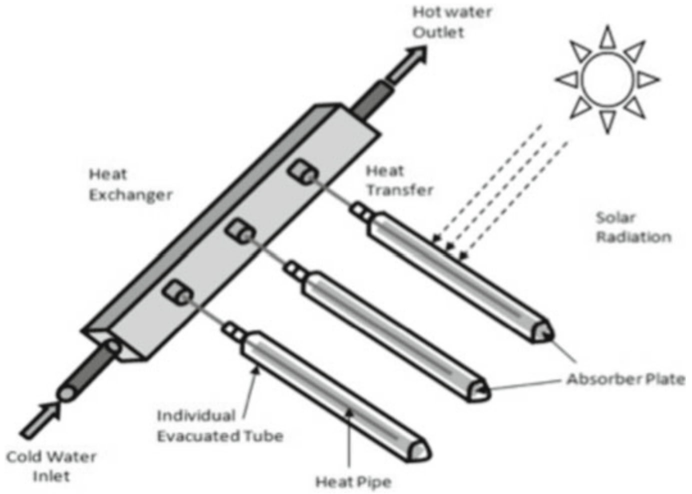

Fig. 6.2 Evacuated tube collector

The amount of solar radiation received by a collector is given as

$$Q_i = I \times A \tag{6.2}$$

Here Q_i is heat gained by the collector,
I is the intensity of incident solar radiation in W/m^2, and
A is collector surface area in m^2.

Q_i is not fully used, and there are convection losses as heat is lost to the surroundings. There are reflection losses due to system cover, and some absorption losses in the transparent cover sheet. If the transmission rate of cover is t_r and absorption rate is t_a, the actual heat gain Q_i is modified as a function of transmittance-absorption product and can be written as

$$Q_i = I(t_\mathrm{r} \cdot t_\mathrm{a})A \tag{6.3}$$

If the temperature of the collector becomes higher than that of the surroundings, some heat is lost to the atmosphere. The rate of heat loss (Q_o) is proportional to the difference in the temperature of the collector and the temperature of the atmosphere. It is given by

$$Q_\mathrm{o} = U_\mathrm{L} A (T_\mathrm{c} - T_\mathrm{a}) \tag{6.4}$$

Here T_c and T_a are the temperatures of the collector and the atmosphere, respectively.

U_L is the heat transfer coefficient of the collector.

The useful heat gain Q_u is given by $Q_i - Q_o$ and is written as

$$Q_u = A[I(t_r \cdot t_a) - U_L(T_c - T_a)] \tag{6.5}$$

In practice, another factor F_R is needed to determine the effectiveness of transferring heat absorbed by the absorber plate to the heat removal fluid. The famous Hottel Whillier-Bliss equation for flat plate collector efficiency is as follows.

$$Q_u = F_R A[I(t_r \cdot t_a) - U_L(T_c - T_a)] \tag{6.6}$$

Three important design parameters for determining the efficiency of the collector are; t_r, F_R and U_L. Both F_R and U_L are variables depending on the surrounding temperature, wind, etc. The t_r is a function of glazing material. The thermal efficiency η is ratio of Q_u and Q_i.

By knowing the thermal efficiency of a collector, the total surface area of the collector (A) can be determined using the following relationship.

$$A = 1.16 \times 10^{-3} \times Q_w \times T_e/I_s \times \eta \tag{6.7}$$

Here, Q_w is the quantity of water to be heated
T_e is the expected rise in temperature of the water
I_s solar insolation/m^2 in a day
η is the thermal efficiency of the collector in %.

It is estimated that for heating 100 L of water to 40 °C above its average temperature, the collector area required will be 1.86 m^2, assuming it has 50% efficiency. About 5–10% more collector area should be planned to compensate for actual radiation losses.

6.2.2 Concentrating Collectors

For attaining higher temperatures from the solar heat, concentrating collectors are used. A concentrating collector uses mirrors in different designs and shapes to reflect the sunlight at the focal point on an absorber panel. The area that can be intercepted by the solar radiation is much greater than the flat plate collector by having a curvature in the collector. The absorber absorbs the reflected light at the focal point, increasing the flux of sunlight many folds. A concentrating collector captures much larger radiation and has reduced size of the energy-absorbing surface, which helps in minimizing radiation losses. We can reach much higher temperatures.

Different configurations have been developed for concentrating collectors. The reflectors can be of various shapes as spherical or parabolic, either concave or flat mirrors. The absorber surface is blackened and is mounted with a tracker so that sun rays are always focused on it. Three main components of a solar concentrating collector are; a Reflector, an Absorber, and a Tracking system. Tracking systems can move on 1 or 2 axes to track the Sun for optimum utilization.

The ratio of the collecting aperture area to the reflector surface area gives the concentration ratio C for solar radiation. It can be expressed as,

$$C = A_r/A_a = r_a^2/r_r^2 \tag{6.8}$$

where A_r is the aperture area of reflector surface,
A_a is the area of collecting absorber, which gets irradiated by the reflector,
r_a is the aperture radius, and r_r is the reflector area radius.

A concave mirror is a segment of a circle. Light is reflected its focal point. A parabolic shape is used for maximizing the reflection of the incident light and increasing C. Higher the value of C, the better it is. The highest achievable concentration ratios in concentrating collectors vary from 5000 to 8000.

In practice, a parabolic reflector makes two important contributions in comparison to a concave mirror reflector;

(a) it provides a higher concentration ratio and
(b) higher absorber surface temperature.

Three different configurations of the concentrating collectors are;

(i) Line-focusing cylindrical parabolic concentrator, the absorber along the focal axis, and Sun tracking along the axis help get the maximum concentration. Or a paraboloid dish collector with a point focus.
(ii) A point focus collector requires two-axis tracking.
(iii) An array of flat mirrors is used to reflect the sunlight to a receiver placed along the central axis. The mirrors are rotated independently to track the Sun.

In all these configurations the heat transfer fluid in the absorber tube at the receiver absorbs the heat. Three configurations are shown in Fig. 6.3.

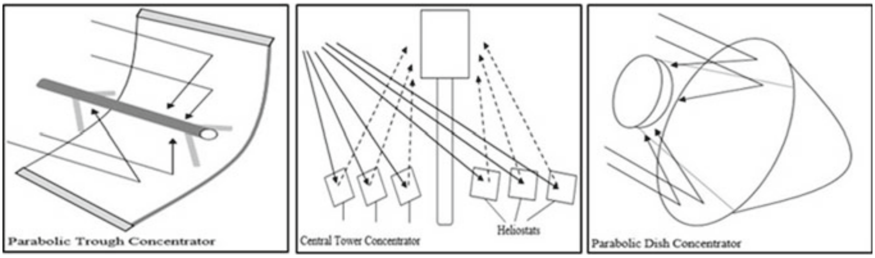

Fig. 6.3 Different configurations of solar concentrating collectors

Table 6.1 Types of solar collectors and their broad parameters

S. No.	Status of sun-tracking	Collector type	Concentration ratio	Temperature range (°C)
1.	Stationary	Flat plate	1	30–80
2.	Stationary	Evacuated tube	1	50–200
3.	Single-axis	Parabolic trough	40–100	200–500
4.	Two-axis	Parabolic dish	100–1200	500–1500
5.	Two-axis	Heliostat central receiver	200–1500	500–2000

Source Compiled by author

Solar high-temperature heat can be used for steam production, materials processing, and/or for production of electricity.

Different types of solar collectors and their concentration ratio and indicative temperature range are summarized in Table 6.1.

A concentrating collector can also be used in the photovoltaic (PV) systems, to increase the light intensity on the collector. It helps in increasing efficiency of the cell, but also raises its temperature.

6.3 Low-Temperature Low-Cost Solar Energy Systems for Homes

Solar water heating is the most widely used technology for collecting solar energy for heating water, both in households and industrial applications. In families, they are used for water heating, space heating, solar cooking, and swimming pool heating (both in homes and commercial complexes), among others. Many industries like food processing, paper and pulp, fertilizers, textiles, and the chemical industry use low-temperature solar energy systems. These are discussed in the next chapter.

6.3.1 Solar Water Heater (SWH) Technology

Early solar water heaters were designed as tanks painted black from inside to absorb solar heat. These were highly cost-effective but impractical in use as they took a long time to be heated up. In 1891, Climax Solar Water Heater was built by Clarence Kemp and became famous for households in the USA as it could retain heat when the Sun was not shining. In the 1920s, another solar water heater named ‘Day and Night’ was built. Several improvements have taken place since then [6].

A solar water heater uses a collector, a tank, and water tubes. Water passing through the tubes gets heated up and transfers heat to a reservoir or storage tank.

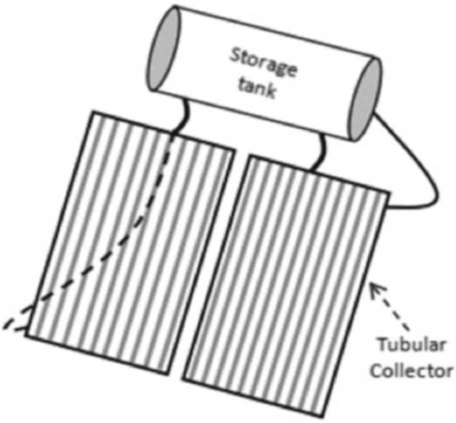

Fig. 6.4 Thermo-symphonic solar water heater with a tubular collector

Solar water heating systems are two types (i) Naturally Convective and (ii) Forced Convective. They can also be classified as Passive and Active devices. When fluid from the collector flow to the utility by natural convection, the system is called a passive collector. A dynamic system uses pumps to force the fluid from collector to utility. Both flat plat and tubular collectors can be used.

(1) **Naturally Convective Heater**: Naturally convective heaters are most common for domestic systems. The storage tank is kept at a height more than the collector's, and cold water from the storage tank naturally flows down to the collector's inlet (Fig. 6.4). On passing through the collector, it gets heated by absorbing solar thermal energy. The solar-heated water flows up to the storage tank by convection currents and a thermo-symphonic flow is maintained due to the difference in hot and cold water density. On a good sunny day, we can achieve a temperature up to 80 °C. The re-circulation of the heated water through absorber panels in the collector can raise the temperature further.

The expression gives Thermo-symphonic pressure P,

$$P = h(d_2 - d_1) \tag{6.9}$$

where h is the difference in height between collector outlet and tank outlet
d_1 is the density of water at the collector outlet (heated water)
d_2 is the density of water at the collector inlet (cold water).

The useful heat gain for a collector is dependent on the difference between outlet and inlet temperatures. A naturally convective heater is also called a thermos-symphonic solar water heater. It is a mature technology and is comparatively less expensive. We can use a tubular collector in place of a flat plat collector for attaining higher efficiency. Solar water heater (SWHs) of 100–300 L capacity is suited for home use. We can install it on rooftops, building terraces, and open ground where there is no shading.

(2) **Forced Convection System**: A forced convection system is an active solar collector. It uses an external pump to maintain the fluid flow. An active system is preferred when the storage tank cannot be raised to a greater height, and a large quantity of fluid is to be heated under controlled conditions, as in a solar pool, which acts as a storage tank. As the collector is at greater height, water from the storage tank is pumped into the collector area. A thermostat switch controls the pump, which turns on only when the collector fluid temperature becomes sufficiently high. To maintain the fluid flow, a float valve is provided both in thermo-symphonic and forced circulation systems.

A variety of solar water heaters designs are made suiting the requirement and site characteristics. Storage tanks can be two types (i) pressurized and (ii) non-pressurized. The non-pressurized tank is made from low-cost materials like fiberglass or plastic, but a pressurized tank is made of metal. When fluid used in the application is the same as the fluid used in the collector (usually water), it is called an open-loop system. Special precautions are needed to avoid freezing water at night and damage to the collector pipes in freezing climates. In such cases, a fluid other than water is used, which acts as a heat exchanger. It transfers the heat to the water in the storage tank. Such a system is called a *closed-loop system.* A closed-loop system can be designed when water quality is terrible, and corrosion in collector pipes might occur.

6.3.2 Solar Swimming Pool Heater

Swimming pool heating is one of the oldest applications of solar water heating. Roman hot water baths were built as early as the twelfth century. Modern solar-heated swimming pool systems are designed on same principles as an SWH, but their temperature requirement is quite different. With the advancements in science and technology, wide-area collectors are designed in combinations as arrays in 'series and parallel' for heating large volumes of water. Collectors are primarily unglazed and consist of black-colored tubes made from rubber or plastic-based materials through which the pool water is continuously circulated. Water from the pool is directly pumped to the collectors and returns to the pool after heating. The pool itself acts as a reservoir.

A swimming pool heating system can be designed as a closed-loop or an open-loop type. A closed-loop design uses a heat exchanger. In an open-loop solar water heating system, a diverter valve is used to direct water flow through the collector. It uses a differential controller that monitors the water temperature in the collector and controls the pool temperature. The valve is opened when water in the pool needs to be heated. The diverter is closed when water is to be circulated back to the pool. The differential controller helps to know whether the *diverter valve* should be opened or closed. When the water temperature in collectors reaches 3 °C or more above the pool water temperature, the controller opens the diverter valve. The system's energy demand depends on the atmospheric temperature, which in turn determines the rate of heat gain and the rate of heat loss in a swimming pool.

In swimming pool heating the temperature required is around 28–30 °C and the entire pool must have a uniform temperature. The efficiency of a collector system in pool heating is dependent on solar radiation captured by the collector, the pool area, and the temperature required. It is given by,

$$E_c = Q_h A_p f / R_p A_c t \tag{6.10}$$

where E_c is season's average efficiency of the solar collector field.

Q_h is the total heat energy requirement/m^2 of the surface area for the entire swimming season.

A_p is the water surface area in the pool.

F is the fraction of the total energy requirement to be met by solar energy.

R_p is total solar radiation over the entire surface.

A_c is a collector area.

We can calculate the optimum collector area for a pool by knowing various pool parameters and total incident solar radiation averaged over the entire season. In warm climates, heat gain due to the direct absorption of solar radiation during the day could affect the balance and increase the temperature. During the night, the temperature could fall. There could be rapid radiation loss in cold climates, requiring a constant energy supply to maintain the temperature. The use of a pool covering at night can minimize energy losses.

The collector area requirements A_c for open and covered pools are different [7]. We can express the ratio of collector surface area and water surface area A_p for an open, as well as covered pool in terms of f as;

For an open-air pool: $A_c/A_p = 2.58f$, which means that the collector area should be almost two and half times the pool surface.

For a covered pool: $A_c/A_p = 1.12f$ and the collector area required is 11% higher than that of the pool surface area.

A bubble wrap or a vinyl cover can help to reduce the collector area and extend the swim season. The extra investment in a pool covering can be partly compensated by using a smaller collector area requirement in a covered pool.

6.3.3 Solar Cooking Technology

As one of the earlier applications of solar heat, the world's first solar energy collector as 'hot box' was perhaps built in 1767 using a plate collector by a Swiss scientist Horace-Bénédict de Saussure, who said, '*it is a known fact, and a fact that has probably been known for a long time, that a room, a carriage, or any other place is hotter when the rays of the sun pass through glass.*' A solar cooker is a hot box that can be designed in different forms.

Fig. 6.5 An Indian woman cooking in a box-type solar cooker [9]

(1) Box-Type Solar Cooker

Maria Tekes, in 1951, designed a reflecting type box solar cooker for home use [8]. It consisted of a double-walled container with the space between outer and inner walls filled with an insulating material. The inner wall was made of metal and painted black to absorb maximum solar radiation. It used a glass cover to trap maximum heat and helped in creating a greenhouse effect. It was a slow cooking device. We could use it for cooking those food materials which did not require very high-temperature.

A solar cooker is completely clean and uncontaminated by fuel gases. Today's box-type solar cooker has mirrors on the inside of the cover, which is inclined to receive maximum radiation and reflect it on the food container. In this system, the temperature could reach up to 145 °C within 2–3 h when placed in sunlight. For optimum results, the box could be rotated manually to face the sun rays always. The food container placed at the center is divided into four chambers to make it more efficient and cook more than one item simultaneously. The box-type of solar cooker has been extensively promoted in rural households in India since the 1990s (Fig. 6.5).

(2) Concentrating Type of Cookers

A concentrating solar cooker uses a parabolic dish outside the box to focus Sun rays on the food container. Abbot, in 1920, first designed a combination of parabolic mirrors as concentrators in place of plain mirrors. It used oil as a heat transfer fluid for cooking. A modern version uses a parabolic dish that can attain a higher temperature up to 400 °C. The cooking vessel is supported at the focal point of the parabola and produces steam. The reflector or mirrors mechanically track the Sun for optimum results. Paraboloid concentrator dish solar cookers (Fig. 6.6) have received the most attention in semi-commercial use. Different concentrator designs using plane mirrors or metallic reflectors have also been developed for community uses with better efficiency.

The performance mainly depends on the optical efficiency, which is affected by the orientation of the reflector concerning Sun. Environmental conditions like solid

Fig. 6.6 A parabolic dish solar cooker [10]

winds at a place also affect its performance. The placement of the cooking chamber is such that reflected heat for a significant part of the day is incident at the bottom of the vessel. Because of the considerable temperature difference with the ambient temperature in a concentrating cooker, the heat loss is higher than in a box-type cooker. For large-scale cooking, such as in Institutional canteens, a series of parabolic dishes can be deployed.

Box 2: Indian Research Experience in Solar Cooker

In India, several designs of solar cookers as two-container and four-container models have been developed, and research carried out. A box-type cooker has been sold in millions for domestic cooking in rural and urban areas. Practical difficulties faced by the consumers due to uncontrolled operation, low reliability, and the long time required for cooking have been resolved with research inputs. For a stabilized operation, electrical backup to a solar cooker has been developed. In box-type cookers, low optical efficiency of the reflector and the high heat loss factor are the main disadvantages.

Parabolic dish-type cookers have gained popularity in community kitchens. First Scheffler Community Kitchen was installed in Brahmakumari Ashram Mount Abu, Rajasthan, in the 1990s. Since then, it has been adopted in many institutional and other religious kitchens and institutional canteens. In 2002, solar-operated Tirumala Tirupati Devasthanam kitchen came up at Tirupati catering to 15,000 pilgrims annually. It helped the shrine to save INR 1.7 million a year and reduce carbon dioxide emissions by 1.2 tons per day [11]. Many other solar cooking facilities for other shrines, residential schools, and defense establishments have come across India. World's largest concentrating solar cooker with many dish concentrators was installed in 2009 at Sai Baba temple in Shridi, enough to make food for 20,000 people.

Research and development for solar cookers with higher efficiency continue. A Scheffler dish solar cooker has been designed at the Indian Institute of Technology, Delhi [12]. It has small section of a paraboloid to act as a reflector. With a concentration ratio of 20, temperatures at the cooking chamber could reach up to 425 °C. Its use for the community could save up to 57% of the total energy demand. The efficiency attained was 26% for the Indian conditions.

This chapter covers fundamental concepts in low-temperature solar devices for applications in-home use. Low-temperature systems have merits in being free from greenhouse gas pollution and saving depleting fossil fuel reserves. It is estimated that one thousand solar water heaters of 100 L capacity would reduce peak load electricity consumption by 2000 kWh in one year and prevent greenhouse gas emissions equivalent to 1500 tons of CO_2. In India, solar heating applications have grown rapidly since 1990s. There is scope for adoption of these low-cost technologies on a larger scale. Widespread use of solar water heaters can reduce a significant portion of the conventional energy needed for heating water in homes, factories, and other commercial and institutional establishments.

References

1. Jones G, Bouamane L (2012) Power from sunshine: a business history of solar energy. Working paper 12-105, Harvard Business School, 25 May 2012. Available at https://www.hbs.edu/ris/Publication%20Files/12-105.pdf
2. http://www.climate.org/archive/topics/international-action/israel-solar.html
3. John P. Let it shine: the 6,000-year story of solar energy, Kindle edn. New World Library, p 209
4. Goel M (2005) Energy sources and global warming. Allied Publishers Pvt. Ltd., New Delhi, p 492. ISBN 81-7764-844-6
5. Hudon K (2014) Solar energy—water heating, chap 20. In: Letcher TM (ed) Future energy: improved, sustainable and clean options for our planet. Elsevier, pp 433–451. ISBN 9780080994246. https://doi.org/10.1016/B978-0-08-099424-6.00020-X
6. Spitzzeri P (2019) Solar panels in the roaring twenties: a day & night solar heater company pamphlet, ca. 1921. The Homestead Blog. [Online]. Available at https://homesteadmuseum.blog/2019/08/22/solar-panels-in-the-roaring-twenties-a-day-night-solar-heater-company-pamphlet-ca-1921/
7. https://www.energy.gov/energysaver/solar-swimming-pool-heaters
8. https://solarcooking.fandom.com/wiki/M%C3%A1ria_Telkes
9. https://www.dsource.in/resource/kitchen-products/stoves/solar-cooker
10. https://gosun.co/blogs/news/solar-oven-designs
11. Siraj MA (2012) Looking up to the sun. The Hindu, 06 July 2012
12. Indira S, Kandpal TC (2020) Solar energy for institutional cooking in India: prospects and potential. Environ Dev Sustain 22:7153–7175. https://doi.org/10.1007/s10668-019-00471-9

Chapter 7
Low-Temperature Solar Energy Systems for Industry

7.1 Solar Heat in Industry

Widespread use of solar energy in industrial applications by low and high-temperature devices or photovoltaic systems would have an essential role in reducing CO_2 emissions and providing energy security in a place. Trends in global industrial energy demand suggest a 1.3% rise per year until 2030. Heat or thermal energy is a significant part of the global energy consumption and industries are substantial stakeholders with a share of 25–50%. Solar heat provides thermal energy for a wide variety of industrial applications. In last few years, the use of low-temperature solar energy technologies, namely, solar water heating, solar air drying, solar water desalination, and water purification, is growing for industrial applications. Examples from the Indian textiles and spice industry are presented.

7.2 Solar Water Heating Potential in Industry

Water heating constitutes a significant industrial process application that consumes about 13% of total industrial energy. Textiles, Food, Agriculture, Buildings, Chemicals, and other industries extensively use water heating devices. Preheated water is used in many industrial components; such as boiler feed, cleaning, washing, and dyeing [1]. Table 7.1 depicts industries and applications of heat in the temperature range of 60–200 °C. Both thermosiphon and forced convection water heating type systems have been developed since the 1980s for industrial use. However, forced convection-type designs are preferred in commercial and industrial processes. In these systems, a loading pump controls the flow of hot water, and after use, water does not flow back to the storage tank. The choice of a system to use a flat plate or concentric collector is dependent on the application in view.

The dairy, food processing and beverages, automotive components, textiles, chemicals, and pharmaceuticals are most the promising sectors. It is seen that several

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Table 7.1 Heat demand industries, processes, and ranges of temperatures

Industry type	Process used	Temperatures (°C)
Dairy	Pressurization	60–80
	Sterilization	100–120
	Drying	120–180
	Concentrates	60–80
	Boiler feedwater	60–90
Tinned food	Sterilization	110–120
	Pasteurization	60–80
	Cooking	60–90
	Bleaching	60–90
Textiles	Bleaching, desizing	60–90
	Scouring	90–110
	Drying, degreasing	100–130
	Dyeing	70–90
	Fixing	160–180
Paper	Cooking, drying	60–80
	Boiler feed water	60–90
	Bleaching	130–150
Chemical	Soaps	200–260
	Synthetic rubber	150–200
	Processing heat	120–180
	Preheating water	60–90
Meat	Washing, sterilization	60–90
	Cooking	90–100
Beverages	Washing, sterilization	60–80
	Pasteurization	60–70
Flours and by-products	Sterilization	60–80
Timber by-products	Thermo diffusion beams	80–100
	Drying	60–100
	Preheating water	60–90
	Preparation pulp	120–170
Bricks and blocks	Curing	60–140
Plastics	Preparation	120–140
	Distillation	140–150

(continued)

Table 7.1 (continued)

Industry type	Process used	Temperatures (°C)
	Separation	200–220
	Extension	140–160
	Drying	180–200
	Blending	120–140

Source Adapted from [1]

processes from preheating water, sterilization, drying to blending and curing and industrial space heating, can be performed using solar energy.

7.2.1 Solar Energy Use in Indian Textiles Industry

Textiles industry in India is one of the oldest industries and contributes 14% of total industrial production. It has 15% share of India's export market and 3.7% share of global market at present [2]. Textiles have a vast infrastructure having 3400 mills of different sizes across the country dominated by cotton industry. In a study with the Indo-German Chamber of Commerce, the Solar Thermal Federation of India (STFI) [3] concluded that dairy, food processing and beverages, automotive components, textiles, chemicals, and pharmaceuticals are the most promising sectors for the use of solar water heating processes in India. Among these, the textile industry is one of the highest energy-consuming sectors in India, with electricity having a share of 15–20% of total production cost. Textile processes like bleaching, dyeing, drying, degreasing, fixing, and pressing require a lot of hot water in the range of 60–180 °C at various stages.

The government of India has been providing incentives to install solar water heating systems in several textile mills since the 1980s. The textile mills have successfully installed solar water heaters of capacity up to 5000 Lt in the mills for providing hot water in the temperature range of 70–85 °C. It uses hot water for several fabric processing steps such as scouring, bleaching, dyeing, etc. Solar air heating devices also operate for fabric drying. Parabolic trough type collectors are used in the processes which require steam generation. These are more efficient and used in processes such as sterilization, steam-flash, and direct-steam generation. Solar rooftop plants are installed. Key examples of solar heating in Indian textiles industry [4] are provided in Table 7.2.

Three demonstration plants of Solar Kier, designed to optimize the use of solar energy in the textile industry, have come up in Faridabad, Tamil Nadu, and Rajasthan. A kier is a cast-iron vessel connected to a solar water heating system through a heat exchanger. The heat exchanger fluid was heated to 70–80 °C gaining heat from solar-heated water, and circulated through the kier loaded with cotton fabric. Feasibility for processing different qualities of cloth, cotton yarn, and threads has been established. In addition, the GEF-UNIDO program for solar thermal industrial process

Table 7.2 List of solar water heating process integration at various textile industries in India

Industry	Industrial operation	Solar collector	Operating temperature	Collector supplier
Chelsea Mills, Gurgaon	The plant is a garment manufacturing company producing apparel wear majorly denims	Non-pressurized flat plate collector (FPC) solar water heating system with 943 m^2 total aperture area	Non-pressurized hot water at 60–65 °C	M/s Inter-Solar Systems Pvt. Ltd., Chandigarh
Sharman Shawls, Ludhiana	Manufacturer of textile	Flat plate collector with 360 m^2 gross area	Hot water at 60–80 °C for bleaching, dyeing and washing garments	Aspiration Energy Pvt. Ltd.
Purple Creations, Baramati	Children clothing company	30 dishes of Scheffler concentrating collectors with an absorber area of 480 m^2	Steam at 150 °C at 6 bar	M/s Thermax India Pvt. Ltd.

Source Ramaiah and Shekar [4]

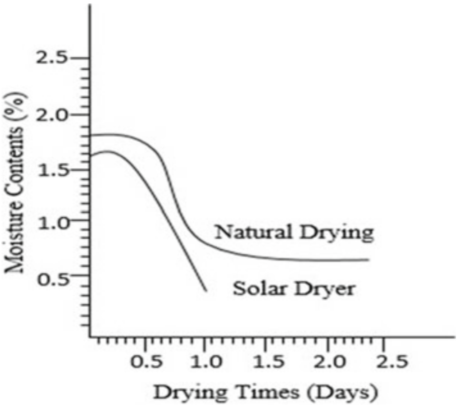
heat boosted the use of concentrating solar power in textile mills. Navkar Textiles, located in the heavy industrial area of Jodhpur, Rajasthan, has installed Schaeffer-type solar dish concentrators for meeting steam requirements [5]. A silk factory in Mysore uses a parabolic trough-concentrating collector to heat water up to 150 °C for steam generation.

Government of India launched the 'Solar Energy Scheme for Power looms' in 2018 to encourage the use of off-grid and on-grid solar PV for attaining energy sustainability in the textiles sector. The assistance is provided to set up solar power plants in power loom units [6]. Many big mills have reached a solar power share of as much as 30–60% in total energy including contributions from power looms and solar rooftop installations. The first 100% solar power-enabled Jai Bhawani Women's Cooperative Textile Mill in Asia, is to come up in Parbhani district, Maharashtra in India on 30 acres of land [7] using solar heating and solar PV production of electricity [8].

7.3 Solar Dryer Technology

The drying of agricultural produce in the open Sun has been the most ancient and widely used traditional method for food preservation. It helps in removing excess moisture content. Industrial use of solar drying began in Japan in 1948. The Kaneko-Kogyosho Company began mass-producing Yamamoto's heater for farmers for rice

Fig. 7.1 Natural and solar drying times



crops. By widespread use, each family could achieve a saving of about 1½ tons of rice straw annually for use as cattle fodder or fertilizer [9]. In a solar dryer, the air collectors work on the same principles as solar water collectors. A solar air heater makes use of air collectors in place of water collectors. In the agriculture or food industry, it helps in removing the moisture.

Open-to-sun drying is a slow and uncontrolled process. Though the capital and operational costs are negligible changing weather from rains clouds and make it less efficient, it suffers from several drawbacks: large land area requirements, contamination, susceptibility to the growth of bacteria and damage due to sudden rain, etc. It can result in undesirable product quality, nutrition loss, and loss in quantity of up to 40% of the total produce. In open Sun-drying there are several other issues about insect and fungus infestation, bird encroachment and wastages, etc. A solar dryer dries agriculture produce in a controlled manner. Figure 7.1 shows a relative comparison of drying time in the open Sun and using a solar dryer.

A solar drier is designed according to the crop or food to be dried and the available solar radiation. It uses a heat absorber plate which is either porous or non-porous. A porous absorber allows maximum absorption of solar radiation and good flow of heated air through the absorbing medium. In a non-porous type, air flows take place either from above or below the plate. It has a plastic or glass cover kept above the absorber. The external design parameters are; solar Insolation, ambient temperature, relative humidity, wind flow rate and enthalpy, etc. The measure of drying efficiency in a food product depends on its internal parameters such as its moisture content (m), surface characterization, physical structure, and chemical composition.

The reduction in moisture content m of a product can be as ascertained from,

$$m = (w_1 - w_2)/w_2 \tag{7.1}$$

where w_1 and w_2 are the weights of the wet and dried samples.

Equilibrium Moisture Content in a product is the minimum moisture to which a material can be dried under a given set of drying conditions. The equilibrium reaches when the water vapor pressure in the material becomes equal to the partial pressure of water in the surrounding air.

There are passive and active driers. A solar passive dryer overcomes the drawbacks of conventional open-to-sun drying. Several benefits include;

- smaller land area requirement,
- the shorter time needed,
- protection against weather and
- higher output as compared to open-to-sun drying.

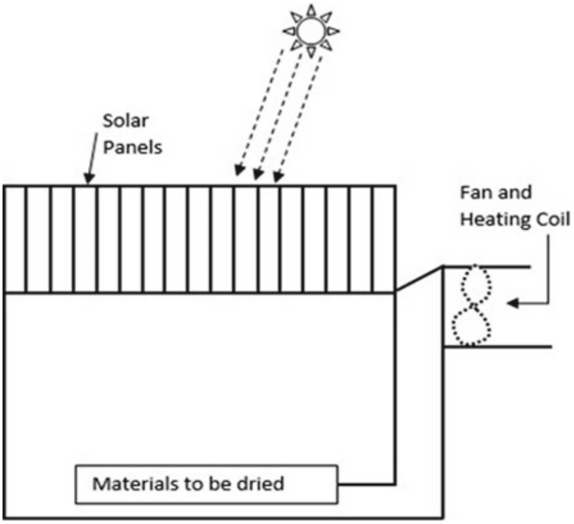
7.3.1 Naturally Convective Crop Drying

A direct or naturally convective crop drying system has a drying chamber as a large enclosure with a transparent covering on the sides (Fig. 7.2). Inside bottom and side surfaces are painted black to absorb maximum solar radiation. A collector with a glass covering is placed at an inclination of 30 °C to the horizontal on the chambers top. Ventilation holes are made in the bottom of it for fresh air to get sucked in. In a naturally convective dryer, hot air convection currents flow in the chamber. The product to be dried is placed inside the enclosure.

Trays are made of wire mesh bottom, and a stream of solar-heated air is circulated over the product. The moisture of the food is taken away by air entering the cabinet from below. On the upper side of the dryer, holes or chimneys are provided for moist warm air to escape.

A solar tunnel drying system consisting of a collector and a drying tunnel connected in series is used to dry multiple agricultural products. The collector and

Fig. 7.2 Direct solar drying



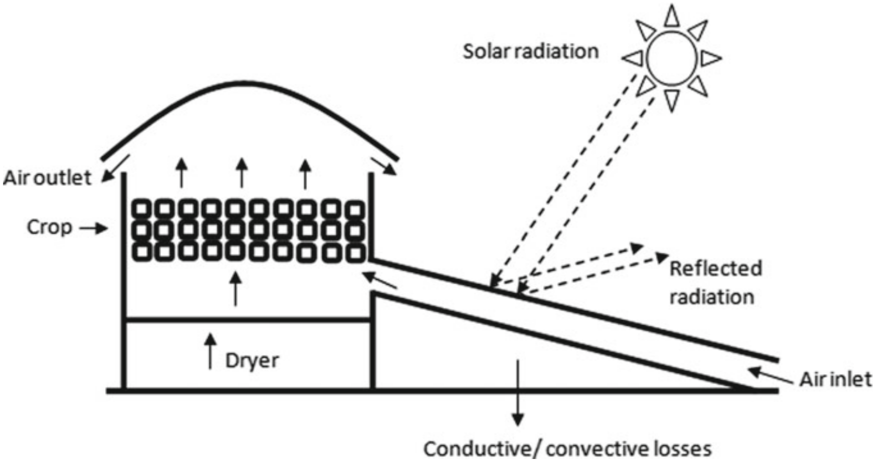


Fig. 7.3 Indirect solar drying system

drying tunnel is covered with transparent glasses or plastic sheets. The collector element comprises black coated metallic absorber plate, while the drying chamber has a number of trays for loading the product to be dried. An enclosed structure covered with stabilized UV-resistant polythene sheets acts as a solar collector and drying chamber.

7.3.2 Indirect or Active Crop Drying

Indirect or force-convective crop dryers, also called active dryers, have separate units for the solar collector and the drying chamber. It is adopted when the product is not in direct reach of Sun. A fan or a blower pumps the air into the drying chamber. It creates forced convection and also maintains a desired flow through the product. It can handle more products with improved efficiency and, therefore more suited for large-scale applications. Indirect solar dryers offer reasonable control over the drying process. Air as heat transfer fluid helps in various industrial space heating applications. The active dryers are primarily used in industry (Fig. 7.3).

7.3.3 Hybrid Systems

For industrial use, we prefer hybrid systems as a combination of direct and indirect crop dryer technology. The design of a dryer depends upon the availability of sunshine and the temperature needed for heating. Using hot air or gas, it can attain temperatures up to 140–220 °C. A hybrid system also uses other energy sources such as biomass or fossil fuel combined with solar drying technology. The capital cost of a hybrid system is more, but it can better manage the quality and quantity of the product. It provides greater efficiency and reduces drying time further for industrial systems.

Solar drying has applications in many other industries. In the building industry, wood panel manufacturing drying is the most energy-demanding process for large-scale applications. Solar kilns designs with flat plate solar collectors are used for drying timber in tropical countries. Enormous potential exists, and several drying units of 4 m^2 capacity are built with a large solar collector area. Such prominent solar collectors are made of hollow concrete blocks. A thick clear socket glass is used as a glazed cover. The timber of 25 mm thick board could dry in about 2–3 weeks to the requisite moisture content of less than 10% at the cost of about two-thirds of electricity.

7.3.4 Indian Spice Drying

Indian spices are famous world over, not only for adding taste but also for their therapeutic value. India also being the second-largest producer of fruits and vegetables, solar dryers have been developed for fruits, vegetables, non-timber forest produces, spices, and different herbs on a commercial scale. Solar Cabinet Air Dryers of various sizes have been designed to resolve the problem of wastage. A dryer preserves several horticultural produce, medicinal and herbal products. Spice drying needs low-grade heat, and drying in open sun could result in loss of color. A solar dryer contributes to improvement in the quality of dries products and reduces GHG emissions. A collector area of 212 m^2 can reduce the fuel consumption equivalent to 200 tons of coal over two years.

Different designs have been built according to material to be dried. An efficient solar dyer using a transpired collector is considered ideal for drying spices like cardamom, chillies, seeds, and coriander. Conservation Engineering Inc. and National Renewable Laboratory in the USA have designed a transpired collector. It is made of metal, has no glazing and has a perforated top to create an air gap. The air gets sucked in through perforations and gets heated from the metal surface. The collector is mounted on the rooftop. Preliminary tests have indicated that each square meter of solar panel can dry varying amounts of produce depending on the initial and final moisture contents, such as 12 kg of seeds, 8 kg of cardamon, and 4 kg of chillies per day. Solar convective systems for crop and agriculture drying with temperature required and reduction in moisture content are shown in Table 7.3. The payback period of most dryers is small and can be 2–3 years. It has benefits for the control of airflow rate and temperature by increasing collector area. The study reported that a commercial solar dryer could reduce oil consumption by about 33% [10].

A Solar Conduction Dryer (SCD), a UN award-winning portable solar-powered-electricity free-dehydrator [11], using all the three modes of heat transfer and delivering the world's highest drying efficiency, was built by S4S Technologies. It has been

Table 7.3 Solar convective systems for crop and agriculture drying

Crop/spice	Solar heater configuration	Temperature required	Reduction in moisture content (%)
Paddy	Hot air	60–80 °C	16
Timber	Solar kilns	40–65 °C	12
Cash crops	Solar air heaters in hybrid mode	100 °C	10–20
Chillies	For preheating naturally convective solar heater	40–50 °C	5
Pepper	For preheating naturally convective solar heater	40–50 °C	30
Cardamom	Forced convective solar heater	In phases 40, 50 and 55 °C	10

Source Compiled by authors using data from various sources

installed at 1200 locations. A Solar Tunnel Dryer has been developed and installed at Sardar Patel Renewable Energy Research Institute (SPRERI), Vallabh Vidyanagar, to dehydrate Amla, Chilli, Mango, and other Agro-Products. The northeast is known as the ‘spice hub of India’. Zizira, a startup from Meghalaya, has made a solar dryer virtually at home and provides a fast, safe, and efficient way of drying the farmers’ produce.

Hybrid solar drying machines have been built in different models by many industries in India, not only for edible products like food, spices, and fruits but also for large-scale agriculture and industrial applications. M/s Jayveer Food Industry, Gujrat retrofitted biomass combustor-cum-air heater with the solar drying system. It enabled the new hybrid system, which can switch between any of these three modes, namely;

(a) heating the air by solar energy alone when adequate sunshine is present;
(b) heating the air by using both the biomass heater and solar dryer during the solar hours; and
(c) modulating the hybrid system between solar alone, biomass alone, or solar and biomass mode of operation, depending upon the sunshine and the temperature needed for heating a particular product.

This breakthrough in solar drying technology increased the output capacity of the industry by almost 100%. It can reduce the time of drying by 25% and increase the quality of the product. Solar dryers are extensively used in the food and agriculture industry to improve both quality and quantity.

7.4 Solar Desalination and Purification of Water

The water desalination industry is developing to provide clean water to communities to overcome their water shortages. Purification of contaminated water and desalination of seawater are two important and useful low-temperature applications of solar energy for industry. We can utilize solar energy as heat, light as well as chemical energy in water purification. Chile, way back in the 1880s, built the first commercial-scale desalination plant using solar energy. Since then, various technologies have been developed for water desalination, distillation, and disinfection, as discussed below.

We can classify solar desalination systems into direct and indirect processes.

- *Direct* solar desalination system combines a solar energy collector and desalinator in one process and produces freshwater distillate from seawater.
- *Indirect* solar desalination comprises a solar collector to collect heat and supply it via the heat exchanger to the thermal desalination process and a desalinator. It uses different solar distillation methods.

7.4.1 Solar Distillation by Flash Evaporation

Seawater contains about 0.25% of dissolved salts, whereas the accepted tolerance limit per WHO guidelines in drinking water is 0.05%. Therefore desalination is required for using it. The conventional basin solar desalination technology makes use of a device known as *solar still* [12]. The still has a shallow basin painted with black waterproof paint. The basin is covered with a sloping glass transparent plastic sheet. It acts as a condensing cover. Due to the temperature difference between the evaporating surface and condensing cover, water mass condenses on the inner surface after releasing its latent heat. *The sea's brackish or saline water* gets heated by absorbed solar radiation and evaporates on a larger surface. The vapor condenses on the plastic sheet, and pure water trickles down and is collected at the bottom, making ocean water potable. A water channel runs along the lower edge of the glass.

A roof-type solar still of 1–2 m^2 can produce about 2.5–3 L of distilled water daily in households. To further increase efficiency and production, different advanced processes have been deployed. Advancement is *holosol*, a process that requires treating water with a large dose of sodium hypochlorite or iodine and then exposing it to solar radiation in a reactor. It helps in increasing the efficiency of solar water distillation. A Flash evaporation system for desalination of water has been demonstrated using a solar pond technology [13]. A multi-stage flash (MSF) evaporation plant in Bangladesh produces 6–60 L/m^2/day of desalinated water, whereas a single stage can make only 3–4 L/m^2/day. Multi-stage flash evaporation process using a series of stills increases the productivity of simple distillation units. This method is currently in use in a large number of distillation plants around the world.

7.4.2 Reverse Osmosis for Water Distillation

The reverse osmosis (RO) for saline water distillation is a chemical process. In this, we create a chemical potential gradient at the junction of two systems using solar energy. A salt solution containing 3% of salt across the junction or a membrane exerts a pressure of 30–40 bars at 300 K. An equivalent pressure is created on the other side of the membrane in an electromechanical approach either by using energy from an array of PV cells or mechanical energy using thermal storage of solar ponds. The membrane allows selective diffusion of water molecules as a result of the pressure gradient.

The efficiency of a Solar-Powered Reverse Osmosis process is higher than the *still* distillation method. The MSF and RO are the most common technologies adopted for desalination. Total water desalination capacity is growing worldwide.

7.4.3 Capillary Film Distillation

We can use Capillary solar distillation to purify water other than saline water. It is a chemical process of water purification. It comprises a thin fabric with a single, finely woven layer, held in contact with an overhanging metal plate through an interfacial tension. The surface tension is kept much greater than the force due to gravity. Fabric adheres to the plate forming a capillary film at the plate-fabric interface. The metal plate absorbs the solar radiation, and water gets heated. The back face of the first interface serves as the evaporator for the second stage. The second plate acts as a condenser at the first face and evaporates at its second face. A series of such combinations are used so that first plate on its first face acts as an absorber and becomes an evaporator at the second face. The fabric is dipped in a saline water tank which facilitates suction of water by capillary action. The process continues in a series, and water gets condensed dropwise. The efficiency increases with the increasing number of stages.

7.4.4 SoDis—Solar Disinfection of Water

Solar water disinfection (also called SoDis) is a device that uses solar energy to make contaminated water with bacteria, viruses, protozoa, and worms, safe to drink [14]. SoDis uses both Ultraviolet (UV) and infrared (IR) components of solar radiation for water disinfection. The UV-A radiation has a germicidal effect. The IR radiation raises the water temperature to 70–75 °C, and the process is known as pasteurization. SoDis is a solar reactor consisting of a transparent tube made of pyrex glass in a serpentine shape. The tube is placed south facing in a metal frame at an inclination of 35 °C to maximize solar gain. The water in the tube gets exposed to solar ultraviolet radiation. The flow is adjusted in a manner such that pathogens are killed. Reactors of 10–15 cm in diameter have been designed and developed for supplying pure drinking water in areas where groundwater is contaminated. The infrared radiation kills the microorganisms, which are sensitive to heat.

7.5 Solar Pond Electricity Generator

Solar ponds have been a source of electricity in far-flung areas. A Solar Pond is water pond that can deliver the dual function of a solar collector and a storage type water heater. It differs from a pool, as it does not use any external collector field. When water is heated by solar radiation in an ordinary pond, it rises upwards and loses heat. The pond water gradually attains a temperature that is nearly the same as that of the atmosphere. A solar pond has salt in huge quantities, and the salt gradient by added salts helps retain the heat inside. The salt concentration is highest at the bottom, and the bottom layer becomes too heavy to rise to the surface. A temperature gradient results and long-term thermal storage is built up. A solar pond can produce electricity directly or can be used for low-temperature heating applications.

A solar pond configuration and its salinity gradients are depicted in Fig. 7.4. It is known as salt gradient solar pond (SGSP): a pool of water about 1–5 m deep. It has three salt zones; namely, upper convective zone (UCZ), lower convective zone (LCZ), and a salinity gradient non-convective zone (NCZ) in the middle, having different concentrations of salt solutions.

(1) The *upper layer or convective zone* (UCZ) is of uniform low density and has little salt. It transmits incident solar radiation through convective processes

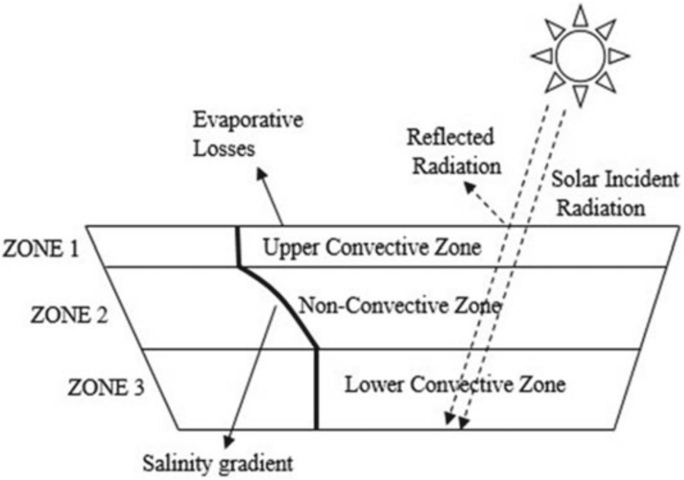


Fig. 7.4 Solar pond configuration with its temperature gradient

to the lower parts of the pond and has a temperature nearly the same as air temperature. It is thinnest as compared to the other two zones.

(2) The *middle layer or non-convective zone* (NCZ) has a non-uniform salinity density known as a gradient zone. It separates the upper and lower convective zones, and the salinity gradually increases as one goes deeper. It effectively acts as a heat-insulating layer between the top and bottom layers, allowing light to pass, but not allowing heat exchange.

(3) The *bottom layer or lower convective zone* (LCZ) is of the highest density of the order of 250 kg/m^2. It collects and stores heat and acts as a heat *storage zone*. It attains the highest temperature.

Solar Desalination Plants in India

In India, desalination plants exist for both saline sea and well waters at

- Narayan Sarovar (2400 L/day) in Kutch,
- Birla Island (2000 L/day) in Lakshadweep,
- Awania Village (5000 L/day) in Bhavnagar and
- Bhaleri (8000 L/day) in Churu.

A large solar desalination plant at Kanyakumari, near Vivekanada Memorial in a 120 m^2 area, uses flash technology and can generate 10,000 L per day of fresh water from seawater. Many other water purifiers have been developed and tested in the field.

A Solar Water Purifier, developed by scientists at the Nimbkar Agricultural Research Institute at Phaltan, Maharashtra is made up of four tubular solar water heaters attached to a manifold.

The Bhabha Atomic Research Center (BARC) has developed a water purifying technology that is either driven by solar or wind energy for desalinating contaminated water.

The Department of Science and Technology (DST) has supported KG Design Services (KGDS), Coimbatore, and National Institute of Ocean Technology (NIOT) to develop and demonstrate a solar thermal desalination plant that produces steam which in turn is used for desalination of sea water through the Linear Fresnel Reflector (LFR) system.

Gerindtec, India has two solar desalination pilot projects based on the patented technology called Multi-Effect Humidification (MEH) process of 1000 L capacity each.

Carlsberg Group, Multinational brewer has partnered with Netherlands-based solar desalination technology company Desolenator for converting saline water into clean drinking water for a town of 4000 in Sundarbans, West Bengal.

An SGSP can store heat at temperatures up to 100 °C in its lowest zone with minor seasonal variations of 10–20 °C. The temperature difference between the UCZ and

LCZ of an SGSP can be in the range of 40–60 °C. This temperature difference can be used in thermoelectric power generators (TEG) for electricity production. The thickness of middle zone NCZ with appropriate salinity gradient and the storage zone LCZ are similar. In the NCZ, besides the salinity gradient, temperature attained depends on several other factors, such as convective and conductive heat losses through the middle non-convective zone and the amount of solar radiation that penetrates the lower zone conductive heat loss from the bottom to the earth [15]. The surface impurities, bacteria, and algae and suspended dust affect the efficiency of the process.

The expression gives useful heat delivered from a solar pond,

$$Q_u = A_s[t_e R - U_L(T_e - T_s)] \tag{7.2}$$

where A_s is the surface area of the pond
t_e is effective transmissivity and absorptivity product for the pond
U_L is overall heat loss coefficient
T_e is temperature of the lowest zone
T_s is the temperature of surface layer.

The energy hot brine from the storage zone is continuously removed through a heat exchanger and returns to the bottom. Extracted heat from the pond gets transferred to the generator and electricity is produced using Rankine cycle turbine. The brine is pumped back to the lowest zone of the pond. The heat exchanger is kept either submerged in water or placed outside. The overall efficiency is low because a solar pond absorbs a lesser amount of solar radiation (~50%) than a collector on the ground, which is directly exposed to the Sun and can track the Sun if required. Another reason for low efficiency is the low transitivity (t_e) of saline water, which is about 45% for a clear pond.

A solar pond requires adequate open space for water collection with appropriate concentrations of salt in water. It has critical dimensions for giving the best results. The minimum depth required is 0.95 m, and the corresponding diameter is 1.65 m [54]. The thickness of UCZ is the smallest so that the solar radiation incident on the top surface can penetrate the upper two layers and gets absorbed in the third layer. The solar pond research is highly location-specific. A solar pond may cost less if a similar collector area is designed, but its efficiency is also lower. Its two important parameters are;

(i) *Performance Parameter* of a solar pond is the ratio of its thermal and viscous energy. Viscous energy is generated due to salt diffusion from the lower convection zone to the upper convective zone. A pond should have low viscous energy.
(ii) *Eckert Number* is defined as the ratio of the diameter of the pond and the time in which solar energy takes to reach the lowest zone. A Low Eckert number is preferred for better performance.

A salt gradient pond was first demonstrated in naturally occurring lakes in 1902 in the salt region of Hungary. Solar ponds have since been built in many locations around the world. The size has varied from experimental solar ponds of a few m^2 surface area to large solar ponds of 10,000 m^2. In Israel, the first artificial pond was studied in 1958. Subsequently, a 6 kW unit in a pond with a salinity gradient and surface area of 625 m^2 was demonstrated in 1972. It reached a temperature of 96 °C. India built a Pond in the 1970s at the Central Salt and Marine Chemicals Research Institute in Bhavnagar, Gujarat. Israel Dead Sea region is an ideal location for constructing a solar pond electricity generator with its highest salt concentration as 33%, close to saturation. Some other solar ponds were built and tested across the world. A solar pond was built in a 7500 m^2 area with a demonstration electricity plant of 150 kW capacities at Ein Bobek in 1982. The temperature attained was almost 100 °C, which is the highest achieved in a solar pond. The largest salt gradient solar pond in the world has also been built in Israel at Beith Ha'Arava. It has a surface area of 210,000 m^2 and had 5 MW electricity and operated until 1988. It could be comparatively more efficient, especially for the utilities that required direct thermal energy.

7.6 Outlook for Indian Solar Thermal Industry

India has an established solar thermal industry and has more than 78,000 m^2 of plants for Solar Heating for Industrial Processes (SHIP) [16]. The industrial heat processing has contributed to optimizing heat demand in many industries, such as food processing, textiles, agriculture, pharmaceutical, automotive, and water purification that meaningfully reducing GHGs emissions. Every 3 million m^2 of installed area for low-temperature solar collectors could offset 55,000 tons of CO_2 annually. Payback is quite attractive in industrial process heating applications as most processes use low-temperature heat lower than 250 °C. However, there are limitations such as every installation requires different engineering according to space, which is often scarce at many industrial plants. In India, Research and Development (R&D) on advanced solar collectors with optical efficiency greater than 75% is targeted with reduction in heat loss coefficient for flat plate collectors. The incentives and new regulations can further help in finding solar energy solutions for commercial and industrial sectors.

References

1. Kalogirou S (2003) The potential of solar industrial process heat applications. Appl Energy 76(4):337–361
2. Dasari R (2019) Textile industry eyeing benefits of renewable energy like solar. Indian Text J
3. https://www.saurenergy.com/solar-energy-articles/tailoring-solar-power-for-textile-industry
4. Ramaiah R, Shekar KSS (2018) IOP Conf Ser Mater Sci Eng 376:012035

5. Sun Focus (2016) A quarterly magazine on concentrated solar heat. UNDP-GEF project, vol 4, issue 2
6. Solar energy scheme for power looms (2018) Ministry of Textiles, Government of India. https://ipowertexindia.gov.in/solar-energy-scheme-for-powerlooms.htm. Accessed 6 Sept 2021
7. Arora S (2020) Asia's 1st solar power-enabled textile mill to be unveiled in Maharashtra. https://currentaffairs.adda247.com/asias-1st-solar-power-enabled-textile-mill-to-be-unveiled-in-maharashtra/. Accessed 6 Sept 2021
8. Nair S (2020) Asia's first solar powered textile mill to come up in Maharashtra's Parbhani district. Jagran Josh. https://www.jagranjosh.com/current-affairs/asias-first-solar-powered-textile-mill-to-come-up-in-maharashtras-parbhani-district-1605695266-1
9. Perlin J. Let it shine: the 6,000-year story of solar energy, Kindle edn. New World Library, p 209
10. Sharma A, Chen CR, Lan NV (2009) Solar-drying energy systems: a review. Renew Sustain Energy Rev 13:1185–1210
11. https://www.electronicsforu.com/india-corner/innovations-innovators/solar-conduction-dryer-boon-indian-farmers
12. Bhattacharyya A (2013) Solar stills for desalination of water in rural households. Int J Environ Sustain 2(1):21–30. https://doi.org/10.24102/ijes.v2i1.326
13. Esmaeilion F (2020) Hybrid renewable energy systems for desalination. https://link.springer.com
14. Cowie BE, Porley V, Robertson N (2020) Solar disinfection (SODIS) provides a much under-exploited opportunity for researchers in photocatalytic water treatment (PWT). ACS Catal 10(20):11779–11782
15. Krishnasamy K, Murugumohankumar K, Muthukumar MR, Sankarlal P (2013) Heat balance and heat transfer analysis in a pilot solar pond. In: 2013 IEEE international conference on research and development prospects on engineering and technology (ICRDPET), vol 1, Nagapattinam, Tamil Nadu
16. http://ship-plants.info/

Chapter 8
High-Temperature Solar Power Systems

8.1 High-Temperature Solar

High-temperature solar technology (HTST) is known as concentrated solar power (CSP). It uses specially designed collectors to achieve higher temperatures from solar heat that can be used for electrical power generation. In contrast to the low-temperature solar devices, high-temperature solar systems achieve temperatures beyond 250 °C and can go up to 3000 °C or more by using concentrating collectors in the path of solar radiation. In these systems, solar radiation is captured in a much greater area than a flat plate collector. Due to curvature in the collector, radiation is reflected the focal point. The heat is transformed into a turbine through a heat exchanger and electrical energy is generated. A Solar Thermal Power Plant (STPP) has higher efficiency than a solar PV plant or a low-temperature electricity generator. The other advantage is that a STPP can store heat energy for a longer time than a photovoltaic plant. High-temperature system can also be used as source of heat for industrial thermal applications as a solar furnace for the processing of the materials.

First parabolic trough CSP was successfully demonstrated in 1984 with 85 MW capacities. It operated from 1984 to 2015 [1]. In 2018 the world's installed electricity capacity of CSP had reached 5500 MW, with Spain having almost half of the share.

8.2 A Solar Thermal Power Plant (STPP)

A Solar Thermal Power Plant (STPP) utilizes solar energy flow from a concentrating collector system for generating electricity. The plant comprises of following main components, namely;

(i) Concentrating solar collector,
(ii) Heat transfer fluid,

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(iii) Thermal storage,
(iv) Electricity turbine.

Concentrating solar collector absorbs incident solar light and converts it into heat. The heat is transferred to storage system, where heat transfer fluid collects it and transfers it to drive a steam turbine for producing electricity. The thermal energy storage can store the heat for a longer time and helps in running the plant uninterrupted when Sun is not there. This is unlike the SPV plants which have no inbuilt storage.

The overall efficiency of plant is combination of efficiencies of its sus-systems. Basic laws of thermodynamics apply, and the power cycle is based on the Rankine cycle. The efficiency of the collector system is around 80% but decreases as its temperature rises, while the efficiency of the electrical conversion system (35%) increases if we are able to achieve higher temperature. The annual generation capacity E_i of a CSP power plant is given in terms of the collector aperture area (A_r), degradation rate (DR) or losses, efficiency of the plant (η), tacking factor (TF), and direct normal irradiation (DNI) [2].

$$E_i = \mathrm{DNI} \times \mathrm{TF} \times \eta(1 - \mathrm{DR})^I \tag{8.1}$$

Three different solar collector configurations for a STPP are commonly known as,

1. Parabolic trough collector system/linear concentrating system with a long cylindrical parabolic reflector
2. Central Receiver Tower system/Solar power tower with flat or planner reflectors called Heliostats
3. Big parabolic dish system/solar dish-engine system with a parabolic reflector dish.

8.2.1 STPP with a Parabolic Trough Concentrator

The parabolic trough system comprises a long parabolic trough type reflector in a cylindrical shape with a line focus. The long absorber tube carrying the heat transfer fluid is placed along the focal line. By increasing the length of the absorber tube we can get a high concentration ratio for the solar energy received on the collector's surface and reflected the absorber tube. The absorber is either a metallic tubular pipe or a flat plate so that a heat exchanger fluid can pass through it.

Box 1: Solar Thermal Power History

Auguste Mouchout used a parabolic trough to produce steam from solar energy for the first time in 1866 [3]. The steam, however, was not used for power generation, but for running a steam engine and doing mechanical work. The first parabolic trough electricity plant was built in Egypt in 1912, using a 62 m long parabolic reflector. It was designed for water pumping applications, generated 45 kW for 5 h, and could pump 20,000 L of water/minute for agriculture use.

After World War II, there was a revival of interest regarding solar heating, with a focus on active systems for solar energy. In the following decades, there were continued and innovative discoveries regarding solar energy. Gaetano Vinaccia (1889–1971) a mathematician, engineer, architect, and city planner promoted the idea that solar heat can be collected at high temperatures and harnessed to power industries and power plants. He was the first person to apply the Fresnel Reflector Technology principle in real systems, with alien-reflector in Marseille in 1963, and a dish reflector, in S. Ilario in 1965. First concentrating collector parabolic trough solar plant for power generation was demonstrated in 1984 in USA.

Solar thermal power concentrator design of parabolic trough is shown in Fig. 8.1. The parabolic trough STPP uses a synthetic fluid in the heat exchanger. The synthetic oil transfers the heat to water which runs the Rankine cycle turbine to produce electricity. The concentration ratio of a parabolic reflector varies from 10 to 100, with temperatures attained between 150 and 400 °C. The efficiency of a parabolic trough power system is most sensitive to the efficiency of the receiver, which is the ratio of the useful energy received divided by the total solar radiation incident on the reflector surface. If the absorber surface temperature remains constant, the system's efficiency can be increased with the increasing concentration ratio of the parabolic trough. The losses due to radiation and convection are low in this case. But, if the absorber temperature keeps increasing and becomes higher, heat losses, rising as the fourth power of temperature, become high and the efficiency falls.

World's largest Parabolic Trough Power system is known as Luz Solar Field. It started building in California in the 1980s. It was named after the company that built it. Luz system was the first to successfully demonstrate the use of solar concentrating collectors in power production. Since then, parabolic trough technology is fairly advanced and has reached commercial viability. Largest Luz system is 454 MW, having 11 sub-plants. These subsystems are named solar energy generating systems (SEGs). In each SEG, a number of parabolic troughs with a concentration ratio from 40 to 100 are connected in series or parallel. An 80 MW SEGs required about 960 such solar collectors' assemblies, each being 100 m in length.

The parabolic trough system technology is most developed today, and almost 90% of STPP systems are based on this technology. The world's most prominent parabolic trough collectors are in operation in the USA. In Blythe, the plant has a parabolic trough of 240 m in length to demonstrate the feasibility of plants up to 250 MW. Other significant projects are the Mojave Solar Project: a 280 MW project in Barstow, California, and Solana Generating Station; a 280 MW project in Gila Bend, Arizona.

Fig. 8.1 A solar thermal power concentrator of parabolic trough type [4]

Fresnel concentrators with flat mirrors are also in use in linear concentrators. In this case, the need for high pressure rotating components used on parabolic trough is eliminated and the cost is also reduced.

8.2.2 STPP with a Central Receiver Tower System

A central receiver tower system comprises hundreds or thousands of plain mirrors (20–200 m^2) around a tower known as a Solar Tower. It has a high concentration ratio than parabolic trough and we can expect to get higher temperatures. The Sun's energy is reflected from the two-axis mirrors to the central receiver placed at the converging point on the tower. Each mirror is steerable by its tracking system known as *heliostat* so that it always faces the Sun. The computer known as a heliostat computer controls the tracking system of mirrors. In the process, the computer compensates for the movement of the earth and makes corrections for other obstacles appearing from time to time, such as clouds or the shadow of trees. A solar sensor is provided along the line joining the center of mirrors to the absorber for making finer adjustments and helps in improving control on mirrors.

The heat absorber fluid is placed near the top of the tower. The heat extracted through a heat exchanger is delivered to the bottom of the tower to produce steam. It uses molten salt mixture as a heat exchanger fluid. The remaining liquid is then transported back to the top of the receiver. In a central receiver system, the efficiency

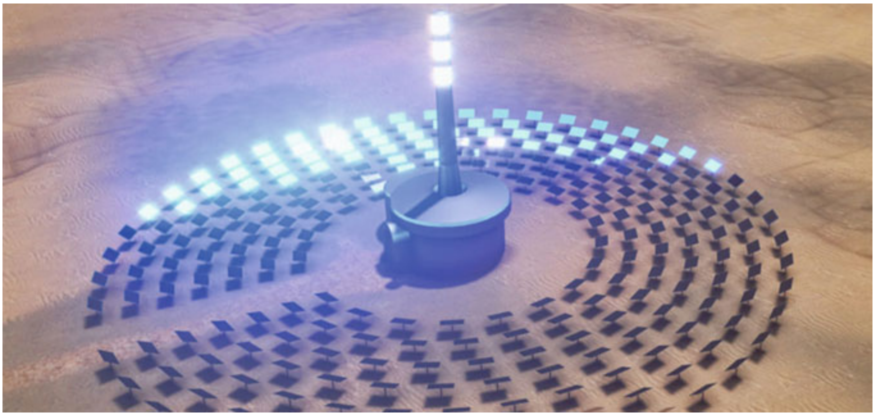

Fig. 8.2 Solar thermal power plant with a central receiver [5]

of a mirror field is somewhat higher than the parabolic trough and is expected to be about 60–75%. The concentration ratio is higher than the parabolic system. The higher temperature can be reached, but the area requirement of the mirror field becomes enormous. For a 100 MW power plant, the mirror field area can be as large as 3.3 × km^2, which means the last row of mirrors is located at a distance of approximately 1300 m from the tower.

The concentration ratio achievable in a central receiver system is 200–1500 for a 100 m high tower, with temperatures up to 500–1500 °C. The mirror field in the system can be designed either in a circular arrangement or in a one-sided semi-circular arrangement. A circular arrangement is more suitable in places near the Equator and requires an open type of absorber (Fig. 8.2). On either side of equator, one-sided mirror field with a cavity-type closed absorber is preferred, placing mirror fields toward the North in the Northern hemisphere and toward the South in the Southern hemisphere.

Varieties of solar tower concepts are under development. Two types of receivers used are the Tubular and Volumetric types. A Tubular receiver can be either an external cylindrical receiver or a cavity receiver. In an outer cylindrical receiver, vertical tubes are arranged in a cylindrical fashion. While, in the cavity receiver, welded tubes are kept inside a cavity to reduce convection losses. The heat transfer medium is appropriately selected to achieve maximum efficiency.

A Volumetric receiver can be either open volumetric or pressurized volumetric. It uses air as a heat transfer medium. In open volumetric ambient air is sucked through the porous receiver of a wire mesh made of metal or silicon carbide. Air gets heated up to a high-temperature of 600–700 °C and is used for producing steam. Whereas, the pressurized volumetric receiver consists of mechanically charged air received through the blower and a transparent window seals the receiver aperture.

Solar energy towers are considered good prospects due to their high efficiency and production of low-cost electricity in the long-term for larger units of 100–200 MW capacity. At present, over a dozen central receiver plants have been built or are under construction. The first was Planta Solar PS 10 commercial plant with grid-connected solar power at Saville in Spain in 2004. Having 624 heliostats of area of 120 m^2 each, it occupied a land area of 0.55 km^2. Weizmann Institute of Technology, Israel, built a central solar tower of 30 m in height and 100 kW capacity in research mode in the 1990s.[1] Plants of lower capacity of 0.5–5 MW have been built at various places. A *Solar One* of 10 MW built in Barlow, California of 10 MW operated during 1981–88. In 1995 it was converted to *Solar Two*, but after a few years of operation, it closed down in 2009. The PS 20, another plant of 20 MW in Saville in Spain, started the process in 2009. It had 1225 heliostats around a 165 m high tower, occupying 0.80 km^2 land area. In the United States, solar tower projects are; Sierra Sun Tower: a 5 MW two-tower project located in the Mojave Desert in Southern California; Crescent Dunes Solar Energy Project: a 110 MW one-tower project located in Nevada and Ivanpah Solar Power Facility: and a 392 MW three-tower project proposed in Ivanpah Dry Lake, California [6]. It has three 140 m tall towers and over 300,000 software-controlled mirrors that are tracking the Sun in two dimensions.

Ashalim Power station, located in the Negev desert of Israel, is the tallest solar tower today at 260 m height. The plant capacity from the thermal power tower is 121 MW. It has added solar photovoltaic and natural gas capacity, adding to 259 MW. Jordan has a high potential for solar thermal up to 1000 GWh per year. A central receiver system of 30 MW capacity is in the planning stage in Jordan.

8.2.3 A Big Dish Concentrator System

A Big Dish solar concentrator consists of a parabolic dish, primarily a paraboloid segment, formed by the rotation of a parabola along its vertical axis (Fig. 8.3). It resembles a big satellite dish. In the dish system, solar energy is received on the parabola and gets reflected at one focal point. The temperature attained can be higher than the parabolic trough system, and the concentration ratio is also high. For a concentration ratio between 100 and 1200 and a temperature of 500–1500 °C is achieved. It uses hydrogen or helium or any other heat exchanger at high pressures in a closed cylinder at the center point for power generation. In Sterling cycle expansion of the gas due to solar heat causes movement of the piston and creates mechanical power, which runs an alternator to produce electricity. The power-generating system is mounted such that it always points to the Sun. The sterling engine has higher efficiency than a steam turbine and requires temperature in the range of 800 °C. Conversion efficiency up 30% is demonstrated.

For remote locations, parabolic dishes are preferred.

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[1] First author had the honor to visit Weizmann Institute of Technology, Israel in 1998 where a central solar tower of 30 m in height and 100 kW capacity was being built for research.

Fig. 8.3 Solar thermal power plant with big dish concentrator [7]

A concentrated paraboloid dish generates power in a few watts to few kilowatts. A solar farm or STPP can be integrated with a thermal power plant to achieve continuity in power production.

Small size Big Dish Plants of a few kW have been tested at different locations. Solar Farm comprises several parabolic big dish concentrators for achieving the desired output. The solar farm concept has been demonstrated in Kuwait, consisting of an array of parabolic dish solar collectors. Kalahari Desert Big Dish in South Africa showed 34% efficiency. The U.S. Army has a 1.5 MW system with 429 Sterling engine solar Dishes. The world's largest 'SG4' prototype Big Dish solar concentrator with a 500 m^2 antenna has been built on the Australian National University campus. Wizard Power plans to build an SG4 Big Dish structure for commercial installations, which will use 300 Big Dishes to deliver a 40 MW. Higher efficiencies are expected.

Box 2: Concentrating Solar Thermal Power Technologies in India

In India, a beginning was made by demonstrating 50 kW capacity parabolic trough collector plant at Gwalpahari, Gurgaon, in 1989 and operated till 1990 [8]. The parabolic trough pilot plant of 3 MW was built and tested at the Indian Institute of Technology, Mumbai in 2012. Godawari Green Energy Ltd.

operated a 50 MW capacity power plant using a parabolic trough and featuring a solar field aperture area of 400,000 m^2. The plant generated up to 118,000 MWh of electricity per year with a state-of-the-art SKAL-ET 150 trough structure in 2013. It became the nation's first Solar thermal power plant in industry. Its outlet temperature reached 385 °C.

An integrated solar thermal power plant was planned in 2016 at the National Thermal Power Corporation (NTPC) Dadri, India. It uses Compact Linear Fresnel Reflector (CLFR) solar thermal technology and can achieve temperatures of up to 550 °C by focusing the sunlight on the absorber tubes. The CLFR system with flat reflectors that reflect heat radiation on elevated receivers containing water and pressurized steam is generated for direct power production. A heat exchanger can be used if receiver pipes use another fluid in place of water. The STPP is the best way to integrate solar energy into existing fossil fuel plants.

Navkar Textiles has installed 12 solar Dish concentrators for cloth processing utilizing steam in the Textile industry [8]. Each Dish is having an aperture area of 16 m^2. The total collector area for the dish assembly system is 192 m^2. The overall system comprises of a concentrator, a Dish receiver, and supporting structure. It deploys a tracking system for improving efficiency. It is proposed to set up a STPP of 125 MW capacity based on Linear Fresnel reflector technology in Mathania, near Jodhpur in Rajasthan. India one, a solar thermal power plant with a Big Dish has come up at Mount Abu, Rajasthan, near Brahmakumari Ashram.

8.3 A Solar Furnace for Industry

A solar furnace is a structure that uses concentrated solar power to produce high temperatures, usually for industry. A furnace can reach a temperature up to 3000 °C by concentrating the heat of the Sun into a beam that can fire ceramics without fuel. A solar kiln can be designed to achieve desired temperatures for materials processing and other industrial applications. Its four subsystems are; (i) the heliostat system, (ii) the tracking mirror, (iii) the shutter system, and (iv) the temperature controller for the furnace. We can harness Sun's energy to achieve high temperatures by using large lenses or mirrors at the focal point. A set of flat mirrors as a heliostat automatically follows the Sun's path and reflects its rays onto the stationary furnace mirror. An electric motor may drive the tracking mirror system to move through precisely 15 min of arc every hour. The temperature control system is designed to compensate for the perturbations in the radiation and has a linear response.

The solar furnace principle is used to make inexpensive solar cookers and solar-powered barbecues, and solar water pasteurization. Several countries have used solar concentrators to build solar furnaces. Currently, a giant solar furnace is at Odeillo in the Pyrenees-Orientales in France; it has been operational since 1970. The French Center National de la Recherche Scientifique built a 1000 kW furnace at Odeillo, Purtgal. The solar oven was constructed in France in 1972, using solar concentrators made of 63 heliostats tracked along two axes. The oven was 7.5 m wide and 6 m high. It had a mirror field of 45 m^2 in a land area of 2835 m^2. The system achieved a thermal power density equivalent to 16 MW/m^2 at its focal point. It was an experimental device for high-temperature metallurgical studies.

National Academy of Sciences of Ukraine later built some solar furnaces for carrying out a variety of experiments on thermo-physical properties of materials at high temperatures, synthesis of high purity materials, reduction in energy consumption, decrease in material use and equipment corrosion, and simulation of different technological processes for space studies. By 1981 several countries, including the Soviet Union, the USA, Japan and Chile, built solar furnaces. The solar furnace at Mont-Louis in France could reach up to 3000 °C (5430 °F), which is enough to melt most metals.

If we can have a solar kiln in a Space Satellite, it could achieve much higher temperatures there due to the intense solar radiation in Space. The development of material processing in outer space could provide opportunities for the production of new materials. Solar furnaces have many advantages and also disadvantages. The main advantage is saving on fossil fuel use and no greenhouse gas emissions. But they have a high initial cost for materials, and efficiencies are not yet 100%.

8.4 Performance of Solar High-Temperature Systems

The solar thermal concentrator energy technology aims to achieve higher efficiency than low-temperature or photovoltaic systems. High-temperature solar energy devices have higher initial costs than conventional systems, but the factors in their favor are lower operational costs and reduced burden on fossil fuel resources. The huge collectors, which should remain oriented toward Sun, dominate the capital cost of most solar thermal systems. They require additional investment in Sun tracking and power grid connectivity, since the most suitable locations for a solar thermal plant are remote desert areas.

Solar thermal power systems have an advantage over photovoltaic systems in terms of storage. A STPP can store the heat of solar energy in molten salts. The plant can continue to supply electricity during day or night. Comparing the cost of three types of concentrators used in solar thermal power generation suggests that the installation cost of the parabolic trough is the lowest. In contrast, electricity cost is lowest in the case of the central receiver system. Solar high-temperature devices provide a source of electricity free from pollution, but land area requirement is enormous. It is estimated that a 40 MW plant would need approx. 2 km^2 of land.

In recent years, thermal storage systems are gaining momentum due to their potential in providing uninterrupted, efficient power, which is becoming cost-effective.

However, the growth has been much slower than anticipated. Globally, STPP was 354 MW in 2005 and became 5500 MW in 2018. In 2000, Australian Cooperative Research Center for Renewable Energy (ACRE) forecasted that the contribution of STPP is set to increase by 50,000 MW in 2030, which looks like a remote possibility. The multiple challenges in materials design to withstand high temperatures, the optimum heat transfer fluid development, excessive water consumption in the power generation, and adequate thermal energy storage and receiver subsystems are needed to be resolved for achieving success.

References

1. https://www.eia.gov/energyexplained/solar/solar-thermal-power-plants.php
2. Ahmadi MH, Ghazvini M, Sadeghzadeh M, Nazari MA, Kumar R, Naeimi A, Ming T (2018) Solar power technology for electricity generation: a critical review. Energy Sci Eng. https://doi.org/10.1002/ese3.239
3. Ragheb M (2014) https://www.solarthermalworld.org/news/india-honeywell-successfully-showcases-solar-cooling-project
4. Puiu T (2011) Solar-thermal flat panels up to eight times more efficient than existing technology. ZME Science. [Online]. Available at https://www.zmescience.com/research/solar-thermal-energy-eight-times-more-efficient-4324234/
5. https://contextsolar.com/csp-concentrated-solar-power-explained/
6. https://www.energy.gov/lpo/ivanpah
7. https://www.energy.gov/eere/solar/dishengine-system-concentrating-solar-thermal-power-basics
8. Dwivedi A, Bari A, Dwivedi G (2013) Scope and application of solar thermal energy in India—a review. Int J Eng Res Technol 6(3):315–322

Chapter 9
Solar Cooling Technologies

9.1 Solar Cooling

With increasing global warming and accelerated climate change, higher energy consumption in creating comfortable living conditions is giving boost to the adoption of solar cooling. Solar cooling is seen as an option to reduce air-conditioning load and improve energy efficiency for electricity produced from fossil fuel systems. According to the International Energy Agency (IEA), almost one-sixth of the world's total energy use could be met by solar energy for heating and cooling in 2050. The total global market for solar cooling is projected to become 417 TWh per year, i.e., having a share of 17% in total cooling energy needs (Fig. 9.1). It was estimated that from 2004 to 2014 global solar cooling market has grown by 40–70%. In 2014 there were 1200 cooling installations, most of these in Europe [1]. Regions of hot climates have a growing need for cooling energy demand, and solar cooling system installations have been increasing substantially in recent years. It is projected that energy consumption will increase by an average of 2.7% per year from 2015 to 2040. The market share for solar cooling is expected to grow faster as the technology becomes more user-friendly. In Arab countries, cooling energy needs can be as much as 75% of total energy consumed in the building sector. Other than buildings, agricultural products, pharma products, and vaccines all need refrigeration in remote areas, and solar cooling needs are expected to grow. By 2040 it could save 800 Mt of CO_2 emissions per year, globally (Fig. 9.1).

9.2 Main Drivers for Solar Cooling

Solar space cooling uses solar energy and requires a well-designed solar-assisted air-conditioning system. The main drivers for solar cooling systems are;

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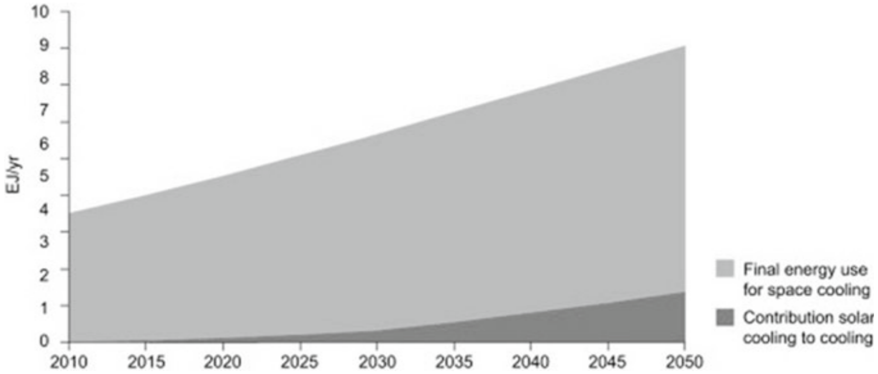

Fig. 9.1 Roadmap vision for the share of solar cooling in final energy use for space cooling [1]

(i) Hot climates and the need for space cooling,
(ii) Saving on fossil fuels and reducing peak energy demand, and
(iii) Abstaining from the use of ozone-depleting substances.

Conventional air-conditioning technologies consume high energy and produce harmful gases like chlorofluorocarbons, which contributed excessively to global warming and caused ozone depletion in the atmosphere. Although countries have signed Montreal Protocol to replace CFCs gradually, new coolants like hydrofluorocarbons are safer for ozone holes but are adding to global warming. A solar air conditioner is free of such hazardous elements. Solar cooling can be achieved with considerably less or no electricity demand than a conventional air-conditioning system, thereby saving ozone depletion and greenhouse gas emissions.

9.3 Solar Cooling Technologies

Solar cooling technologies work in two categories (i) Passive solar cooling systems and (ii) Active solar cooling methods.

Passive solar cooling is the most cost-effective way to cool, especially for buildings. It relies on natural heat sinks and removes heat by processes such as convection, radiation, and evaporation. Common passive cooling techniques seen in Indian vernacular architecture principles are indigenous planning of courtyards, windows, landscaping, ventilators, and use of local materials. Trombe walls, wind towers, and the creation of earth air tunnels are designed and found to be quite efficient.

Trombe Wall: A Trombe wall consists of an air channel sandwiched between a window and a sun-facing wall. During the ventilation cycle, sunlight stores heat in the thermal mass and warm the air channel causing circulation through vents at the top and bottom of the wall. During the heating cycle, the Trombe wall radiates stored heat.

Wind Towers: Wind tower is a traditional architectural element used to create natural ventilation and passive cooling in buildings. The functioning of the tower depends on the ambient fluctuations of temperature changes and wind velocity. The difference in density creates a draft, pulling the air either upwards or downwards, through the tower and creating a cooling effect.

Earth Air Tunnel: This is a passive solar technique invented by Romans. The main principle behind the earth tunnel system is that about 4 m below ground, the temperature inside the earth remains nearly constant round the year. The system consists of a pipe or network of pipes buried at reasonable depth below the ground surface. The ambient air ventilated through the tunnel gets cooled in summer and warmed in winter.

Active solar cooling systems are air-conditioning devices in industries. Three main application areas of active solar cooling are;

(a) domestic refrigeration,
(b) industrial refrigeration in the pharma industry and
(c) cold storage with deep freezing for the preservation of agro-products.

Active solar cooling systems work by utilizing

(i) solar photovoltaic technology
(ii) solar concentrator technology.

(i) When solar photovoltaic (PV) panels provide the energy as electrical energy, it is used to drive a conventional electric vapor compressor air-conditioning cycle. In a conventional air-conditioning, we use a refrigerant, and the refrigeration cycle has an evaporator, condenser, compressor, and a valve. (ii) Solar concentrator technology uses solar heating devices. The cooling process is driven by solar concentrators collecting solar heat; it drives thermal cooling systems in vapor absorption processes. Applications of these absorption cycle and compression cycle technologies in air-conditioning and refrigeration processes can significantly save electricity. In solar cooling applications use of solar heating devices have a share of 80%, while solar PV devices share 20% only (Fig. 9.2). Two leading solar air-conditioning technologies are Vapor Absorption and Vapor Compression cycles.

9.3.1 Vapor Absorption Cycle

The Vapor Absorption or **Vapor Absorption Machines** (VAMs) are solar thermal energy driven. Vapor absorption cooling is one of the oldest refrigeration processes. The absorption refrigeration cycle operates on a similar principle as a conventional vapor compression refrigeration cycle with a difference. In it, the mechanical compressor is replaced by a thermal compressor. The cooling process is directly driven by heat from solar collectors. The refrigerant is condensed and expanded (instead of mechanical compression) to produce a cooling effect and get the desired

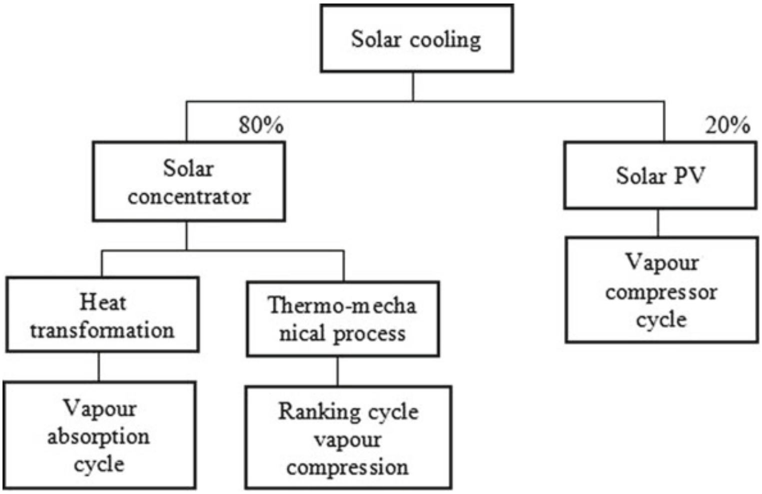

Fig. 9.2 Solar cooling technologies

temperature for a particular application. In these machines, the refrigerant is in the form of a liquid. It is mixed up in the absorbent and separated using thermal heat in the form of vapor. The leading pair of refrigerants/absorbents used in solar air-conditioning is water/lithium bromide (H_2O/LiBr), where water is the refrigerant (coolant), and LiBr is the absorbent [2]. Another combination is the ammonia/water pair (NH_3/H_2O), where ammonia is the refrigerant and water absorbent. Contrary to most working fluids in conventional compression chillers, these working fluids are environmentally benign and free from GHG emissions. The use of environmentally friendly refrigerants and low operating costs make a VAM an attractive option.

The VAMs in general have low coefficient of performance (COP) in comparison to conventional cooling systems, smaller capacity, but are large in size. The size is determined by the size of the solar concentrator. The use is preferred in locations where conventional electricity is not available all the time and/or for small-scale applications.

Adsorption air-conditioning and **Desiccant air-conditioning** are other technologies for solar cooling using concentrators. In the adsorption air-conditioning, a solid adsorbent is used instead of the liquid absorber used in VAMs. The refrigerant is adsorbed on the internal surface of highly porous solid material such as silica gel or carbon. This type of adsorbent type of machine is also known as dry cooling system and is compact. Desiccant air-conditioning use desiccant material that absorbs moisture and also acts as a refrigerant. Air is first dried by passing through a desiccant such as silica. Removing the air moisture content during the adsorption cycle provides better thermal comfort as they control temperature and humidity. The desiccant cooling system can be more suitable in climates with high humidity. Another innovation is **Rankine cycle compression cooling**, under development. In a solar Rankine system, the compressor of the vapor compression cycle is mechanically coupled with the expander of organic Rankine cycle and is, therefore, more efficient.

The fourth approach to cooling using solar thermal energy for air-conditioning is a solar **thermo-mechanical system**. It uses vapor compression cycle. This thermal energy generated is first converted into mechanical work and the working fluid is directly compressed by the mechanical force. In recent years, solar thermo-mechanical cooling systems are receiving a renewed attention. Hybrid solar thermo-mechanical cooling with conventional cooling systems can be adopted for reducing air-conditioning energy demand. Such systems are designed to achieve dual purpose with the ability to produce low refrigeration temperatures by using appropriate working fluids and the ability to produce electricity when cooling is not needed.

9.3.2 Vapor Compression Cycle

A Solar **Vapor Compression Machine** (VCM) works on solar photovoltaic electricity. The principle is the same as that of conventional air-conditioners used for cooling that work on the vapor compression cycle. It uses a refrigerant in vapor/liquid, which is compressed/expanded to obtain the required temperature for a particular application. A block diagram is shown in Fig. 9.3. The system is compact and uses Freon/R22, which does not have a shallow freezing temperature. The machine has four components: a compressor, condenser, evaporator, and throttle valve. Solar PV systems are used to supplement electricity with a DC to AC converter. The compression machines have a high coefficient of performance. The VAM solar systems are also compact, except for the size of solar panels. Solar electricity share to meet part of the electricity demand determines the size of solar panels. The percentage of solar PV electricity also determines the reduction in greenhouse gas emissions [3]. With falling prices of solar modules, solar VAM use is getting widespread, and such cooling system installations have increased substantially in recent years.

An option for solar PV-based cooling is a **thermoelectric cooling** system that works on the principle of the Peltier effect [4]. In thermoelectric cooling devices, the materials are semiconductors, a series of p and n-type semiconductors, sandwiched between two conducting plates. A temperature gradient is created by the flow of electric current across two dissimilar materials/conductors like copper and bismuth. The current passes through the two junctions; heat is removed at one junction and deposited at the other. The junction where heat is removed absorbs the heat from its surrounding space and creates a cooling effect. When the direction of the current is reversed, the air-conditioning system starts operating in a heating manner. With a proper selection of materials, the system can be used for both cooling and heating applications.

Though solar heating applications have been practiced for long, solar energy for air cooling and air-conditioning has come to the maturity level of late and is developing.

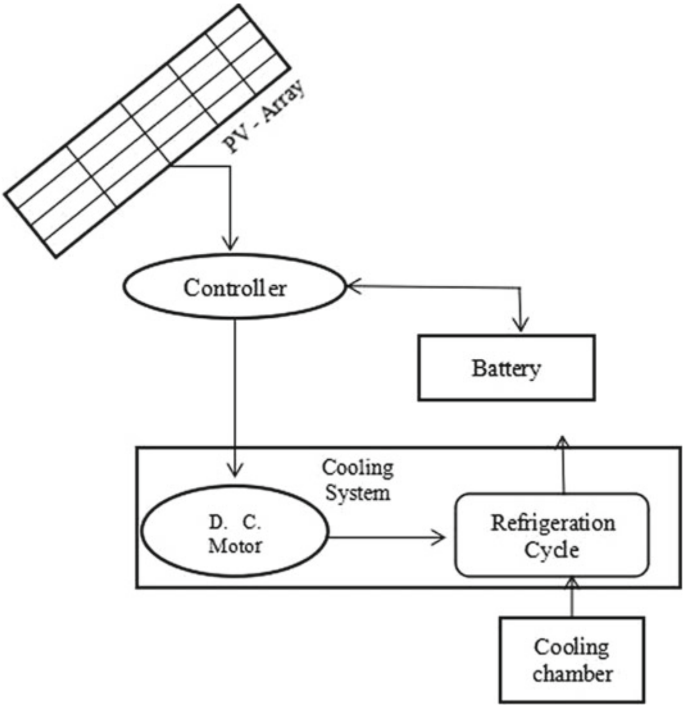

Fig. 9.3 Solar PV powered vapor compression system. *Source* Adapted from [3]

9.4 Phase Change Materials for Solar Cooling

Phase Change Materials have a vital role to play in the success of solar cooling technologies. By definition, a Phase Change Material (PCM) is a material that undergoes a phase change from one form to another, i.e., from liquid to solid phase or vice versa, when substantial energy is supplied, without undergoing a change in temperature. When heat is released, the change must be reversed. The storage capacity, in this case, is given by

$$Q_l = m \cdot L \tag{9.1}$$

Here, m is the mass of the material undergoing phase change, and L is its latent heat.

The PCMs have high latent heat and are also known as latent heat or thermal energy storage (TES) systems. For selecting a PCM for an application, its melting point and high latent heat are two main properties. For long-term use of PCMs in solar cooling, the basic parameters are high heat of fusion, high thermal conductivity, high specific heat and density, long-term reliability during repeated cycling, and dependable freezing behavior [5]. The PCMs are of three types, Organic, Inorganic, and Eutectic.

Organic—Most common PCM examples are paraffin waxes and salt hydrates. It is found that they are promising materials for low-temperature applications with many advantages such as being less corrosive, less toxic, and safe ecologically. Paraffin wax is an organic material. It has a high heat of fusion per unit weight, dependable cycling, and is cost-effective, but low thermal conductivity and high volume change during phase change.

Inorganic—Salt hydrates, on the other hand, are inorganic and have high heat of fusion per unit weight and volume. They have a relatively high thermal conductivity for non-metals and show small volume change. They are extensively used in large-scale applications in solar high-temperature power plants as TES.

Eutectic—Eutectic are combinations of two or more substances which could be organic–organic or inorganic–inorganic.

From an application point of view, we can divide the PCMs into three categories as;

(i) low-temperature heat storage (less than 120 °C),
(ii) medium-temperature heat storage (120–300 °C), and
(iii) high-temperature heat storage (more than 300 °C).

The low-temperature PCMs are most appropriate for thermal energy storage in building applications, and salt hydrates are excellent PCMs as in high-temperature solar plants. Medium-temperature PCMs are primarily used in low-temperature solar energy applications in industrial processes such as paper, food processing, and textiles industry to maintain continuity. They also are used in industrial waste heat recovery. High-temperature PCMs such as molten salts and metalloids can go up to 700 °C. They are most suited for solar energy applications in concentrators as they have high latent heat and undergo phase change without much change in density, unlike paraffin.

(1) *PCMs in Solar Air-Conditioning*

Solar energy is intermittent. The use of PCMs for solar cooling is a growing area of research to maintain continuity. The PCMs offer the best solution to energy storage as the fundamental requirement, thereby resolving the problem during peak demand. In active solar air-conditioning machines, PCMs-based thermal energy storage ensures a constant heat input to the absorption chiller and maintains a continuous operation [6]. A PCM is placed between the solar collector and the cooling machine when required. The system is designed to store the heat produced by the solar collector and release it to the cooling device to maintain a constant temperature at the chiller. The use of PCMs for solar energy storage thus improves the efficiency and efficacy of a solar air-conditioning system.

(2) *Use of PCMs in Passive Cooling*

The use of PCMs in buildings helps in passive air cooling. The most common way to use PCM in a building is through gypsum boards that contain microencapsulated paraffin as PCM. The use of PCM in inner walls or floors does not lower the average temperature in the building, even during nighttime when daytime heat is not there. To avoid heat discharge from PCMs to inside space, PCMs are sometimes provided in building facades. They discharge the stored thermal energy to the outside and help to cool. A technique for passive cooling of buildings using PCM filled façades has been developed in Iran to reduce the solar gain in buildings. Through the use of PCM, the power requirement for the air-conditioning is reduced, and comfort conditions are created inside without the use of a conventional air-conditioning system. When a façade is used as a heat exchanger, use of PCMs can provide for both solar passive cooling and heating in buildings, in different climates.

9.5 Solar Cooling Installations in India

In India, total cooling load has been estimated to be 35,000 MW of electricity. With high solar irradiation and great cooling degree days, solar energy can make a significant contribution to meeting the demand. India has had a most extended history of the application of passive solar cooling instruments in buildings. With India having favorable boundary conditions for solar energy use, active solar cooling and application of solar refrigeration in official complexes are growing. Moreover, the application of solar-powered cooling technologies would add to improvement of energy efficiency and provide an opportunity to fulfill international commitments of the Paris Climate Agreement and the Kigali Amendment to the Montreal Protocol. It would add to implementation of Sustainable Development Goal (SDG12).

With this in view, the government of India proposed an action plan for intensifying Solar Cooling applications in India in 2009. A number of large-scale air-conditioning systems have been built of 100 kW and more, for commercial buildings using rooftop-mounted parabolic troughs and triple-effect VAMs. About 25 solar cooling installations with solar concentrators exit in industry, institutions, and hospitals. These installations highlights are as below.

(i) Gujarat State Electricity Corporation has installed the first solar thermal air-conditioning system to cool the Gandhinagar Thermal Power Station's office building in India [7]. It has 150 tons of refrigeration with 528 kW capacity and has installed solar parabolic concentrators in 1575 m^2 area. The system supplies hot water at 90 °C to a new vapor absorption machine. In summer, this machine could lower the water temperature to 7 °C. Chilled water circulated through three air handling units, and supplied conditioned air to the building. The system was connected to the existing cooling plant, powered by electric compression chillers, and saved 250 MWh of electricity per year.

(ii) Solar cooling has been demonstrated at the Solar Energy Center, Gurgaon by M/S Thermax Ltd., for air-conditioning the office complex. A 30-ton capacity solar cooling standalone system came up using indigenously made concentrating parabolic trough collectors and triple-effect VAM. It has 288 m^2 of solar collector area, generating nearly 60 kW of 210 °C pressurized hot water. This heat is used in a VAM to create chilled water at 7 °C, which circulates in the center's 13 rooms.

(iii) Swiss Embassy in New Delhi has installed a solar cooling system, which uses heated water in solar to generate chilled water. The system cools most when it is needed more, i.e., when the sun is at its strongest. This system could save 134,000 kWh of electricity and 132 tons of CO_2 per year in ideal circumstances [8].

(iv) Honeywell Technology Solutions, Hyderabad has been operating a pilot project for solar thermal cooling since March 2013. It uses lithium-bromide chiller connected to 128 parabolic trough collectors [9]. Each collector area has a reflector area of 6.41 m^2 and was designed by Thermax. System working at 90% efficiency provides air cooling at temperatures between 21 and 23 °C to the Industry's office.

(v) In Mahendra Automobile Co., a solar cooling system has been installed for meeting the Paint Shop chilling requirement. It is a combined heating and cooling system, integrates 70 Solar Dishes and through vapor absorption machines hot water at 130 °C is pumped from the expansion tank to the double-effect VAM and produced chilled water at 10.3 °C [10].

9.5.1 Outlook

India is moving ahead with solar cooling as an emerging application area. The technology is still developing and capital intensive, not yet cost-effective, though the operating cost can be significantly lower. Combined solutions using a biomass-solar-hybrid-electricity grid with cold storage as cost-effective systems are under development. Vast potential in space cooling and integrated hybrid solar systems for heating and cooling to work in all seasons exist. In addition, India being an agriculture-based economy, post-harvest cooling facilities are needed in rural areas, where grid electricity is lacking, safeguarding the agriculture produce. Industrial refrigeration in the pharma industry and cold storage with deep freezing milk and dairy products and agro-products are promising. Solar energy-based cold storages have the potential for a range of applications: fishing, agricultural produce, milk, dairy products, etc.

References

1. International Energy Agency (2012) Technology roadmap—solar heating and cooling. Technical report. Paris, p 28. Available at www.iea.org

2. Hwang Y, Radermacher R, Alili AA, Kubo I (2008) Review of solar cooling technologies. HVAC&R Res 14(3):507–528. https://doi.org/10.1080/10789669.2008.1039102
3. Ajib S, Alahmer A (2020) Solar cooling technologies: state of art and perspectives. Energy Convers Manag 214:112896
4. http://ffden-2.phys.uaf.edu/212_spring2007.web.dir/sedona_price/phys_212_webproj_peltier.html
5. Zheng L, Zhang W, Liang F (2017) A review about phase change material cold storage system applied to solar-powered air-conditioning system. Adv Mech Eng 9(6):1–20. https://doi.org/10.1177/1687814017705844
6. Oro E, Gil A, Miro L, Peiro G, Alvarez S, Cabeza LF (2012) Thermal energy storage implementation using phase change materials for solar cooling and refrigeration applications. Energy Procedia 30(2012):947–956. https://doi.org/10.1016/j.egypro.2012.11.107
7. Department of Foreign Affairs FDFA (2021) Cooling with solar energy in India. Retrieved from https://www.eda.admin.ch/eda/en/fdfa/fdfa/aktuell/dossiers/alle-dossiers/dossier-nachhaltige-schweizer-botschaften/mit-gutem-beispiel-voran/solarenergie-in-indien.html
8. Malaviya J (2018) First cooling installation on Indian government building. https://www.solarthermalworld.org/taxonomy/term/50741
9. Malaviya J (2017) India: Honeywell successfully showcases solar cooling project. https://www.solarthermalworld.org/news/india-honeywell-successfully-showcases-solar-cooling-project
10. Sun Focus (2014) A quarterly magazine on concentrated solar heat. UNDP-GEF project, vol 4, Apr–June 2014

Chapter 10
Solar Chemical Energy and Green Hydrogen

10.1 Solar Chemical Energy

Solar chemical energy is a vital emerging technology. It facilitates energy as well as its storage for use when Sun is not there. Terrestrial biomass, which has survived humankind for ages, is a form of solar chemical energy. Biomass stores solar chemical energy for the long-term. Success in artificial photosynthesis will revolutionize the use of solar energy. How is solar chemical energy produced and stored? So far, we have seen that solar radiation at different wavelengths gives rise to solar light and solar heat. Solar heat has a vast portfolio of technologies described in Chaps. 6, 7, and 8. To explain solar chemical energy generation, we need to understand that light has a dual nature, i.e., it is both a wave and a particle. Isaac Newton proposed the corpuscular theory in 1675, and the wave theory of light was put forward by Thomas Young in 1801. The Quantum theory of Physics theoretically explained this concept of duality in the early 1920s. The light particles, called photons, energize the organic molecules in matter, which attain higher energy states from the ground state. The chemical energy gets stored in the bonds in atoms or between the molecules. In a process known as Photosynthesis, plants in the presence of sunlight, water, and CO_2 produce biomass as chemical fuel.

10.1.1 Photosynthesis

Photosynthesis is a natural process of conversion of solar light energy through interaction with matter into chemical energy. In natural photosynthesis, incident solar radiation having photons gets converted to chemical energy. It gets stored in the living matter such as plants, forests, algae, coal, oil, and gas. From photosynthesis, firewood, vegetables, and animal oil come directly or indirectly (when animals eat

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the plants). Carbon dioxide (CO_2) in the atmosphere and water (H_2O) in the soil in sunlight get converted into glucose or lipid and oxygen. The reaction is catalyzed by the presence of chlorophyll in plant leaves [1].

$$6CO_2 + 12H_2O + \text{solar light} \rightarrow C_6H_{12}O_6 + O_2 + 6H_2O \qquad (10.1)$$

In this reaction, chlorophyll acts as a catalyst. The energy is first stored in the higher states of the chlorophyll molecule. It is then transferred to an energy storage molecule called adenosine triphosphate (ATP). The ATP then drives the process to synthesize glucose from carbon dioxide and water. Plants, when they decay, store this energy underground for millions of years and get converted into fossil fuels, which are the fuels we currently use to generate electricity on a large-scale. Fossil fuels as indirect solar energy resources are therefore the product of photosynthesis. In human beings, solar radiation is a source of Vitamin D, produced through chemical reactions in the skin.

The efficiency of solar chemical energy is the ratio of the chemical energy of the products of photosynthesis and the solar energy received on the leaves. The energy of glucose is only a tiny part of the total chemical product of photosynthesis, which includes the plant's roots, branches, and leaves. The rate of energy storage by the process of photosynthesis is 100 TW in a year [2]. It is equivalent to less than 0.1% of the solar energy that arrives on our planet. The net efficiency of the photosynthesis process has been computed as 5%. 5% is rarely achieved. When the biomass product is converted into fuel, the efficiency is further reduced. The final efficiency is of the order of 0.2–0.3%. It is pretty low compared to solar cells or solar thermal conversion, but no equipment, except sunlight and water, is used in this process. Therefore, increasing the efficiency of the solar energy conversion process into chemical fuels is seen as an important goal toward a sustainable energy economy.

10.1.2 Artificial Photosynthesis

Artificial photosynthesis is a chemical process that can produce hydrogen. It biomimics the natural process of photosynthesis and aims to create different chemical fuels. In the natural process sunlight, water, and carbon dioxide get converted into carbohydrates and oxygen. The process has low conversion efficiency. Artificial photosynthesis is expected to achieve higher efficiency and produce chemical fuels other than biomass, storing energy that can be used later [3]. The basic principle is the same as photosynthesis, i.e., to break a compound into its components using solar photons. When these components unite, heat is released in an endothermic reaction, which can then be utilized. An increasing rate of photosynthesis is targeted to achieve production of other fuels. Hydrogen is one of them and can be an alternative to fossil fuels. These solar fuels can store energy in the long-term. Before we describe the production of hydrogen, let us first understand the need for solar energy storage.

10.2 Need for Energy Storage

Increasing use of renewable sources of energy, which are intermittent like solar and wind, has given rise to the need for cost-effective storage devices. By storage, it is understood that energy is produced at one time and can be used later. In the process, energy from one form is converted and stored into another form for use when the demand arises. Storage increases system efficiency and flexibility. We are familiar with external devices such as dry batteries or dry cells used as the most convenient and cost-effective energy storage for various applications such as watches, mobiles, electronic toys, and small gadgets for home use.

Solar light and solar heat are intermittent. The solar light is available during the day and changes with seasons and varies in clouds and shades. In a solar PV plant, the storage lasts just a few seconds or minutes and allows smooth operation during output fluctuations due to temporary changes in irradiance, such as passing clouds. It requires external storage to run smoothly. Solar thermal energy uses solar collectors for energy storage. The heat can last a few hours, depending on the fluid used. These devices need external storage for continuous operation. Storage technology balances out the energy demand and has a crucial role in increasing the contribution of renewable energy.

A storage battery is an electrochemical cell with a cathode and anode. Different electrode materials and different electrolytes are used in other batteries. Rechargeable batteries further make life easier, as they can be charged again and again for more extended use. Electrochemical storage, such as lead-acid batteries, is one of the least expensive options currently used for the solar energy storage sector. They can have higher capacity and are preferred in off-grid applications. On the other hand, lithium batteries are lighter, most efficient with an efficiency of up to 100%, eco-friendly, and have high energy density. They are compact and have a longer lifespan when compared to lead-acid batteries. In lithium batteries, metal oxides are used as cathodes. The anode is made of large area of graphite material. The electrolyte is prepared from lithium salts in an aqueous solution. Sodium Sulfur (NaS) technology has been developed, having potential in microgrid applications. It consists of molten sodium and sulfur as its two electrodes. Other than electrochemical storage, thermal storage, mechanical storage, pump storage, compressed air storage, and virtual storage options exist (please see Box). Solar chemical storage is described below.

10.3 Solar Chemical Storage

Solar chemical energy is an option that provides fuel and long-term storage [4]. The energy storage density is defined as the amount of energy stored per unit mass of the material. Two options are Physisorption and Chemisorption dominated by physical and chemical bonding. When stored by Physisorption in weak chemical bonds, for example, water molecules on silica gel,[1] chemical boding is weak and energy density is low. In Chemisorption, energy is stored through chemical reactions in strong chemical bonds. The silica or zinc gets oxidized to silicon oxide or zinc oxide through oxidation.

In comparison to physical energy storage, chemical energy storage has a higher energy density, and energy can be stored for a longer time. Photosynthesis provided biomass as a solar fuel through chemical means. Solar fuels produced by enhanced or artificial photosynthesis to store energy in chemicals can become a promising storage device. Production of hydrogen, which has a much higher energy density than the batteries, provides long-term storage for use at any time.

Box: Energy Storage Systems

Thermal Energy Storage

Solar energy can be stored as sensible heat or latent heat of a material. A water tank stores sensible heat. Solids like rocks, concrete, or stones can be used in buildings and help in storing solar heat in the walls and the roof. A thicker wall of concrete maintains temperatures during the day and night. When material undergoes a phase change upon heating, without changing its temperature, it stores heat as latent heat. Applications of thermal energy storage are important for solar heating and cooling.

Pumped-Storage Hydropower

Pumped-storage hydropower is preferred option for solar energy. It uses solar energy to pump water uphill into a reservoir when energy demand is low. Water is allowed to flow back downhill and run a turbine to generate electricity when demand is high. Pumped-storage plants have high efficiency of 70–80%. However, pumped hydro system requires suitable landscapes and reservoirs near the location of the solar plant. Integration of pumped hydro with variable renewables does not fully realize its potential and the financial payback period is long.

Compressed Air Storage

Compressed air storage systems have been developed consisting of large vessels, or underground tanks where air is stored and compressed. As the demand arises the pressure can be released and air is assorted with natural gas, reheated, if necessary, and burned and expanded in a turbine that produces electricity. The process has low efficiencies of less than 50%.

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[1] Silica gel is a desiccant and absorbs moisture by physical absorption.

Flywheel Storage

Flywheel storage is a heavy wheel attached to a rotating shaft. A motor or generator is present in the rotor to translate energy as electrical and mechanical. To store energy, steel rotor systems are dependent on mass and composite flywheels are dependent on the speed of the rotor. Stored energy in a flywheel can be extracted by attaching the wheel to an electrical generator. Although flywheels are capable of providing quick power and other benefits, they have storage limitations.

Virtual Storage

Virtual energy can also be stored when it is not needed and can be used later. It uses no external device for storage and uses the devices we already have. For example, a building can 'store' thermal energy in its walls and roof so it does not need to consume electricity when Sun is not there. The building itself can act as a thermos by storing cool or warm air.

Evidently, residential and commercial solar customers, utilities, and large-scale solar operators alike, can benefit from solar-plus-storage systems. As research continues and the cost of solar energy and storage comes down solar, in combination with storage solutions will become more accessible.

10.3.1 Production of Hydrogen

In the Universe, hydrogen comprises approximately 75% of all matter by weight, but on the earth, free hydrogen molecule (H_2) is present only in trace amounts. It is required to be extracted from other molecules. In a chemical experiment, Henry Cavendish made the revolutionary discovery and produced hydrogen gas in 1766 and found it highly inflammatory gas. Today we know that hydrogen is the first element in the Periodic Table of Elements and is the most abundant gas. Hydrogen is a carbon-free clean energy fuel and possesses the highest energy density of 140 MJ/kg of all gaseous fuels. It is the lightest gas used in a wide range of applications, from balloons to space vehicles. It is a possible replacement for fossil fuel. Economically renewable energy with storage could bring clean energy transition faster. Hydrogen produced from renewable energy and water is called Green Hydrogen.

Hydrogen is a colorless, odorless, and invisible gas. Then why name it 'Green Hydrogen'. Indeed, many colors are assigned to hydrogen depending on the source of its production. Since little hydrogen exists as free gas on earth, hydrocarbons and water are their major resources. All fossil fuels, coal, oil, and gas, are hydrocarbons comprising carbon and hydrogen in different ratios. Each of these can be used for hydrogen production if we can remove carbon from the molecule. Current energy systems are fossil fuel dependent. The hydrogen color code is dependent on the source, as discussed below.

Coal—*Brown hydrogen* is formed from coal gasification. The reaction is followed by steam reforming of the gas produced for generation of hydrogen. A large volume of carbon dioxide is produced in the process.

Natural gas—*Gray hydrogen* is produced from natural gas by steam methane reforming process. A large volume of carbon dioxide is produced in this process as well.

Natural gas—*Blue hydrogen* is produced when the carbon dioxide generated from natural gas in the conversion process is also captured, stored, or reused.

Water—Electricity breaks water molecules into hydrogen and oxygen in a process known as electrolysis. *Green hydrogen* is produced through electrolysis when energy for electrolysis is supplied from renewable sources like solar or wind.

10.3.2 Methods of Producing Green Hydrogen

Currently, Natural gas or methane is the most preferred cost-effective source for producing hydrogen. Water is undoubtedly the most abundant source of hydrogen, and Green hydrogen can be made from the electrolysis of water by different methods using solar photons.

(1) *Electrolysis*

Production of hydrogen by splitting water has been an important goal of artificial photosynthesis. Water gets decomposed into hydrogen and oxygen by passing an electric current. The laboratory-scale demonstration for water splitting called Hoffman voltmeter was designed way back in the nineteenth century. It came to be known as a Reduction–Oxidation reaction, called Redox in short. Water is split during oxidation at the anode, producing oxygen and protons, and electrons move toward the cathode. In the reduction, process electrons combine with protons and produce hydrogen. An external voltage is applied, and at the cathode, electrons pass into the solution and cause a reduction reaction. The energy required is Gibbs free energy, a constant given by 237.2 kJ/mol. The overall efficiency of the process is low at 4% [5]. The storage density is high at ~530 kWh/m^2. The reaction takes place as,

$$H_2O + 2.46\,\text{eV} \rightarrow H_2 + {}^1\!/_2 O_2 \tag{10.2}$$

The energy (2.46 eV) can be supplied as solar heat. Direct photo-thermal dissociation of water using sunlight needs a high-temperature of ~2500 °K. A huge solar concentrator will be required to reach such a temperature. Other options have been developed for the electrolysis of water.

(2) *Photolysis*

Various chemical reagents and catalysis are deployed to lower the dissociation temperature. Photolysis is done by suspending metals as catalysts in water [6]. As it breaks into its components, the components store energy that can be utilized. It can be depicted as

$$M_1 M_2 = M_1 + M_2 \tag{10.3}$$

Here M_1M_2 is a compound that breaks through solar heat into M_1 and M_2.

When the components combine, they release heat in an endothermic reaction. The use of metal oxides such as Iron oxide can help reduce the temperature of the redox reaction. Iron oxide breaks into Iron and oxygen in the presence of sunlight.

$$\mathrm{Fe_3O_4} = 3\mathrm{Fe} + 2\mathrm{O_2} \tag{10.4}$$

In an endothermic reaction, Iron (Fe) reacts with water to produce hydrogen.

$$3\mathrm{Fe} + 4\mathrm{H_2O} = \mathrm{Fe_3O_4} + 4\mathrm{H_2} \tag{10.5}$$

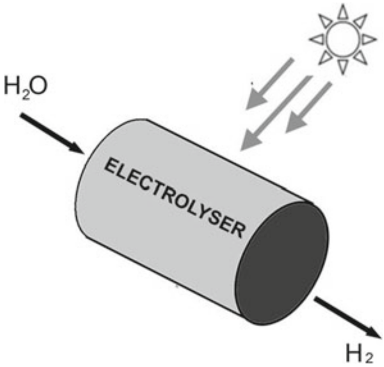
In a multi-step process, thermolysis or thermochemical splitting occurs by supplying heat from solar concentrators or waste heat from nuclear reactors. A large number of materials have been tested since the 1980s for thermolysis [7]. Many other catalysts have been tested.

Overall Solar-to-Hydrogen efficiency is given by

$$E_\mathrm{H} = \frac{I_\mathrm{oc} \times 1.23}{I_\mathrm{r}} \tag{10.6}$$

Here, E_H is the efficiency for the solar-to-hydrogen conversion process, I_oc is the operational current density, and I_r is solar irradiance at the location (Fig. 10.1).

Fig. 10.1 Electrolysis of water to produce solar hydrogen



The production of hydrogen from water splitting is an example of chemisorption. HYSOLAR, a joint collaborative program of Germany and Saudi Arabia, was conceived to come up at Riyadh in Saudi Arabia of 350 kW capacity [8]. The HYDROSOL plant uses high-temperature heat (800–1400 °C) to drive a series of chemical reactions that produce hydrogen in a thermochemical water-splitting process. The metal oxides used in this process are reused within each cycle, creating a closed-loop that consumes only water and produces hydrogen and oxygen.

(3) *Biophotolysis*

Microorganisms such as using green algae and blue-green algae (cyanobacteria) to split water into hydrogen and oxygen via direct or indirect biophotolysis in a biotechnology approach. In direct biophotolysis, hydrogenase in green algae drives hydrogen evolution. In indirect biophotolysis, nitrogenase in blue-green algae causes nitrogen fixation [9]. Hydrogenase as a catalyst uses green microalgae and undergoes anoxygenic photosynthesis in the dark. The algae are deprived of sulfur, and it produces hydrogen. Nitrogenase enzyme in blue-green algae as a catalyst is responsible for nitrogen-fixing cyanobacteria producing hydrogen when starved of nitrogen. The Source of light is solar radiation. As a source of biofuel, microalgae have several advantages. Algae grow in water and save on land. It can have a very high oil content of up to 50% and yields more than even the most efficient plants on land. It also takes care of the waste disposal problem.

(4) *Artificial Leaf*

A novel process, also known as the photo-electrochemical (PEC) water splitting process, uses semiconductors to produce hydrogen. 'Artificial leaf' consists of a silicon wafer, a semiconductor with different catalysts on each side [10]. Hydrogen is produced when it is placed in water and exposed to sunlight. Both n-type and p-type semiconductors can be used. If the n-type semiconductor is light sensitive, it makes a photoanode and acts as an electron donor. In the presence of solar light, matching the band gap create electron-hole pairs. A wire transports electrons released from anode to metal cathode at which H_2 evolves. If the p-type semiconductor is light sensitive, it makes cathode and acts as an electron acceptor. Electrons are moved to the interface by the internal electric field, and oxygen is produced. Many semiconductors other than amorphous silicon and catalysts have been tested for the production of H_2 using the PEC method.

Artificial leaf achieves efficiency of 6.7% for solar-to-hydrogen. It has the advantage to produce many other industrially applicable chemicals using oxygen produced. A recent breakthrough in this field has been the introduction of multi-junction solar cells. Using a triple-junction solar cell of Indium Gallium Phosphide (InGaP) and two electrolyte membranes in place of one increased the efficiency to as much as 30%. Using a multi-layer array of Indium phosphide (InP) quantum dots activated by synthetic iron-sulfur electrocatalyst, very high efficiency up to 60% has been demonstrated [11]. Intensification of research in green hydrogen production would enhance the production of hydrogen and also degrade pollution. The most significant benefit of solar hydrogen is that it helps in the reduction of carbon dioxide from the atmosphere.

(5) *Solar Factories of 'Tomorrow'*

Scientists at CSIR-National Chemical Laboratory Pune, India, have developed an ultra-thin artificial leaf device consisting of semiconductors stacked in a manner to simulate the natural leaf system. In the presence of solar light, electric current flows through the semiconductors and results in water splitting. A palm-sized device can produce six liters of hydrogen fuel an hour. The results are promising and suggest that it could become the basis of 'solar factories' in which solar collectors' arrays split water into hydrogen fuel stores. Israel Institute of Technology Haifa, Israel, has developed an Artificial Leaf using a platinum-tipped nano-rod catalyst [12] to turn water into hydrogen from artificial photosynthesis with 3.6% efficiency. Researchers from the Australian National University and the University of New South Wales have set a new world record in efficiency for producing renewable hydrogen from solar energy using low-cost tandem solar cells with low-cost catalyst materials. Electrolyzer development and floating solar rigs to produce hydrogen fuel using seawater are other promising ongoing research.

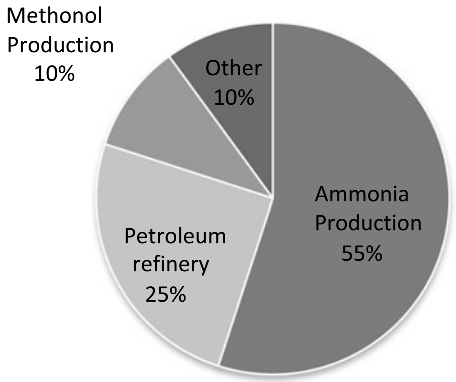
10.4 Hydrogen as Future Energy Resource

Using hydrogen in automobiles to replace gasoline in IC engines can add to efficiency and produce negligible pollution. However, hydrogen's most promising commercial application is in fuel cells for use in the transport sector. A hydrogen fuel cell is an electrochemical energy storage device. It uses hydrogen or hydrogen-rich gases as fuels to produce electricity. Like a battery, it comprises two electrodes viz., anode and cathode, separated by an electrolyte. Therefore, a fuel cell does not need to be recharged frequently; it operates as long as the fuel supply is on. Several fuel cells are combined in series or parallel combinations to form a fuel cell stack and obtain the desired power output. Hydrogen fuel cell vehicles will in future replace internal combustion vehicles in the transport sector. The adoption of hydrogen in other sectors like buildings and power generation will accelerate clean energy transitions.

Hydrogen, a versatile gas, is extensively used in the industrial sector in processes like ammonia production, as a reducing agent in refineries, in ammonia production for fertilizers, chemicals, and other industries (Fig. 10.2). As the cost of green hydrogen reduces, its adoption in most carbon-intensive industries, including steelmaking, shipping, chemicals production, and power generation, would reduce emissions. At present, 6% of global hydrogen production is from natural gas, while 0.1% is from water.

Disruptive technologies like Solar Hydrogen or Green Hydrogen are being pursued the world aggressively over. More than 30 countries have developed Hydrogen Roadmaps. In its drive toward clean energy transition and to celebrate75th year of Independence, the Prime Minister of India, Shri Narendra Modi, announced

Fig. 10.2 Global share of hydrogen consumption by industry [13]



launch of India's National Hydrogen Mission (NHM), with the ambition to make India a global hub for the green hydrogen production and export [14]. Projects in industrial, academic, and research institutions aim to address challenges in hydrogen production from renewable energy sources, its safe and efficient storage, and its utilization for energy in transport applications. A large number of hydrogen pilot projects are in the pipeline in industry and national laboratories.

Earlier in the 2000s, the MNRE, India, had supported a broad-based Research Development and Demonstration (RD&D) program on 'Hydrogen Energy' and Fuel. Under the program, the development of hydrogen use in internal combustion engines, two-wheelers, three-wheelers, and mini buses was demonstrated. Two hydrogen refueling stations were also established. In September 2020, an 18% blend of hydrogen with CNG (H-CNG) was declared as an automotive fuel to promote commercial applications in the transport sector. Hydrogen CNG pilot projects were launched to operate 50 buses in Delhi with blended hydrogen in Compressed Natural Gas (CNG).

In India, National Thermal Power Corporation (NTPC) Ltd. has a hydrogen program aiming at production, storage, and use. In July 2021, NTPC's renewable energy arm and union territory of Ladakh have signed an agreement to ply five transport buses powered by the green hydrogen gas in the region. Further, a pilot project in Ladakh to use hydrogen to power heavy transport vehicles in military use is taking shape. The goal is to reduce the dependence of the armed forces on fossil fuels that are transported across high altitude passes at a high cost. Many others including Reliance Industries, Indian Oil Corporation, Adani Industries, Arcelor Mittal, JSW Energy, and ACME Solar are pursuing Hydrogen ventures. Reliance Industries Ltd. aims to create a 100GW facility from renewable energy sources that can be converted to green hydrogen, free from carbon. Although the cost of generation is high, between 3$ and 6.5$ per kg, the RIL 1-1-1 vision is to produce hydrogen at 1$ for 1 kg in one decade.

According to the International Renewable Energy Agency (IRENA) report, green hydrogen is 2–3 times more expensive than blue hydrogen produced from Natural gas in 2020. But it is expected that it will be made from water using intermittent renewable energy sources like sun and wind as power input in the future. Green hydrogen production cost has already fallen by 40% since 2015 and is expected to fall further. Green Hydrogen production will increase 50 folds in the next six years, says Mike Scotts in 2021[2]. According to Goldman Sachs, the share of hydrogen could become 25% of world energy demand in 2050 [15].

New R&D investment is being made for development of Electrolysers with industry involvement. India has launched its first green hydrogen electrolyzer gigafactory in Bangalore. Green hydrogen as clean energy will add to the contribution of intermittent solar energy to total energy generation and a move toward net-zero emission for the global economies.

References

1. https://www.livescience.com/51720-photosynthesis.html
2. Report of the basic energy sciences workshop for solar energy utilization, 18–21 Apr 2005. http://www.sc.doe.gov/bes/reports/files/SEU_rpt.pdf
3. Harrima A (2013) Prospects for conversion of solar energy into chemical fuels: the concept of a solar fuels industry. Philos Trans R Soc A 371:20110415. https://doi.org/10.1098/rsta.2011.0415
4. Dimitriev O, Yoshida T (2019) Principles of solar energy storage. https://doi.org/10.1002/est2.96
5. Baykara SZ (2004) Hydrogen production by direct solar thermal decomposition of water, possibilities for improvement of process efficiency. Int J Hydrogen Energy 29:1451–1458. https://doi.org/10.1016/j.ijhydene.2004.02.014
6. Kalamaras CM, Efstathiou AM (2013) Hydrogen production technologies: current state and future developments. Conf Pap Sci 2013:9 pages. Article ID 690627. https://doi.org/10.1155/2013/690627
7. Barber J, Tran PD (2013) From natural to artificial photosynthesis. J R Soc Interface 10:20120984. https://doi.org/10.1098/rsif.2012.0984
8. Abaoud H, Steeb H (1998) The German-Saudi HYSOLAR program. Int J Hydrogen Energy 23(6):445–449
9. https://www.csiro.au/en/work-with-us/ip-commercialisation/hydrogen-technology-marketplace/biophotolysis-direct-and-indirect
10. https://www.chemistryworld.com/news/artificial-leaf-in-the-shade-but-still-growing/6417.article
11. Tessier MD, De Nolf K, Dupont D, Sinnaeve D, De Roo J, Hens Z (2016) Aminophosphines: a double role in the synthesis of colloidal indium phosphide quantum dots. J Am Chem Soc 138. https://doi.org/10.1021/jacs.6b01254
12. https://www.acs.org/content/acs/en/education/resources/highschool/chemmatters/past-issues/2021-2022/october-2021/artificial-leaf.html
13. WHA International, Inc. (n.d.) Hydrogen applications in industry. WHA International, Inc. [Online]. Available at https://wha-international.com/hydrogen-in-industry/

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[2] https://www.forbes.com/sites/mikescott/2020/12/14/green-hydrogen-the-fuel-of-the-future-set-for-50-foldexpansion/?sh=1cfd14cc6df3

14. Gupta U (2021) Indian prime minister announces national hydrogen mission. PV Magazine International. [Online]. Available at https://www.pv-magazine.com/2021/08/17/indian-prime-minister-announces-national-hydrogen-mission/
15. https://www.goldmansachs.com/insights/pages/gs-research/green-hydrogen/report.pdf

Part III
Large-Scale Solar: Local and Global

Chapter 11
Building-Integrated Photo-Voltaic Systems

11.1 Solar Buildings Concept

Solar energy has been traditionally an energy source for buildings. In view of sustainability concerns, the use of solar panels in buildings has increased significantly in the recent years. At first, the integration of PVs in buildings was constrained due to the cost, rigidity, and weight of standard PV panels. However, finiteness of fossil fuels and improved cost dynamics of the solar PV is leading to the integration of solar energy systems in buildings. Falling prices and increased efficiency make solar panels cost-competitive compared to other conventional energy solutions. With the increasing use of solar photovoltaics in buildings, a new type of renewable energy responsive architectural vocabulary is emerging about the use of passive and active solar systems. Continued technological advancements in PV systems are making various shapes and forms possible for PV systems.

A building is a solar building if it is systematically designed by understanding the interactions between the energy demand systems and different energy supply systems using solar energy [1]. Solar energy can be harnessed using either passive or active methods. Solar passive architecture for space and water heating are traditional methods adopted for centuries for human comfort by utilizing solar energy. Successful application of technology and innovations has led to active solar architecture and has revolutionized the building designs.

11.1.1 Passive Solar Systems

Passive solar energy methods adopt design, placement, or materials selection to optimize the heat or light directly from the Sun. Passive solar design strategies are among the most cost-effective and straightforward methods to reduce energy use in buildings. By the 1200s, the use of passive solar energy in buildings was evident

M. Goel et al., *Solar Energy*, Green Energy and Technology,
https://doi.org/10.1007/978-981-19-2099-8_11

in Egyptian, Greek, Persian, Hindu, and Native American civilizations. Before the clocks were invented, sundials were used to track the sun's movement throughout the seasons. This information was used in the homes that were designed to capture the Sun's heat during the winter.

Hindus and Romans also used passive techniques for maximizing solar gains in their buildings. Glass windows were invented, and passive approaches to harness Sun energy developed. The famous Roman bathhouses had large south-facing windows to let in the sun's warmth. Indians used passive design techniques extensively for heating, cooling, and lighting.

Attempts to harness solar energy saw resurgence in the nineteenth century, with Augustin Mouchot and Edward S. Morse further developing solar high-temperature technology. In the 1930s, American architect George F. Keck experimented with basic principles of passive solar houses to harness solar energy. He designed and built solar houses in Chicago and propagated the six pillars of the 'Keck and Keck' solar program[1]: orientation, shading, thermopane, ventilation, plan, and rooftop pool [2].

In Europe, the first passive solar house was built in Darmstadt, Germany, by Dr. Wolfgang Feist [3] in the early 1980s. The passive energy considerations have grown in Indian vernacular architecture to encompass the concepts of superinsulation, airtight envelopes, energy recovery ventilation, and high-performance windows in modern buildings. Environmental temperature and heat transfer are the basis of a passive system.

When solar energy enters a window and strikes a surface, it is converted to heat energy. Direct heat gain is the amount of heat gained from the Sun and is directly related to the amount of incident radiation transmitted through the glass. The indirect heat gain is heating an unconditioned space adjacent to the space receiving radiation from Sun. In both direct- and indirect-gain cases, it is essential to store the incoming solar energy. Elements that can be incorporated while designing passive solar buildings include:

i. The placement and size of the windows
ii. The type of glazing
iii. Thermal insulation
iv. The thermal mass
v. Shading
vi. Air movement and natural ventilation.

The placing of windows has the most crucial role in natural ventilation. Provisions for appropriate glazings and shading approaches from direct solar radiation in summer give a cooling effect (Figs. 11.1 and 11.2).

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[1] Homes designed by Keck and Keck, the brothers (George "Fred" and William) created the first "solar house" in 1942 in Glenview. There are a few places where you can see a bunch of Keck and Keck homes in USA [2].

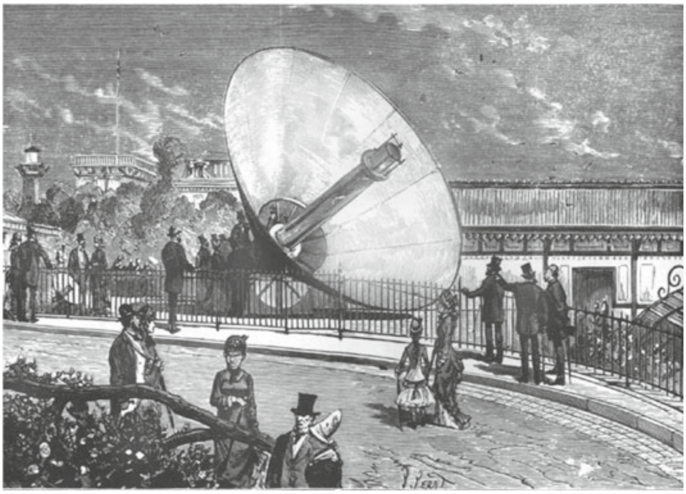
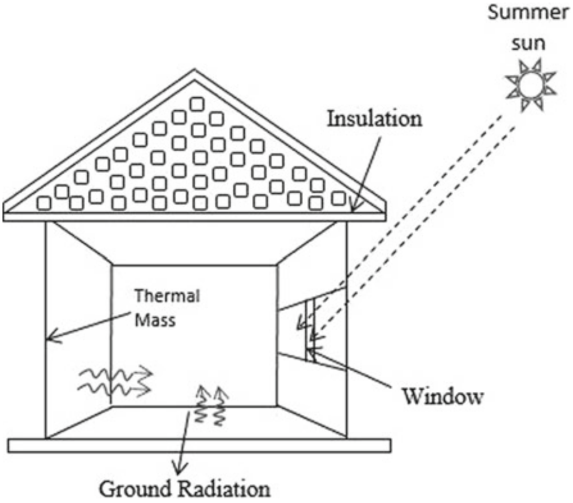


Fig. 11.1 Solar concentrator built by Augustin Mouchot on display at the Universal Exposition in Paris, 1878. *Source* https://landartgenerator.org/blagi/archives/2004

Fig. 11.2 A passive solar house



11.1.2 Active Solar Systems

Active solar energy methods primarily involve transforming incoming radiation into heat, cooling, or electricity. An active solar system includes solar devices like photovoltaic panels, collectors, and associated accessories like voltage controllers, blowers, and heat pumps that work together to process the Sun's usable heat. It is possible to get a low-temperature or high-temperature using collectors of different designs.

Table 11.1 Architectural design considerations in passive and active solar buildings

Design parameter	Passive solar building	Active solar building
Building orientation	Preferred to have north-south orientation. Most common orientation is toward the south side of building	The solar panel installation angle is such that maximum energy generation is determined by the design
Windows	Sizing of windows to minimize heat loss and fenestration orientation in hot climates	Solar windows with photovoltaic glass panels with structural strength
Solid wall	Thermal mass and designing of Trombe wall can help to reduce indoor temperature and humidity fluctuations	PV-Trombe wall with energy dashboard installed for tracking and displaying the solar performance
Structure strength	High albedo roofing materials reflect sunlight and limit the amount of heat absorbed. Green roofs contribute to the reduction of the urban heat island effect	The type of roof installed can significantly affect the kind of solar PV that can be installed
Rooftop	Provisions for appropriate shading devices that further reduce or increase heat gain to the building	The roof must be capable of carrying the load of the solar equipment and be structurally safe

Source Compiled by authors

Solar PV integration in buildings [4] has become possible with advancements in solar PV cell technology. A solar PV system installation shares the energy demand of a building and correspondingly reduces CO_2 emissions. As the active solar energy system is a relatively new field in architecture, many researchers have experimented with solar home designs that incorporated other than solar PV devices, like solar pumps and energy storage devices. A BIPV system comprises lightweight weather-resistant PV modules on building facades, curtain walls, skylights, and windows during the initial designing and construction phases.

Architectural Design considerations in passive and active solar buildings are depicted in Table 11.1.

11.2 Energy Consumption in Buildings

The building sector has a significant share of total energy demand. Energy is used at every stage of the building life cycle, starting from conceptualization, architectural design, structural systems, material selection, building construction, usage and maintenance, demolition, and waste disposal [5]. According to the World Green Building Council, buildings and construction account for 39% of energy-related CO_2 emissions worldwide [6]. Among all the building energy requirements; operational and maintenance are recurring energy consuming and have a major share in life cycle

Table 11.2 Energy consumption pattern in different building types according to usage

S. No.	Building type	Average energy consumption
1.	Residential	5 kWh
2.	Office	50–500 kWh
3.	Factory	1 MW
4.	Utility	2 MW+
5.	Industrial facility	2 MW (depending on the nature of the industry)

Source NREL, 2007 (could not locate the source)

cost. There can be two approaches to minimizing energy consumption (i) to design energy-efficient buildings and (ii) to integrate renewable energy systems in buildings. Both are important for sustainability. Among the renewable energy sources, solar energy technologies are the most advanced and can be directly applied at the building level. Therefore meeting the growing energy needs of the building sector through solar energy becomes a sustainable option.

As buildings are designed for different functions, they will have different energy use characteristics. For example, industrial and retail buildings typically have large lighting loads compared to residential buildings. Resultantly, buildings have different needs based on the usage and the electrical appliances and machinery that need to be powered within. Before deciding on the solar PV system, it is crucial to understand activities, and analyze the needs of a building based on its energy usage. According to NREL (2009), the energy consumption pattern in buildings is shown in Table 11.2. For the concept of net-zero emission buildings as highly efficient green buildings, please see Box 1.

Box 1: Net-Zero Emission Building (NZEB)

The Net-Zero Emission Building can be described as an extremely energy-efficient building in which the electricity demand is met by the renewable energy. Although there is no single agreed definition, NZEB implies that all the energy used by a building should be generated by renewable energy systems within certain site boundaries and it is energy efficient [7]. The zero-net energy building is a structure with zero net energy consumption where the total amount of energy used in the premises on an annual basis is more or less equal to the amount of renewable energy created on the site. Much of the difficulties of deciding on a common definition for worldwide application are caused by discrepancies in how the energy balance should be calculated (kWh, CO emissions, etc.) and how the site boundary is to be defined.

The cost factor is one of the biggest bottlenecks in the adoption of NZEBs; the overall cost of NZEB is nearly 30% higher than that of conventional buildings. NZEBs—100% energy-efficient, sustainable buildings—can be a game-changer, not only for the building sector but also for the whole energy sector.

Simulation studies are carried out using different software to optimize energy consumption in buildings and determine the extent to which solar energy can be used.

11.2.1 Building Energy Modeling

Building energy modeling (BEM) is a physics-based software simulation of building energy use. Determining solar energy achievable energy targets requires a complete understanding of where and how the building will use energy. A detailed whole-building energy model accurately summarizes all project-specific features and provides accurate energy use predictions. Furthermore, energy simulation is beneficial in pre-design for a new building as it identifies areas with high potential for energy savings and peak reductions. In the case of existing buildings, the baseline energy can be used to evaluate buildings' energy consumption and performance.

A BEM program considers energy information regarding building geometry, construction materials, lighting, HVAC, refrigeration, and water heating.

Similarly, Performance-based goals (expressed in percentages) can be set to reduce electricity use with energy efficiency projects, potentially making it easier to achieve a given share of renewable electricity generation or use. The PV system required for any building can be designed based on this energy baseline.

The BEM helps to understand energy consumption patterns and accordingly set energy system size goals (expressed in kilowatts or megawatts of generating capacity), i.e., installing a certain amount of generating capacity for PV.

11.2.2 Solar PV Simulation Software

It is also desirable to estimate the solar energy yield of a PV system, and computer simulation-based solar PV software is used. It includes kWh yield per year, performance ratio, and CO_2 emissions. Moreover, PV simulation plays a vital role in determining the expected output values of the solar energy system. The parameters which need to be measured as input into the software are

- Project/site location
- Quantity, specifications of solar PV modules and inverters
- Configuration of solar PV Strings
- Solar PV tilt angle and azimuth
- Battery specifications for electrical storage, if any.

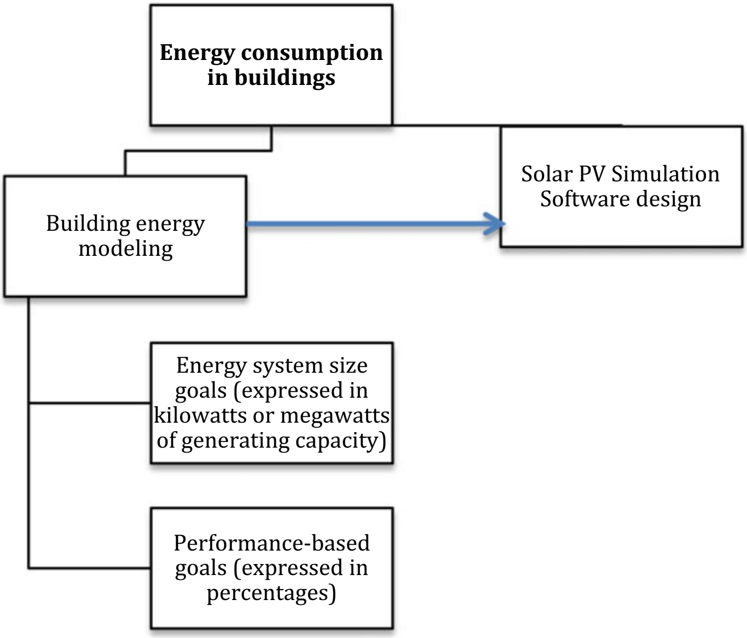


Fig. 11.3 Energy consumption in buildings and targets

Many software packages have been developed for assessing the PV system potential since the mid-80s. PVFORM and PVGRID were some of the first ones. The modeling and simulations are a great help in designing a BIPV (Fig. 11.3).

11.3 Building-Integrated Photovoltaic (BIPV) System

It was in the early 1990s, that the idea of building-integrated photovoltaic (BIPV) systems emerged [8]. The BIPV was considered a functional part of the building structure, which is different from the conventional building in which the photovoltaic system is only mounted on the existing structure. They serve dual purpose. The technology has combined the energy generators' ability of photovoltaics and structural aspects of the envelope of buildings.

The standard element of a BIPV is the photovoltaic (PV) module that can be integrated into the building envelope, such as the roof or the façade.

Advantages of Building-Integrated Photovoltaic Systems

- Most buildings are high-rise in modern urban cities, and the roof area is limited for standalone PV system installation. When BIPV is used as the building envelope in addition to the roof, it saves on land requirements.

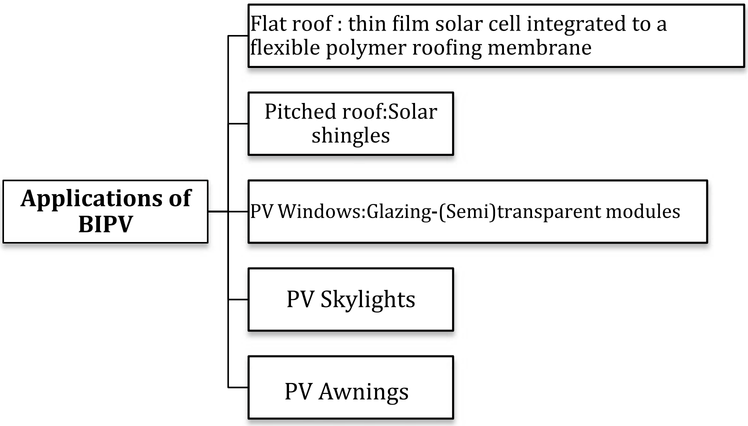


Fig. 11.4 BIPV systems in buildings

- Active PV systems can modulate the daylight to optimize the lighting requirements. Furthermore, the use of PV cells in buildings offers additional benefits like weather protection, heat insulation, and noise protection.
- BIPV serves the dual function of building envelope material and a power generator, providing savings in materials and electricity.

11.3.1 Applications of Building-Integrated Photovoltaic

New and innovative BIPV applications can include solar windows or skylights, PV shingles, entire solar roofs, PV laminates, and awnings. These BIPV solutions can be integrated into and onto the building envelope, often substituting photovoltaic products in place of construction materials. However, with active systems, it is a challenge to manage performance objectives such as thermal envelope performance, lighting, and HVAC energy demand with human factors such as visual comfort, daylight availability, and visual connection to the outdoors (Fig. 11.4).

A wide variety of BIPV systems are available in today's markets. Most of them can be grouped into two main categories: facade systems and roofing systems.

11.3.2 Building-Integrated PV Façade

Facade or building envelop include curtain wall products, spandrel panels, and glazing. Solar panels can be used on walls as a facade cladding solution for both new and existing buildings. BIPV solar glazing products are ranging from windows to glassed facades and tiles facades. Two types of building facades are

Rain Screen Cladding—These are also known as ventilating facades. A steel frame is fitted on the outside wall, and PV panels are mounted. The cavities in the paneling provide ventilation, and the cladding protects from rain. This type of cladding can be done in existing buildings and also in new buildings.

Curtain Walling—The new building structures have a curtain wall with thin PV panels and do not allow penetration of outside weather to inside. Both transparent and opaque panels could be used. The meetings are fully an integral part of building design and give a highly aesthetic look to a building. The inclination and orientation are such that to achieve maximum gain from solar energy. The electricity generated from the BIPV is fed to the grid or directly used by the owner.

PV-Trombe Wall—A photovoltaic cell can be integrated with the Trombe wall. A PV-Trombe wall uses solar cells with a Trombe wall to generate electricity in addition to heating or cooling.

Solar products can be manufactured in a variety of colors and transparency. Today technological advancement provides opportunities for integrating PVs into the buildings with options for façade customization. Besides energy generation, solar glass has the benefits of reducing glare and improving temperature insulation. PV glazing reflects infrared light, reducing heat transfer through the glass. This helps keep heat out during summer and during winter, resulting in a more consistent internal temperature.

Additionally, flexible PV cells that adapt are now available for integration into complex architectural shapes. In fact, the ultra-flexible organic solar cell (OSC), or flexible organic photovoltaic (OPV), have been developed that are ten times thinner than the width of a human hair. While the flexible PV can meet the aesthetic design objectives, they have lower efficiency than conventional panels. Although facade PV systems receive less irradiation than rooftop and ground installations, at the same time, they experience lower diurnal and seasonal variations, which is good.

11.3.3 Building-Integrated Rooftop System

Solar rooftops are growing tremendously. Roofing systems include tiles, shingles, standing seam products, and skylights. Roof integrated solar panels are like traditional roof panels, except they are installed in a section of tiles and act as the roof covering themselves. The BIPV Flat roofs are most widely installed to date is a thin-film solar cell integrated into a flexible polymer roofing membrane.

Solar shingles, also called photovoltaic shingles, are solar panels designed to look like and function as conventional roofing materials, such as asphalt shingles or slate, incorporating a flexible thin-film cell to produce electricity. Beyond rooftops, solar modules can also be mounted on building envelopes. BIPVs have the potential to become an integral part of NZEBs.

11.3.4 Building-Integrated Energy Storage System

Increasing penetration of renewables in electricity generation has introduced several stability issues. The intermittent nature of renewable energy makes the system operation even more complex and can lead to frequency/voltage fluctuations. To meet the challenge, storage systems are the ideal solution. BIPV is used in standalone, off-grid systems as well and is entirely self-sufficient. For these systems, any excess electricity generated is stored using solar batteries. The BIPV systems act as building-integrated energy storage systems and can be adopted in various configurations as per need.

11.3.5 Grid-Connected BIPV Systems

A grid-connected photovoltaic system is electricity generating solar PV power system connected to the electricity distribution network. The voltage and current outputs of the PV modules are affected by temperature and irradiance. Therefore, a Grid-connected PV System comprises a PV panel and a DC/AC converter that is capably connected to the grid. For this type of system, any excess electricity generated is sent to the electrical grid. Net Metering allows the electricity generated by a solar system to offset the electricity used from the grid during the night or on cloudy days. It requires a low-cost of equipment and installation as it does not require the use of batteries.

11.3.6 Economic Feasibility of BIPV

As the technology becomes widespread and more efficient, the design and performance potential of BIPV systems are becoming comparable to conventional energy. The cost of the solar system depends on the type of solar system installed and is a critical parameter. As integrated photovoltaics serve the function of the traditional building material, they replace standard roof materials like roof tiles. Still, the additional cost is incurred to pay for the PV components and electrical installation. In general, the installed prices of BIPV systems are higher than average PV system prices. It can be attributed to BIPV facing more complex product-development issues and market-adoption dynamics than rack-mounted PV. The incremental cost of photovoltaics is partially offset by avoiding the cost of conventional materials, and likewise, its life cycle cost can also be improved.

Box 2: Integration of Renewable Energy in Buildings in India

Distributed generation has been a main feature of renewable energy development in India. Energy consumed by the residential and commercial end-users accounts for more than a third of total energy consumption. Reducing existing building energy consumption consists of two approaches: (1) to reduce the need for energy through energy efficiency measures and (2) to meet a part of building energy needs through the use of renewable energy systems.

In 2007, the government of India launched the Energy Conservation Building Code (ECBC) under Energy Conservation Act 2001. Developed by the Bureau of Energy Efficiency (BEE), the code aims at the energy-efficient design of commercial buildings. In the beginning, it was a voluntary code but now some states have made the ECBC mandatory. The ECBC got integrated with local building bylaws. Green building norms were devised under Green Rating for Integrated Habitat Assessment (GRIHA) certification process that emphasized building lifecycle energy audit. It seeks to improve energy efficiency, minimize resource consumption, and waste generation to set standards for green buildings and sustainable habitats. The rating requires 14% energy efficiency for building envelop and 10% of the building energy to be met from solar energy. The GRIHA rating has since been revised many times.

India has immense solar potential, and solar-generated electricity for buildings seems to be an attractive option for the building sector. The Government of India has a target of 40,000 MW of solar rooftop PV capacity to be installed by 2022. The revised ECBC, 2017 has placed greater emphasis on renewable energy generation, inclusion of passive building design strategies, and integration of solar water heating in buildings. Proportion of total electricity demand to be met through renewable energy systems increases the efficiency level of the project too. Furthermore, each state and municipalities have its own set of codes and regulations that influence the application of renewable energy system in buildings. Some states offer higher incentives to facilitate the easy installation of solar for homeowners. In the past few decades, integration of solar PV to share the buildings' energy needs either through rooftops or through architectural features is seen as an attractive option to make a clean transition in India.

The government policies are progressively instrumental in determining the market development and adoption of BIPV by giving subsidies and incentives to popularize the installation of PV. In 2014 the Indira Paryavaran Bhavan in New Delhi came with integrated energy-conservation methodologies and a super-efficient solar PV system of 930 kW capacity. In 2019, U-Solar Clean Energy Solutions Pvt. Ltd. installed solar PV system facades on all four sides of the building at a Data Center in Mumbai. Covering over 5000 ft^2 of facade area and makes it India's largest BIPV.

11.4 Solar-Powered Buildings of the World

Architects and developers across the world are turning to solar for its costs savings and aesthetic appeal. Architects' imagination only limits the choice of integrated solar applications. Innovation in terms of design is evident in the buildings. Some of the notable solar integrated buildings across the world are:

11.4.1 Albuquerque, New Mexico

The solar building is located in Albuquerque, New Mexico, with architectural features, was built in 1956 to house the engineering firm, Bridgers & Paxton. It became first active solar-heated building and has a solar-heated floor of 5000 ft^2 [9]. The south facade is sloped at 55° and covered with solar collectors assembled from copper tubing laid over aluminum sheeting painted black in airspace sealed behind single panes of glass. In winter, the solar collectors were used to warm the building. Water-to-water heat pumps distributed the heat gained (as much as 140 °F) through a radiant system, while a 6000-gallon insulated underground tank stored the water for use on cloudy days and at night.

11.4.2 Apple Spaceship Headquarters at Cupertino in California, USA

The Apple Park is completely powered by renewable energy [10]. The building is design like a spaceship has the largest solar array for a corporate building in the world. Apple Park in Cupertino, California, the company's new headquarters runs on renewable energy, including a 17-MW rooftop solar panel project and four megawatts of biogas fuel cells. Solar panels on the roof of Apple Park in Cupertino, California are shown in Fig. 11.5.

11.4.3 Sundial Solar-Powered Office Building, Dezhou, China

The building is located in Dezhou, Shandong Province of northwest China. The building covers an area of 75,000 m^2 (Fig. 11.6). The design of the new building is inspired by the Sun itself. The building procures 95% of its energy need from alternate energy sources that include a 5000 m^2 solar panel array on the building

Fig. 11.5 Apple office building, Cupertino, USA [11]

Fig. 11.6 Sun dial office building, Dezhou, China. *Source* [11]

complex [11]. It underlines the urgency of seeking renewable energy sources to replace fossil fuels. The exterior of the building comprises solar panels, and all the facilities in the building run entirely on solar power. The building complex also has a solar hot system.

Fig. 11.7 Indira Paryavaran Bhawan, New Delhi

11.4.4 Indira Paryavaran Bhawan, New Delhi

Building energy consumption accounts for more than a third of India's total energy consumption. Furthermore, it is projected that energy consumption will increase by 2.7% per year from 2015 to 2040 in India. Especially for India, the solar potential is immense, and solar-generated electricity for buildings seems to be an attractive option for the building sector.

Indira Paryavaran Bhawan housing the Ministry of Environment, Forests and Climate Change is India's first Net-Zero Energy Building (NZEB), built with integrated energy-conservation methodologies and a super-efficient solar PV system [12]. Passive design strategies like shading, and orientation have been adopted in addition to active design systems (Fig. 11.7). The building has a solar PV system installed in a 6000 m^2 area of 930 kW capacity with 2844 solar panels that generate 14.3 lakh units annually.

11.4.5 Cochin International Airport

Cochin International became the world's first solar-powered airport in 2015 installed a 12-MW solar plant. Initially, the Cochin International Airport Limited (CIAL) authority started small, installing 400 solar panels on a rooftop as a test pilot in 2013

Fig. 11.8 Cochin International, Kerala. *Source* https://www.unep.org/championsofearth/node/46

and installed a 1 MWp solar PV power plant partly on the rooftop and partly on the ground in the Aircraft Maintenance Hangar facility within the airport premises. The airport's consumption is around 48,000 units (kWh) a day, and using 46,150 solar panels; it produces 50,000–60,000 units (kWh) a day [13]. The solar plant is expected to eliminate 300,000 metric tons of carbon, a sum that is the equivalent of planting three million trees over the next 25 years (Fig. 11.8).

Today, over 20 Indian airports have either installed or are in the process of installing solar capacity within their premises.

11.4.6 CtrlS Datacenters Limited, Mumbai

The CtrlS Datacenters Limited, Asia's Largest Rated-4 Hyperscale Datacenter and managed services provider, has deployed first large-scale building-integrated vertical solar PV system on its Mumbai data center facility. With a capacity of about 1 MW, the system has been installed by integrating solar panels on all four walls of the facility, covering over 5000 ft^2 of facade area. Predominantly, 60% of these modules are installed in the southeast and southwest and the rest 40%, are installed in the remaining direction [14]. The data center has a total solar PV power capacity of 863 kW. To offset the mismatch between energy generation among the modules, the power plant is integrated with 1233 power optimizers. Challenges related to execution were overcome by using custom-designed aluminum rails as the module mounting frameless panels.

11.5 Outlook

The use of smart and intelligent buildings has paved the way to optimize energy generation, and BIPV is rapidly advancing across the world. The BIPV faces challenges like market barriers, demonstration of long-term reliability of the technology, smart interaction with the grid, and disposal of panels after use. But with the increased usage and acceptability and lowering costs for solar PV renewable energy, their use in high-rise buildings and commercial buildings is paving the way for use on large-scale [15]. Energy system that links the PV modules to the building and a district energy system to maximize the local use of the electricity generated, including storage, power conversion, power control, heating and cooling, and e-mobility are becoming the future realities in the building systems. The PV systems are poised to play the main role in building-level projects for sustainable growth solutions in the coming years.

References

1. Noël D, Réné T, Cesar K (2012) A review of solar technologies for buildings. Afr J Sci Technol Innov Dev 4:11–36. https://doi.org/10.1080/20421338.2013.833378
2. https://modernil.com/a-sprawling-keck-keck-home-in-a-somewhat-unlikely-location/?print=print
3. https://passipedia.org/examples/residential_buildings/multi-family_buildings/central_europe/the_world_s_first_passive_house_darmstadt-kranichstein_germany
4. Special issue "Integration of solar PV in buildings". MDPI (under publication). https://www.mdpi.com/journal/sustainability/special_issues/Integration_Solar_PV_Buildings
5. Whole building design guide. https://www.wbdg.org/resources/net-zero-energy-buildings
6. Izzet Y, Tülay K (2017) Energy-efficient building design in the context of building life cycle. https://doi.org/10.5772/66670
7. World Green Building Council (2019) Bringing embodied carbon upfront. London. [Online]. Available at https://www.worldgbc.org/sites/default/files/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf
8. https://www.seia.org/initiatives/building-integrated-photovoltaics
9. http://albuquerquemodernism.unm.edu/wp/solar-building/
10. Apple Inc. (2018) Apple now globally powered by 100 percent renewable energy. [Online]. Available at https://www.apple.com/newsroom/2018/04/apple-now-globally-powered-by-100-percent-renewable-energy/
11. China unveils world's largest solar office building (2018) Available at https://www.alternative-energy-news.info/china-largest-solar-office-building/. Accessed 1 July 2021
12. Khandelwal R, Jain R, Gupta M (2020) Case study: India's first net-zero energy building—Indira Paryavaran Bhavan. Int J Sci Technol Res 9(11):353–357

13. Hunt K (2018) This is the world's first fully solar-powered airport. World Economic Forum. [Online]. Available at https://www.weforum.org/agenda/2018/10/inside-the-worlds-first-solar-powered-airport
14. Prnewswire.com (2020) CtrlS builds world's 1st solar powered rated-4 datacenter building powered by integrated vertical solar system from WAAREE. [Online]. Available at https://www.prnewswire.com/in/news-releases/ctrls-builds-world-s-1st-solar-powered-rated-4-datacenter-building-powered-by-integrated-vertical-solar-system-from-waaree-846025794.html
15. Sharma AK, Kothari DP (2017) Solar PV façade for high-rise buildings in Mumbai. Int J Civ Eng Res 8(1):15–32

Chapter 12
Solar Roof Top Advancements in India

12.1 Solar Rooftop

India has emerged as a global leader in accelerated growth in renewable energy. Solar rooftop is a solution for electricity generation with no use of fuel, no air or noise pollution. In India, the solar rooftop market potential ranges from 124 GW against the technical potential of 352 GW. A goal of 40 GW solar rooftop capacity by 2022 exists. A Roof Top PV (RTPV) system is a smaller PV plant than land-mounted ones. It is an electricity generator at your doorstep, installed on rooftops of houses, offices, commercial or industrial buildings. It is a distributed generation system comprises of solar arrays and associated electronic instruments. The solar array is kept tilted toward the south if the location is in the Northern hemisphere and tilted toward the North in the Southern hemisphere. The peak power output is achieved when Sun is overhead and is incident in a perpendicular direction. The electricity generated from RTPV systems could either be fed into the grid or can be used off-grid.

An early impetus to solar rooftop development came from the National Solar Mission, launched under India's National Action Plan on Climate Change 2008, targeting 20 GW grid-connected solar power, with 2 GW as a contribution from off-grid. In 2010, India's first 1 MW rooftop solar plant was installed on Tyagaraj Stadium during the IXth Commonwealth Games held in Delhi. Later in 2011, Delhi Government announced a policy on Solar Roof Program. Indian Renewable Energy Development Agency (IREDA) launched a centrally driven Rooftop PV small generation program scheme for Delhi and throughout the country. As a result, several initiatives began to take place in different states. The solar energy potential of different states in India has been estimated high, as depicted in Fig. 12.1. For Electricity Acts and policies to promote renewable energy development in the country, please see Box 1.

'Rent a Roof' the Gujarat government brought up Model Rooftop program in 2016. Under this program, 2.5 MW was awarded to two developers to operate 'Rent a Roof' programs for different houses. New solar power policy has been announced in 2020 for Solar Rooftop Projects set up under SURYA-Gujarat scheme

M. Goel et al., *Solar Energy*, Green Energy and Technology,
https://doi.org/10.1007/978-981-19-2099-8_12

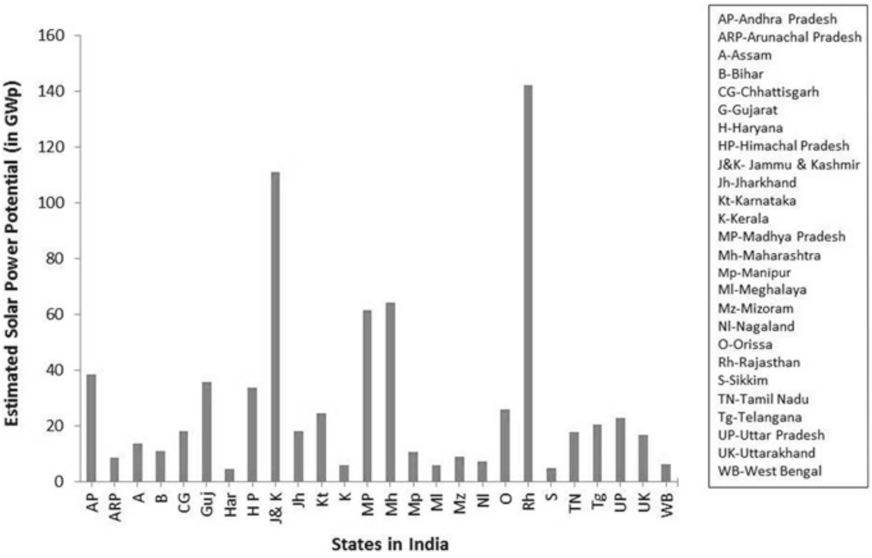


Fig. 12.1 Solar energy potential of different states in India assessed in 2014 [1]

[2]. Kerala government introduced a 10,000 Rooftop program in Kerala. Tamil Nadu and Himachal Pradesh also promoted Solar Rooftop planning.

In 2013, the Climate Change Research Institute, in a workshop held in association with GiZ held in New Delhi [3] recommended three essential requirements for a rooftop to be a game-changer in India (i) a smart grid, (ii) good weather forecasting capabilities, and (iii) constant interaction of generators and DISCOMs. In 2014, from a countrywide study, The Energy Research Institute (TERI) revealed that the market potential of RTS in India stands at 124 GW [4].

12.2 A Roof Top PV (RTPV) System

A complete RTPV system includes:

a. the PV modules (which might be thin-film or crystalline, transparent, semi-transparent, or opaque);
b. a charge controller, to regulate the power into and out of the battery storage bank (in standalone systems);
c. a power storage system, generally comprised of the utility grid in utility-interactive systems or a number of batteries in standalone systems;
d. power conversion equipment including an inverter to convert the PV modules' DC output to AC compatible with the utility grid;

e. backup power supplies such as diesel generators (optional-typically employed in standalone systems); and
f. appropriate support and mounting hardware, wiring, and safety disconnects.

12.2.1 Installation of Solar Rooftop

The solar energy that can be harnessed from RTPV depends on the solar radiation received at the building location. Eleven critical steps involved in its installation include;

(i) Determine the potential and size of a plant using solar data.
(ii) A complete audit of energy consumed in the appliances used in the building helps determine the size of RTPV and understand solar energy will be used.
(iii) Select an experienced vendor or developer.
(iv) Selection of panels according to solar radiation available and for suitability and profitability to the owner.
(v) Information about available government subsidies and incentives.
(vi) Interaction with the utility in the area about the intended plant size and permission for interconnection with the grid.
(vii) Follow norms about the layout and placing of the meter and inform testing parameters required after the installation.
(viii) Preparation of roof with the civil structure to get maximum solar exposure is the next step.
(ix) Building geometry such as roof slope, building orientation, and dimensions of the mounting surface in relation to dimensions of the RTPV. The most straightforward rectangular geometry for the square or rectangular plane of the roof is the most acceptable arrangement.
(x) Ensure that installing roof surfaces and geometries themselves do not shade the PV array significantly to achieve a high-performance ratio.
(xi) Take steps for periodic cleaning of panels and see that plant runs reliable and efficiently by measures about timely maintenance of the rooftop.

Some precautions are necessary for the safety of house owners [5]. High voltage from the rooftop can be dangerous and can cause severe damage to humans and equipment if not appropriately managed. Furthermore, the degradation inefficiency of cells with time and performance ratio should be kept in view for achieving the best results.

Box 1: Promotion of Renewable Energy—Policies and Acts in India (2000–2010)

Electricity Act 2003—The Act provides a framework for overall growth of electricity sector in India with special provisions for preferential tariffs and quotas for integration with renewable energy. Mandatory procurement of RE power for distribution licensees and facilitation of grid connectivity were incorporated. Based on optimal utilization of resources including renewable sources of energy, a policy for permitting standalone systems and open access was introduced for the first time.

National Electricity Policy 2005—The policy allowed preferential tariffs for electricity produced from renewable energy sources. In order to reach the areas where no grid connectivity was there, it aimed to provide access to electricity to all, 'Power to all by 2012' and increase minimum per capita availability to 1000 kWh per year by 2012.

Tariff Policy 2006—Introduction of mechanism of Renewable Energy Portfolio (RPO) to fix a minimum percentage of purchase of energy consumption by the States from renewable energy sources and giving special tariff for solar energy among other RE were its main contributions.

Integrated Energy Policy 2006—This integrated energy policy document while giving overall policy guidelines for action recommended special focus on RE development and set specific targets for capacity addition.

National Action Plan on Climate Change (NAPCC) 2008—Government of India enunciated mission mode action plans for sustainable growth under NAPCC to address climate change. Its first mission was intensification of solar energy development. It also advised that RPO's be set at 5% of total grids purchase, and be increased by 1% each year for 10 years.

Generation Based Incentives (GBI) for Solar—Introduced in 2009 for small grid solar projects below 33 kV, GBIs are provided for bridging the gap between a base tariff of INR 5.5 (by 2010–2011, with an annual escalation of 3%) and the tariff determined by the Central Electricity Regulatory Commission (CERC) as a fiscal incentive.

Jawaharlal Nehru National Solar Mission (JNNSM) 2010—The mission gave specific targets of 20,000 MW of grid-connected and off-grid solar power capacity by 2022 with 2000 MW as share of off-grid capacity.

Clean Energy Cess—Introduced in 2010 clean energy cess aimed to levy the amount of INR 50 to every ton of national or imported coal used in the country. A National Clean Energy Fund (NCEF) created from the cess, is expected to fund clean energy projects and provide up to 40% of the total costs of RE projects through the Indian Renewable Energy Development Agency (IREDA).

12.2.2 Key Drivers and Benefits

In India, key drivers for harnessing solar energy from the solar rooftops are;

(i) Nearly two-thirds of India's land area receives more than 2000 h of sunlight annually.
(ii) In terms of energy, a massive potential for solar rooftops has been assessed in the country.
(iii) The air quality over the urban and rural areas is getting degraded from increasing pollution. The solar generation contributes to a reduction in carbon emissions and a transition toward clean energy development and to fulfill SDGs commitments.
(iv) The climate change threat and commitments to international protocols like Paris Agreement are thriving to increase dependence on non-fossil energy sources to minimize greenhouse gas emissions.
(v) The generation and consumption in a rooftop system are at the same location. A solar rooftop reduces the additional land required for solar energy. It saves on distribution losses, a significant concern in transmission of conventional electricity to long distances.

The benefits to the consumers are;

(i) A solar rooftop is a power plant of your own
(ii) Grid-connected RTPV reduces your power bill by supplying surplus electricity to a local electricity supplier
(iii) Power generated could be used for self-consumption with the net metering approach
(iv) Provides opportunities for skill development and new employment generation
(v) For residential purpose loans and financial assistance, and for commercial and industrial complexes, custom duty concessions, excise duty exemptions, accelerated depreciation, and other concessions from the state governments can be availed.

An RTPV is a good investment; it has a rate of return of 5–6 years and provides environment-friendly power production. A rooftop solar helps to fulfill our climate commitments and is a step toward 'Átmanibharata'. An RTPV installed on the roof of the Climate Change Research Institute in South Delhi is shown in Fig. 12.2. For sample rooftop calculation, please see Box 2.

12.2.3 Performance Ratio

A PV system performance ratio is determined by using Eq. 4.1 in Chap. 4. Environmental factors such as rain, wind, and other natural degradations affect the solar panels during operation. Internationally, the panel manufacturers provide information about the degradation of a panel over 25 years, and it may be around 20% for suitable suppliers. However, in practice, the degradation rate may vary from 0.2% to as high as 5% per annum in extreme cases. There may be other losses from the equipment in use during the operation, which one needs to take into account, such as

Fig. 12.2 A solar rooftop in residential complex on Shivalik road in New Delhi. *Source* Authors own

- Inverter losses (4–10%)
- Temperature losses (5–20%)
- DC cables losses (1–3%)
- AC cables losses (1–3%).

Box 2: Sample RTPV Calculator [6]

The roof is the part of the building with a high potential of possibilities for the integration of solar systems. Assuming that about 30% of the solar rooftop must be in the residential sector, one can follow three steps to determine the output from a solar rooftop.

Step 1: Modeling solar resources.

Solar resource assessment is the most critical factor influencing photovoltaic electricity generation and is determined from GHI and GNI tables at a place. India has 5000 TWh of solar insolation, with most parts receiving 4–7 kWh per square per meter per day.

Step 2: Estimating available rooftop area required.

Area requirement: As a thumb rule, a roof area of 10 m^2 is required for achieving a 1 kW solar capacity system. If each panel selected has a size of 1 m × 0.556 m, then ten panels with a total area requirement of 5.56 m^2 are to be installed.

Step 3: Calculating PV potential from incoming solar radiation.

The total power output of the solar system can be calculated as:

$$\text{Total Power Output} = \text{Total Area} \times \text{Solar Irradiance} \times \text{Cell Efficiency}$$

Assuming that the peak solar irradiance falling on a perpendicular surface on a clear day is about 2000 W/m^2 for the identified location and ten solar panels rated at 100 W each are being used. Also, assuming high conversion efficiency of 18%, the total power out is given by

$$\text{Total Power Output} = 5.56\,\text{m}^2 \times 2000\,\text{W/m}^2 \times 0.18 = 2001\,\text{W} \sim 2\,\text{kW}$$

Solar panels in the market are sold per peak watt. Peak watt means that panel, regardless of size or efficiency, will give 1 W peak at an input solar radiation of 1000 W/m^2. In practice, Sun is not always perpendicular to the panel, and the efficiency is given for ideal conditions. The panel's performance in the field may differ because, at actual operating conditions, the field efficiency is very different. Depending on the location, some PV panels could be in shadow during some parts of the day.

Considering all these factors and various operational losses, the power output may be less and one should plan for 2 m^2 solar panel to produce 1000 W of electrical energy.

12.3 Dynamic Rooftop Policy Infrastructure

India has evolved a dynamic policy infrastructure for renewable energy as a whole and RTPV growth from the beginning (please see Box 2). The policies and schemes after 2010 are reviewed as below.

The Renewable Energy Certificates (RECs) were introduced in 2011 as a market-based mechanism for promotion of renewable energy development. It entitled one MWh of energy for one REC. The threshold price of REC (minimum and maximum) was decided by CERC so that the developers are not at a loss. It required all states to reach 10.5% solar Renewable Purchase Obligations (RPOs) in total electricity by 2022. The RPOs were expected to generate demand for renewable energy. The REC could be sold in the Energy Markets at market price and could be purchased by the entities that cannot fulfill their RPO. This market-based mechanism aimed to enhance renewable energy capacity by leveling the inter-state divergences of renewable energy generation and the requirement of the obligated entities to meet their RPOs with a differentiated price for solar and non-solar.

Net Metering, 2012 the policy of net metering was announced for the solar rooftop. A net metering mechanism allowed for a two-way flow of electricity wherein the consumer is billed only for the 'net' electricity (total consumption – own PV production) supplied by the DISCOM. Such RTPV systems could be installed with one integrated net meter or two separate meters, one for export to the grid and one for self-consumption.

In 2014, with *Nationally Determined Contributions* the government of India embarked on one of the most extensive renewable energy capacity expansion programs with a target of 175 GW installed capacity as a contribution of RE by 2022. The share of solar energy capacity was raised to 100 GW with an ambitious target of adding 40 GW solar rooftop capacity.

In 2015, *Grid-Connected Roof top and Small Solar Power Plants Program* had a goal to install 4200 MW by 2019–2020. Increased provisions of funding for the implementation of grid-connected rooftops were made over the next five years. The subsidy was 30% to all states and up to 70% to special category states. Commercial and industrial sectors were made eligible for accelerated depreciation, custom duty concession, excise duty exemption, and tax holidays. Targets were assigned to Central Public Sector Units (CPSU) for achieving 1000 and 12,000 MW of solar capacity addition in a phased manner.

In 2017, the *Sustainable Rooftop Implementation for Solar Transfiguration of India* (SRISTI) scheme aimed to give much-needed impetus to RTS use. By the Electricity Act, 2003, every state in India had a net metering policy or a rooftop solar policy. SRISTI Scheme 2021 provided incentives for the installation of rooftop solar power plant projects in India [7]. The primary objective of this proposed scheme was to generate 40 GW of power from the solar rooftops.

Gross Metering (10 kW Net Metering Limit), as per new guidelines issued in December 2020, gross Metering was introduced for those generating more than 10 kW. The producers are expected to send electricity to the grid and get compensated for the generation at a fixed tariff applicable.

The progressive policy measures have led to growth but have also introduced uncertainties and acted as obstacles in the faster implementation of RTPV. In 2018, a safeguard import duty of 25% has been introduced on solar imports to boost domestic production of solar cells.

Indeed, the renewable energy landscape in the country has changed rapidly since 2010, with particular emphasis given to promoting solar energy. India is currently having the fourth-largest electricity generation capacity from renewables in the world. As of June 2021, renewable-based capacity became 97 GW in the total installed electricity capacity of 375 GW. Between 2015 and 2021, India's installed solar energy capacity has increased by over 15 times and stands at 41.09 GW. The Rooftop capacity achieved in 2019 was 1.8 GW. In this, the industrial sector had 49%, commercial

21%, residential 16%, and public sector 14%.[1] Many institutional projects have come up with solar rooftop installations. India's largest rooftop plant on a single roof 7.52 MW plant is installed by Larsen & Toubro construction of more than 30,000 solar PV panels in Punjab. India has achieved 4.4 GW of grid-connected rooftop solar (RTPV) in March 2021.

12.4 Advancements of RTPV

Key issues which need to be addressed for the advancement of RTPV are awareness among consumers, manufacturing facilities, grid connectivity, business models, and regulatory framework, as discussed below.

(1) *Consumer Awareness and Acceptance*

Consumer awareness about the RTPV and its acceptance is the most significant concern in promotion, which is social bias. In a developing country, affordability in the residential sector is much lower than in an advanced country. The other issues are information about the vendors, specific products, and approval systems. There is an increased need to educate the resident consumers about the placement and function of smart meters, the process for metering and interconnection with the grid, and maintenance to achieve the maximum potential of the rooftop.

(2) *Manufacturing of Solar Cells and R&D*

At present, there is heavy reliance on imports of solar cells and associated components such as inverters and storage systems. Improving the performance of RTPV require investment in basic research on materials, industrial R&D, and manufacturing capabilities. India has been a manufacturing hub for solar modules and contributed to exports until the early 2000s. By increasing the investment in solar R&D and developing solar PV and RTPV system manufacturing capacities, through support from government and industry, the extraordinary goal of RTPV can be achieved.

(3) *Integration of Solar Energy into National Grid*

Although today India operates the world's largest synchronous grid connecting the entire country, the increasing share of solar rooftop integration of millions of RTPVs is a challenge [8]. The quality of power from conventional sources has to be free from harmonics to avoid frequent imbalances. Power evacuation at the time of generation due to small sizes of RTPV in the residential sector, avoidance of grid congestion in industrial sectors and management of power during shortages are the main issues before the distribution companies. Forecasting of solar generation, related technologies, and strategies that encourage penetration of small-scale distributive generators into the grid will be required to be implemented.

(4) *Business Models*

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[1] Bridge to India.

The high capital cost of PVRT has been a key challenge for its adoption by the industry or small consumers [7]. The payback period is 5–6 and 6–7 years in commercial and residential sectors. Three types of business models are envisaged,

(i) CAPEX Model—Self-owned, the roof owners own the PV system and electricity generated. The risk is of the owner who invests in the system.
(ii) OPEX Model—Third-party ownership, in which a third-party or a developer bears the cost of solar rooftop and sells to the customer at a rate lower than grid tariff. It is called OPEX (operational expenditure) model or RESCO model because the developer and the Renewable Energy Service Company (RESCO) pay for the system for a specified number of years and owes the risk.
(iii) Lease Model—The customer leases the rooftop system and pays for it over time. This type of arrangement is more appropriate for multistory flat owners. It is not yet adopted on a large-scale.

Therefore, the success of RTPV remains dependent on new business models adopted from time to time to overcome the cost barriers and regulatory challenges.

(5) *Regulatory Framework*

The regulatory framework in India for solar rooftops has been continuously evolving. Renewable Energy Portfolios (RPOs) have been assigned to various states. The solar energy cost declined from INR 17/kWh in 2011 to INR 2.63/kWh in 2019 as the lowest solar bidding route for a plant in Andhra Pradesh. Model net metering guideline to allow deemed RPO for utilities against the electricity consumption from net metering based solar rooftop-only against self-consumption by consumers is defined as obligated entities. There is a disparity in various state solar rooftop policies, and DISCOMs have acted as the main barriers. Regulations to remove prevailing cross-subsidy (subsidizing a particular group of consumers and recovering the cost by charging higher price from another group) so that tariffs can become more attractive and execution guidelines for energy accounting process and Time of Day (TOD) settlement to connect at HT lines level and LT level consumers are evolving. At the city level role of municipalities lies in an amendment in building bylaws for considering solar rooftop structure as temporary structure so that it does not need fresh approval for raising the height of the building.

12.5 Future Scenario and Strategic Goals

With encouragement from the government, solar rooftops in India continue to evolve and transform in making India a leader in solar energy [9]. To further scale up RE installations across the country, the following strategic goals in the power sector have been proposed.

(1) *Increase RE share in the energy mix to 225 GW by 2024*: Given India's commitment to reducing carbon emissions as per COP 21 targets, the GOI emphasized

increasing share of RE in the energy mix and improving energy efficiency. One of the key imperatives is to increase this contribution of generated units to installed capacity from about 23% to about 41% by 2024.

(2) *Reduce import dependence*: India has fairly scaled-up solar deployment in the past five years. However, it is lagging in terms of the development of domestic manufacturing capacity. In the case of the development of in-house manufacturing capabilities, solar manufacturing can generate over 125,000 additional direct and indirect employment over the next five years, besides providing equipment supply security.

(3) *Enhance the quality of life of farmers*: In the rural segment, to improve energy access RE installations and RE-based mini-grid systems Solar-Powered Irrigation Systems (SPIS) are emerging as an attractive alternative to electric and diesel pumps in meeting irrigation requirements. It is proposed to take up large programs/initiatives to increase the outreach of solar pumps to the maximum rural population.

(4) *Promote distributed generation*: Distributed generation systems such as solar rooftop (SRT) offers several advantages. Solar rooftop systems have already achieved grid parity for Commercial & Industrial (C&I) customers and are attractive for many residential customers in most solar-rich states. Distributed generation needs to be promoted in other states.

(5) *Launch of Green Hydrogen mission*: Macroeconomic policies like solar rooftop program, smart metering, adoption of electric vehicles, advancements in energy storage options are reshaping the clean energy transition in India. With the launch of the Green Hydrogen mission, it will be imperative to develop technologies for converting solar and wind energy into hydrogen production and usage. Hydrogen adoption across various sectors would provide an opportunity for India to move toward a clean energy transition and reduce dependence on the import of fossil fuels.

The following scenario has been developed to focus on distributed applications of RE in areas including RTPV, solarization of pumps for farming, solar drying and chilling, solar cookstoves, and overall growth of renewable energy capacity, including large hydro (Table 12.1).

Table 12.1 Scenario for renewable energy 2019–2024 [10]

S. No.	Renewable energy (RE) scenario	2019	2022	2024
1	RE in capacity mix	23% (35%)*	37 (46%)*	41% (50%)*
2	RE in generation mix	10% (21%)*	21 (30%)*	24% (33%)*
3	Employment generation (average 4–5 jobs per megawatt)	4.4 lakh	7.8 lakh	9.1 lakh
4	Investments (0.7–0.9 billion USD per GW RE)	About USD 125 billion For RE projects by 2024		

*Including large hydro

12.6 Outlook

India is leading by example by installing solar rooftops widely on government buildings, airports, railways networks, educational institutions, residential sector, and commercial complexes. Unlike thermal power plants, RTPV generation is consumers driven and therefore, peoples' participation and acceptance are critical issues for its success. With part financial support provided by the State to promote their use, RTPV systems are considered more appropriate for urban, rural, and remote areas. High growth is expected as solar generation reaches parity with coal-based power generation. Micro-generator technology as high-performance integrated RTPV can benefit both the rural as well as urban communities. DISCOMS has a role in reducing electricity bills by selling at a lower rate in proportion to higher wattage achieved from solar installation to increase homeowners' contribution in energy security for 24 × 7 power for all. With growing consumer awareness and taking steps toward harmonization of policies, India is on the right track to achieving the target of 40 GW, if not by 2022, then definitely by 2024.

References

1. https://www.researchgate.net/figure/Solar-energy-potential-of-different-States-in-India-source-Ministry-of-New-and_fig1_308004501
2. https://timesofindia.indiatimes.com/city/ahmedabad/gujarat-announces-new-solar-policy/articleshow/80007550.cms
3. CCRI (2013) A solar rooftop. Awareness in green building responsible education. New Delhi. [Online]. Available at http://ccri.in/pdf/proceedings/AGBRES-2013-II.proceedingd.final.pdf
4. Reaching the sun with rooftop solar, 2014. The Energy and Resources Institute, New Delhi, 62 pp. https://www.researchgate.net/publication/318410023
5. Gupta U (2021) Rooftop solar uptake in India: challenges and way forward. PV Magazine. Retrieved from https://www.pv-magazine.com/2021/05/24/rooftop-solar-uptake-in-india-challenges-and-way-forward/
6. Calculator
7. Sarangi GK, Taghizadeh-Hesary F (2021) Rooftop solar development in India: measuring policies and mapping business models. ADBI working paper 1256. Asian Development Bank Institute, Tokyo. Available https://www.adb.org/publications/rooftop-solardevelopment-india-policies-mapping-business-models
8. Gupta SK, Anand RS (2013) Development of solar electricity supply system in India: an overview. J Sol Energy 2013:10 pages. Article ID 632364. https://doi.org/10.1155/2013/632364
9. Goel M (2016) Solar rooftop in India: policies, challenges and outlook. Green Energy Environ 1:129–137
10. Draft national energy policy (2017) NITI Aayog, Government of India, New Delhi. [Online]. Available at https://www.niti.gov.in/writereaddata/files/document_publication/NEP-ID_27.06.2017.pdf

Chapter 13
Solar Energy in Cities

13.1 Mainstreaming Solar Energy Systems in Cities

With growing energy scarcity in the 1970s, the integration of renewable energy sources in electricity systems took momentum across the world. Today, many cities across the globe are striving and incorporating successfully renewable energy into mainstream. The use of solar energy in place of fossil fuel-based electricity can make cities carbon-free and a move toward net-zero emissions. In 2016, a high-level United Nations (UN) meeting held in Abu Dhabi, Dubai, concluded that massive deployment of low-carbon energy in the world's cities is now both vital and economical [1]. With the Industrial Revolution, the relationship between energy and economic activities has been changing within cities, ultimately impacting how cities were designed. According to REN21's Renewables 2019 Global Status Report [2] in 2018, more than 230 cities worldwide adopted 100% renewable energy targets in at least one sector. Evidently, with the right policies and sound urban planning practices at the city level, a new pattern of sustainable urban development using renewable energy sources, generating power by small-scale systems at the local level, is evident worldwide.

Looking back, it is evident to large extent availability of energy influenced the location and direction of urban development during the twentieth century. Generating energy within the city boundaries from renewable energy sources can bring many advantages. Compared to other renewable technologies such as wind, geothermal and solar energy, the latter is most easy to integrate into existing cities. Solar PV systems mostly plug and use, they do not require much space or much extra change within existing infrastructures. Secondly, solar PV projects also enjoy the benefit of scaling up or down as per the need. Solar projects can range from small, residential rooftop systems of 2 kW to utility-scale solar projects as large as 2000 MW. Thirdly, solar PV systems as decentralized systems can be used as supplementary energy to the existing centralized energy system to generate energy.

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13.1.1 Urban Morphology Impacting Solar Generation

Cities by definition have a reasonably high population density and compact urban fabric. Energy plays a vital role in sustaining the metabolism of cities. To analyze the overall energy performance of urban systems, both the consumption and the potential generation of resources are assessed. In this context, the existing city and its urban morphology will play a critical role in energy production. Agriculture, which sustains both rural and urban populations, contributes to GHG emissions. Land-use change (for urban development or cultivation), and agriculture combined can account for more than 30% of global emissions. Indicators of urban form impacting the solar potential in a study for different neighborhoods in London were categorized as:

- Land use
- Building typology
- Building geometry
- Building density
- Vertical and Horizontal distribution.

Cities with high densities of tall buildings especially possess large degrees of untapped solar potential that can be utilized with urban planning. A new area of urban planning tools for solar cities is emerging.

13.2 Energy Consumption Pattern in Cities

Energy consumption has the largest share of carbon dioxide emissions and is the leading cause of global warming and climate change. The cities contribute to nearly 70–80% of the country's greenhouse gas emissions (GHGs). Global GHG emissions by sector suggest that energy use in industry, transport, and other applications contributes to almost 75% of global GHG emissions [3]. Minimizing energy consumption, optimizing all conversion processes to achieve the highest efficiency, minimization of fossil fuel use and recycling and reuse of energy minimum waste production, and adjusting human requirements would be the pre-requisites for reducing GHGs.

The energy audit of production and consumption patterns is essential to understand which sectors consume the most energy and prepare city-specific action plans for emissions reduction. The pattern of energy consumption varies from country to country and city to city. One city is not similar to another. There are substantial differences between and within countries in their experiences of renewable energy use and developments. Cities are setting specific renewable energy targets that best suit their local conditions. Furthermore, we have seen in the previous chapters that various factors contribute to the maximization of solar panels' output power, including cloud cover, temperature, the angle of the Sun, climatic zones, and geographic features.

Table 13.1 Solar energy used in various sectors of the economy

Transport	Buildings	Industry	Agriculture
Electric mobility	Solar water heating	Process heat	Solar water pumps
Solar charging of electric vehicles	Solar space heating	Solar water heating	Solar crop drying
Traffic signals and street lighting	Solar rooftop	Solar water purification	Cold chain
Solar hydrogen	Solar lighting	Utility-scale solar	Portable lanterns

Source Compiled by authors

All these are dependent on the city, geographic location, and prevailing weather conditions.

The energy services that can be provided by solar energy for activities in a city in various sectors, such as heating, cooling, and lighting, industrial process heat, transport and mobility, traffic signals, etc. are depicted in Table 13.1. Most significant changes would occur in the transport sector requiring continuous science, technology, and innovation (STI) inputs for changing from IC engines to electric vehicles (EVs) and hydrogen in future.

13.3 Solar City Defined

There exists no global standardized definition for a Solar City. In very simplistic terms, it implies a significant source of powering the city is solar energy. According to Maharashtra Energy Development Agency (MEDA), ‘the Solar City focuses on implementing renewable energy projects to mitigate the fossil fuel consumption and meet the rapidly rising electricity demand by means renewable energy systems’ [4].

Energy consumption patterns in cities would change as new urban planning tools with an assessment of solar potential. Recent advancements in city 3D modeling and the integration of such data in GIS are emerging as solutions for solar city planning. Several cities have used these technologies to create 2D or 3D solar maps and energy maps to assess solar potential. A Second Solar Revolution in the energy sector is expected to take place according to some. ‘*The optimal diffusion of Building-Integrated Photo Voltaics (BIPV) in cities requires diligent planning to arrange temporal and spatial distribution of energy while preserving the aesthetics of city landscapes*’ [5].

In many cities, the city governments’ leadership and bold commitments have promoted solar energy and achieved climate targets. They have encouraged renewables in government buildings and streetlights and scaled-up renewable energy generation for public buildings and for the transport sector. By 2020 almost 800 cities in the world have put in place 1100 policies about renewable energy addition. The number of targets and policy actions for RE addition by the cities are depicted in Fig. 13.1 [6].

The solar energy installed capacities across the world in different regions are shown in Fig. 13.2; suggesting that the global solar market in 2018 was dominated by Asia, accounting for over half of the world's addition of solar capacity. The European

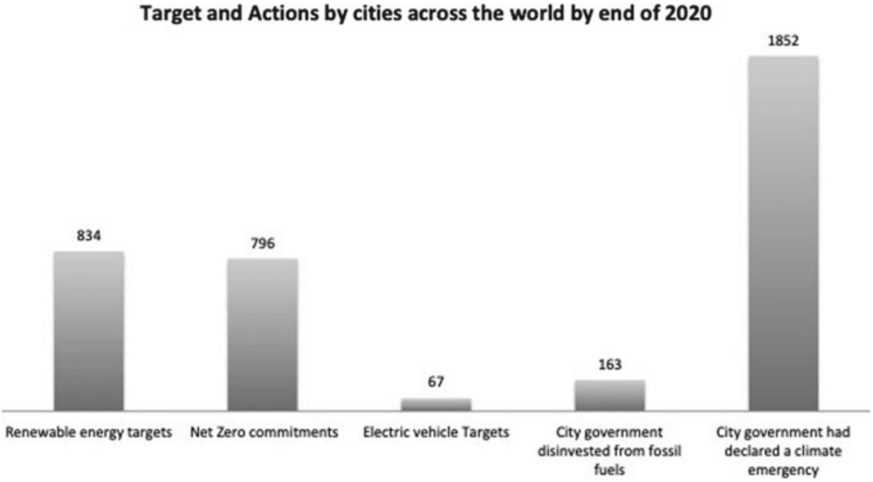

Fig. 13.1 RE targets and actions by cities across the world. *Source* [6]

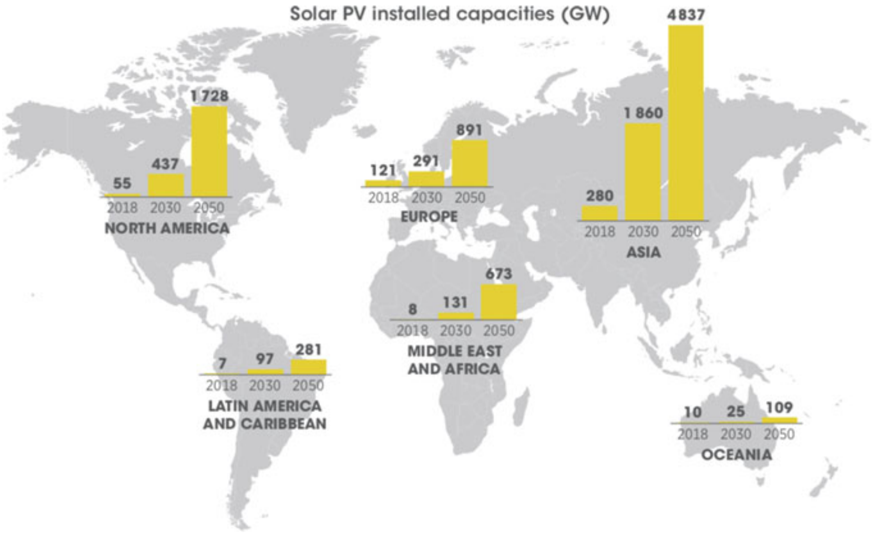

Fig. 13.2 Solar PV installed capacities (GW) across the world regions. Reproduced from International Renewable Energy Agency, 2019

Union represented the world's second-largest solar PV market of 121 GW after Asia (280 GW as seen in Fig. 13.2), mainly driven by Germany with its share of 45 GW. China in Asia had the highest contribution globally with 175 GW installations and is planning to add 619 GW of solar PV capacity by 2030. India has set up a renewable energy target of 450 GW by 2030.

13.4 Solar Photovoltaic Systems Application in Cities

Solar Photovoltaic (PV) power systems are being used for a variety of applications in urban cities [7]. Solar Photovoltaic systems are used mainly in two categories:

- Grid-connected photovoltaic system
- Standalone or Isolated photovoltaic system

(i) A grid-connected photovoltaic system is connected to the utility grid. The systems can range from small residential and commercial rooftop systems to large utility-scale solar power stations. The main advantage of a grid-connected PV system is its relatively low operating and maintenance costs. Grid-connected system allows the power generated from the panels to be back-fed to the grid when the Sun is in the sky and runs the structure off-line when the Sun is down. However, a grid-connected system needs to meet the criteria of voltage regulation, frequency regulation, power factor control, harmonic distortion controls, and quick response time to function.

(ii) A standalone solar-powered street or area lighting system is designed and operated entirely independent of the power grid. Standalone systems can be built to power small loads, like water pumps and streetlights, to the vast loads. Isolated areas and mobile systems are dependent on batteries and can provide access to modern energy services. The most commonly used isolated photovoltaic systems in cities are:

  - Solar water heaters for hot water
  - Solar pumps for water lifting
  - Solar concentrators for steam-based cooking
  - Street lighting, street lights, signage
  - Control like traffic signals, railway signaling
  - Telecommunications
  - Agricultural applications like cold chain
  - Rural electrification
  - Solar charging of electric vehicles.

13.5 Solar Smart Cities

Intelligent grid operations are an integral part of solar energy applications in cities. The solar smart cities have smart grids and automation. Smart technologies involve the use of sensors that are attached to generation, transmission, and distribution equipment and operated from the remote control. The artificial intelligence (AI) devices help companies to monitor and control the working of the equipment remotely in real-time as discussed below.

13.5.1 Automation

Low efficiency proves to be a significant hurdle in harnessing renewable energy. A smart Internet of Things (IoT) solution enables automated controls to improve efficiency with the integration of electricity production from RE sources [8]. Sensors are used for real-time monitoring of generation, transmission, and distribution systems. With the help of these controls, energy from renewable resources can be harnessed with maximum efficiency. An IoT device helps to detect the most favorable conditions for energy production.

13.5.2 Data-Driven Business Decisions

Data science has a vital role in RE sector development and growth for its application in cities. There has been enormous growth in the development of data tools, algorithms, modeling, and machine learning techniques. From sourcing energy and forecasting to demand profiles and business decisions, Big Data has been a particularly active field of research in solar energy utilization. Power distribution companies can determine and analyze users' power consumption patterns using IoT-generated data. Utilities can balance the supply based on the demands of consumers and plan accordingly.

13.5.3 Grid Management

Smart grids and grid management are essential for solar resource utilization. By placing sensors at substations and along the distribution lines, companies can gather real-time power consumption data. Energy companies can use this data to make impactful voltage control, load switching, and network configuration decisions.

13.6 Enabling Policy Instruments for Promoting Renewable Energy in Cities

Much of the solar advancement in cities has been achieved due to enabling and effective policies and planning, coupled with ambitious climate change targets. It is noteworthy that in 2017, investments in new renewable power capacity outstripped the amount invested in fossil-based generating capacity, with most of the installation of new renewable energy capacity currently occurring in developing and emerging countries [9]. The enabling policies adopted across cities around the world highlighting the importance of policy instruments in the growth of solar systems are summarized below.

(i) **Investment-based policies**. Procurement and direct investment, which include renewable energy purchases and direct investments in renewable energy technologies by municipal governments, as well as municipal support for investment in enabling infrastructure in urban areas. Fiscal and financial incentives, which include grants, rebates, and tax exemptions (as well as fees and levies to discourage) have played a vital role in encouraging renewable installations.

(ii) **Enabling policies and urban planning and zoning**. Cities are enacting policies to reduce administrative, permits, and barriers to renewable energy investment and by creating supportive zoning and other laws. There are options like solar leasing and community-funded projects in cities that require attention of local bodies and urban planners.

(iii) **Consumer incentives**. Incentives for changing electricity consumers' behavior by providing them with additional options and information regarding their electricity sources have been adopted.

(iv) **Mandates and obligations**. Technology-specific ordinances and building codes, some of which are stricter than national- or state-level regulations are introduced. A growing number of cities are giving mandates (particularly for new and public buildings) to promote renewable energy projects. For example, in California, State carbon emission targets, encourage the utilities to offer customers the option to install and source their electricity from renewable sources systems.

(v) **Subsidies and additional benefits**. In developing countries promoting solar energy in urban areas involve other incentives and subsidies. Gujarat Solar Policy 2021 at the State level in India is an excellent example of how solar energy can help scale solar power generation. It provides additional term benefits to the residential, commercial, and individual developers. Gujarat has already achieved 11,000 MW of PV production capacity and now has the target of producing 30,000 MW of green energy by 2022.

For solar city initiatives in India, please see Box.

Box: Indian Solar Cities Initiative

The Government of India took a laudable initiative to launch a scheme for ‘Development of Solar Cities’ in 2008, to address climate change concerns. With this in view all types of renewable energy-based projects like solar, wind, biomass, small hydro, waste to energy, etc. were included in a Solar City, along with possible energy efficiency measures depending on the need and resources available in the city to achieve the target. Subsequently, the government has modified and sanctioned a revised program in 2014 for implementation during 12th five-year plan, with a focus on specific targets for solar energy development. A total of 60 cities in the 29 states of India were proposed to be solar cities [10]. As per new guidelines issued in 2020, each state’s city must become a solar city by 2024.

There are currently 63 cities in the development of energy efficiency and renewable energy projects in India, including five model cities and 13 pilot cities. In Gujarat, Surat showed early signs to become India’s leading Smart-Solar City. It is the first city to mobilize consumer demand for rooftop solar in India. To harness this substantial solar resource available in the city, Gujarat Energy Development Agency (GEDA) also provided incentives and government subsidies. Public awareness through workshops on ‘Advantages of installing Grid-Connected Rooftop (GCRT) systems and Net Metering’ to encourage Solar Rooftop and mass publicity for the common public by creating a team of solar friends were carried out. Surat becomes the first district to have 100% solar-powered 52 public health centers (PHCs). Agartala, Tripura was seen as the emerging first Solar City in North East in 2012.

Urban planning has a key role in increasing the use of renewable energy in the cities. Globally, Cities Climate Leadership Group (C40), a private initiative has an objective of reducing global greenhouse gas contributions from cities by 50%, by 2030. With its 94 members, C-40 supports knowledge sharing toward resilient cities, zero waste, zero carbon buildings to achieve ecological sustainability. The Mumbai, a mega city of India on sea coast, as member of C40 has launched a Mumbai Climate Action Plan (MCAP). It has clean solar energy as one of the six priority areas. Mumbai is one of the most vulnerable cities to climate change and is facing worst hazards in recent years as sea-level rise, storm surges and flooding, etc. besides energy crisis and high COVID-19 pandemic incidences.

13.7 Global City Trends in Using Solar Energy

Global solar cities are growing in large number. A few examples of Solar Cities are presented here.

13.7.1 Diu, India

Diu is a town in Diu district in the union territory of Dadra and Nagar Haveli and Daman, India, has become the first union territory in India to be fully powered by solar power. Diu has a land area of 42 km^2 which is relatively small compared to others.

The power department of Diu has set up a total solar power capacity of 13 MW—10 MW in ground-based systems and 3 MW in rooftop systems [11]. Diu is equipped with a 9-MW solar park spread over 50 ha and 79 government buildings with installed solar panels. It runs on 100% renewable energy during the daytime. The city now saves 13,000 tons of carbon emissions every year and has reduced power tariffs by up to 15%.

Diu's peak power demand is about seven megawatts. The solar power installed capacity is much higher than the peak power demand in Diu. Diu is located at the southernmost point of Indian state of Gujarat and can sharing any surplus solar power generated during the day to Gujarat.

13.7.2 Masdar City, UAE

In 2008, Masdar City embarked on a journey to become one of the world's most sustainable cities and zero-emission cities. A 10 MW solar PV plant was the first and largest grid-connected renewable energy project in 2009 in Masdar City, UAE [12]. It was a solar PV power plant with a land area of 22 ha. The plant consists of 87,777 solar modules. The UAE benefits from plenty of sunshine throughout the year. Additionally, 1 MW rooftop solar panels have been installed on the Mohamed bin Zayed University campus buildings. However, the desert conditions come with several challenges as well. Dust, ambient temperature, ground fog and haze impact the energy output and reliability of SPV technologies.

13.7.3 San Diego, California

San Diego city is a state leader in terms of both the number of solar rooftops and the amount of solar energy generated solar energy. It was ranked the No. 1 city in the U.S. [13] city for cumulative and per capita solar panels installations in 2017.

Community Choice Energy program in San Diego is a city-run energy program for residents with a target to achieve 100% renewable energy by 2035. These programs help increase solar PV installation by reducing the soft costs associated with permits, interconnection, and financing. Hence the increase in solar PV in the city can be attributed to the business models, rebates, incentives, tax credits, and citizen awareness.

The net metering scheme is adopted, and local utility companies pay the residents for the energy that their (rooftop) solar energy system produces.

San Diego Gas & Electric Co addresses the issues regarding connecting solar rooftops to grids using smart-grid technology, making San Diego a global leader in microgrid technology. Furthermore, San Diego is also installing EV charging stations to make charging more convenient for EV drivers. Currently, the city has 57 eV charging stations (68 ports) at 15 locations [14].

13.7.4 City of Adelaide, Australia

In 2008, the 3rd International Solar Cities Congress was held in Adelaide. Subsequently, the city launched Solar PV initiatives for engaging consumers and encouraging them to manage their long-term energy use better. The municipality provided financial incentives for installing sustainable technology in apartments, houses, and commercial buildings, promoting smart metering and interactive communication technology [15].

The project's first key solar installation was the Adelaide Central Bus Station. A 50 kW solar PV system was used to power the world's first solar electric bus. The City of Adelaide already boasts 1.1 MW worth of solar power capacity built across eight buildings.

The City has adopted Carbon-Neutral Strategy 2015–2025. To meet carbon-neutral targets, it now plans to develop solar farms that will be accompanied by battery storage. It is visualized that Adelaide will be powered by renewable electricity, including community buildings, electric vehicle chargers, barbecues in the Park Lands, water pumps, street lighting, and traffic lights. In March 2021 the 3.10 megawatts (MW) Streaky Bay Energy Project has 10,000 panels and the 4.95 MW Coonalpyn Solar Farm operational.

13.7.5 Singapore, Singapore

Singapore is dependent on energy imports due to a lack of energy resources and lack of space. Solar energy in Singapore can have only a 10% share in its energy need. Singapore is exploring innovative ways of integrating solar energy systems to become a solar city. With high average annual solar irradiation of about 1580 kWh/m^2, solar photovoltaic (PV) is one of the most viable options for Singapore. Due to land constraints, Singapore is utilizing innovative technology of floating solar farms and vertical panels to increase its clean energy supplies [16]. Floating solar farms can generate more electricity than rooftop or on-ground installations and, at the same time, protect lakes and reservoirs from rising temperatures. Singapore has set a goal to install at least 2 GW of solar power by 2030. A 5 megawatts (MW) offshore floating PV system on the Johor Strait has been inaugurated, and a floating solar farm of size equal to 45 football pitches is under construction on Singapore's Tengah Reservoir.

13.8 Future Solar Applications in Cities

As solar power becomes progressively cheaper and more widespread, and innovations are underway, solar solutions are increasingly becoming part of the built environment in various forms and scales. Solar power has become more flexible, lighter, and applicable in every aspect of life. There are innovative solar technologies from solar paints, and solar roads to solar fabrics. Few noteworthy and promising solar applications are:

13.8.1 Floating Solar Farms or Floatovoltaics

'Floatovoltaics' are photovoltaic solar power systems created for floating on reservoirs, dams, and other water bodies. The cooling effect water has on panels can increase solar performance, while solar panels can shade parts of water bodies such as reservoirs and reduce evaporation. Furthermore, land constraints make it an appealing solution. Currently, the biggest operational floating solar power plant of capacity 2.1 GW, the Saemangeum project, is in China. China and India together account for six of the world's ten most significant floating solar projects (in various stages of development). India commissioned the first largest floating solar PV project of 25 MW for the country in August 2021 [17]. Spread over 75 acres it is built on the reservoir of NTPC Simhadri thermal station in Visakhapatnam, Andhra Pradesh. It has the potential to generate electricity from more than 0.1 million solar PV modules.

13.8.2 Agro-photovoltaic

The combination of photovoltaic and plant production is referred to as agro-photovoltaic (APV) systems. APV combines solar PV and agriculture on the same land and grows crops beneath ground-mounted solar panels. Crop suitability is the most crucial factor in this type of solar system. In 1982, this concept was proposed by Goetzberger and Zastrow as a means of modifying solar power plants to enable additional crop production in the same area. Japan was the first country to develop open field 'Agrovoltaics' in 2004.

13.8.3 Solar EV Charging Infrastructure

Electric vehicles (EVs) can increase the share of renewables by creating supportive solar charging stations. Grid-tied EV charging infrastructures are expensive to meet the requirements of millions of EVs, while a solar-powered car will produce no emissions. Innovative ways to create parking in charging infrastructure and 'Solar Tree' charging networks are developing. Installation of solar-powered EV chargers as solar rooftops in homes, as demonstrated in San Diego, requires no infrastructure. As transport energy represents a large share of urban energy consumption, offsetting this energy demand using solar charging can be highly beneficial for sustainable development.

References

1. https://uploads.habitat3.org/hb3/Press-Release-TM-Abu-Dhabi_20January_89286.pdf
2. https://www.ren21.net/gsr-2019/
3. https://www.mahaurja.com/meda/en/off_grid_power/solar_energy/solar_photovoltaic/solar_city
4. Roy Chowdhury PK, Weaver JE, Weber EM, Lunga D, LeDoux STM, Rose AN, Bhaduri BL (2020) Electricity consumption patterns within cities: application of a data-driven settlement characterization method. Int J Digit Earth 13(1):119–135. https://doi.org/10.1080/17538947.2018.1556355
5. Florio P et al (2021) Designing and assessing solar energy neighborhoods from visual impact. Sustain Cities Soc 71:102959
6. Renewables in cities 2021 global status report. REN21 Secretariat, Paris, p 24. Available at https://www.ren21.net/wp-content/uploads/2019/05/REC_2021_case-studies_en.pdf
7. Strzalka A, Alam N, Duminil E, Coors V, Eicker U (2012) Large scale integration of photovoltaics in cities. Appl Energy 93:413–421
8. https://www.allerin.com/blog/the-use-of-iot-in-renewable-energy-generation
9. https://www.irena.org/newsroom/pressreleases/2021/Apr/World-Adds-Record-New-Renewable-Energy-Capacity-in-2020
10. Solar cities, climate science and research (SAR) newsletter. Clim Change Res Inst VI(2) (2019)
11. https://timesofindia.indiatimes.com/city/surat/diu-countrys-first-solar-energy-efficient-ut/articleshow/63224543.cms

12. Masdar.ae (2021) Masdar clean energy—deploying renewable clean energy worldwide. [Online]. Available at https://masdar.ae. Accessed 1 July 2021
13. Pforzheimer A, Ridlington E (2020) Environment America research & policy center. https://www.ourenergypolicy.org/resources/shining-cities-2020/
14. Sandiego.gov (2021) City of San Diego's EV charging stations | sustainability | City of San Diego official website. [Online]. Available at https://www.sandiego.gov/sustainability/clean-and-renewable-energy/evcharging. Accessed 1 July 2021
15. City of Adelaide (2021) Renewable electricity. [Online]. Available at https://www.cityofadelaide.com.au/about-adelaide/our-sustainable-city/renewable-electricity/. Accessed 1 July 2021
16. Chandran R (2021) Lessons from Singapore: how to generate solar power in a city without much space. [Online]. World Economic Forum. Available at https://www.weforum.org/agenda/2021/04/singapore-solar-floatting-farms-environment-energy-cities/. Accessed 7 Dec 2021
17. https://timesofindia.indiatimes.com/business/india-business/ntpc-starts-indias-largest-floating-solar-plant-in-andhra-pradesh/articleshow/85515835.cms

Chapter 14
International Solar Alliance—Toward Clean Energy Transition

14.1 Introduction

Trans-regional solar energy cooperation is critical to support the transition to renewable energy at the global and regional levels. 'International Solar Alliance' is a coalition of 121 solar-rich countries lying fully or partially between Tropic of Cancer and Tropic of Capricorn to make a positive contribution to the common goal of increasing solar energy utilization globally. The International Solar Alliance (ISA) was launched as a joint initiative of India and France during COP21, the 21st meeting of the Conference of Parties to UN Framework Convention on Climate Change (UNFCCC) to boost solar energy development worldwide as an alliance of the 'sunshine countries'. The ISA is an intergovernmental treaty-based organization to boost the global growth of solar energy and reach the installation of 1000 GW of solar energy capacity by 2030. Paris Declaration of the protocol is reproduced below [1]. For more about other global climate change International Protocols, please see Box.

Paris Declaration on the International Solar Alliance of 30th November 2015

'The launch of the (ISA) was announced by H.E. Mr. Narendra Modi, the Hon'ble Prime Minister of India, and H.E. Mr. Francois Hollande, former Hon'ble President of France on 30th November 2015, at the 21st session of United Nations Climate Change Conference of the Parties (COP-21) in Paris, France. Former UN Secretary-General Ban Ki-moon attended the launch, alongside the Heads of about 120 nations who affirmed their participation in the Alliance to dedicate efforts to promotion of solar energy'.

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Box: Global Climate Change International Protocols

Changing climate in the ‘Anthropocene’ era has offered complex challenges to humanity in growth and development. In the atmosphere, human-induced greenhouse gases are giving rise to global warming and climate change. To address the global crisis, the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992 deliberated on causes of global warming and ways and means for its containment. The UNCED evoked the (UNFCCC) to mitigate climate change and its impacts. The primary sources of these emissions are attributed to the dominance of energy use, accounting for almost 68% of all Green House Gas (GHG) emissions. Greater use of renewable energy sources could address both these concerns, i.e., increasing pollution and resource depletion, and help reduce GHG emissions in the atmosphere. Two international protocols for global climate change control are Kyoto Protocol and Paris Agreement.

Kyoto Protocol

Under the UNFCCC, Kyoto Protocol is the first exclusive Climate Change International Agreement among the countries. It was evoked in the third meeting of the Conference of Parties (COPs) of UNFCCC held on 11th December 1997. The Protocol came into force on 16th February 2005, aiming to stabilize global atmospheric concentrations of greenhouse gases. Technology solutions to reduce GHGs from the atmosphere led to the introduction of a unique market-based financing mechanism. The market-based mechanism as Clean Development Mechanism (CDM) was agreed by Annex I and non-Annex I countries for adopting low-carbon technology.

The Paris Agreement

The Paris Agreement is the second international climate change protocol evoked in the 21st meeting of COPs (COP21) during 2015 to scale up clean energy generation. The Paris Agreement came into force on 4th November 2016, suggesting all countries take Climate Action and fulfill their Nationally Determined Commitments (NDCs) to mitigate climate change. More than one hundred 90 countries have signed the Paris Agreement and are pledged to fulfill their commitments to cut down greenhouse gas emissions to limit global temperature rise to 2 °C by 2100.

14.2 ISA Mission and Framework

ISA's mission is to provide a dedicated platform for cooperation among solar resource-rich countries and the broader global community [2]. It sets to achieve primary goals as follows:

- To invest USD 1000 billion by 2030 with an equal partnership between public and private sectors.
- To strengthen banking to promote innovative financial mechanisms and mobilize finance from International institutions to increase investments in solar energy in member countries.
- To collectively address vital common challenges in scaling up solar energy technology applications in member countries.
- To facilitate collaborative research and development (R&D) activities in solar energy technologies among member countries.
- To promote a common cyber platform for networking, cooperation, and exchange of ideas among member countries.

The Framework Agreement of the International Solar Alliance opened for signatures in Marrakech, Morocco, in November 2016. It became a legal entity on 6th December 2017 when the 15th country ratified it [3]. The ISA, an alliance of 121 countries within the identified boundaries extending on both sides of the equator covering 2600 km has set a laudable goal to mobilize USD one trillion funds. The key objective of the Framework Agreement is to work for efficient consumption of solar energy to reduce dependence on fossil fuels. It is stated as '*Parties hereby establish an International Solar Alliance (hereinafter referred to as the ISA), through which they will collectively address key common challenges to the scaling up of solar energy in line with their needs*' [4]. The ISA enables coordinated actions through programs and activities launched voluntarily, aggregating demand, risk, and resources, and promoting solar finance, solar technologies, innovation, R&D, and capacity building.

The Framework Agreement of ISA calls for the adoption of solar technologies in member countries to reduce the cost of finance and technology so that its deployment can be scaled-up. For these projects and programs formulation to accelerate development and deployment of existing clean solar projects and facilitate capacity building for promotion and adoption of solar technologies and R&D among member countries have been undertaken. Achievement of ISA's goals will directly contribute to the SDG7 (Affordable and Clean Energy) and SDG13 (Climate Action) while strengthening sub-targets of other SDGs in member countries, helping them fulfill the commitments expressed in their NDCs. It is an opportunity to fight global climate change collectively.

14.3 Establishment of ISA Headquarters

The ISA is expected to play a four-fold role in establishing a global solar market: an accelerator, an enabler, an incubator, and a facilitator. The secretariat of the ISA is to be located in India. The ISA interim Secretariat was jointly inaugurated by the Prime Minister of India Shri Narendra Modi and the then President of France, His Excellency Mr. Francois Hollande, on 25th January 2016 [5]. The 1st ISA founders' conference was held in New Delhi on 11th March 2018. Since then, five Assembly meetings have taken place. By that time, 56 countries have signed and 26 countries have ratified it. Many organizations such as World Bank, UNDP, European Investment Bank, European Bank for Reconstruction and Development, Climate Parliament, etc. signed joint declarations for forging partnerships with ISA for the development and deployment of solar energy globally. India has committed $27 million for creating building infrastructure and recurring expenditures for the first five years.

The Delhi Solar Agenda from the founders' conference [6] emphasized the need to facilitate affordable financing, including innovative financing mechanisms to facilitate joint research and development efforts to undertake off-grid solar applications for poorer and or remote communities, to enhance skills, to undertake capacity building and to strengthen ISA to become an action-oriented and member-driven multilateral organization.

The key activities for its members are;

1. Collaborations in joint research, development, demonstration, sharing information and knowledge, capacity building, supporting technology hubs, and creating networks.
2. Acquisition, diffusion, indigenization, and absorption of knowledge, technology, and skills by local stakeholders in the member countries.
3. Creation of expert groups to develop common standards, tests, monitoring, and verification protocols. Members from other countries can also become members.

Each member country must have a Solar Technology Application Resource Center (STAR-*C*) and designate a national focal point. The focal point may interact with one another and with relevant stakeholders to identify areas of common interest, design programs, and proposals, and make recommendations to the secretariat to fulfill the ISA's objectives. It will have 'Infopedia' as a common communicator platform to showcase best practices and policies. As of September 1, 2020, the ISA Framework Agreement had been signed by 98 countries, with 80 countries having also deposited instruments of ratification. The ISA has created a project preparation facility to assist the members in preparing project documentation as consultancy support.

14.4 ISA Technology Focus

ISA goals' success relies on rapid developments in solar photovoltaic (PV) technology, energy storage technologies, collaborative scientific research, and capacity building among the members. It aims to develop solar technology that is appropriate, innovative, and affordable for scaling up commercially and becoming a genuine alternative to unsustainable energy sources. Consequently, solar technology innovation and development, including creating a solar research and development base, must be made.

14.4.1 Scaling Solar Application for Agricultural Use (SSAAU)

The Scaling Solar Applications for Agriculture Use (SSAAU) focuses on deploying Solar Water Pumping Systems in member countries to provide greater energy access and a sustainable irrigation solution. Based on best practices, the wider objective is to adopt common methodologies and procedures for decentralized solar applications in agricultural and rural use. To make the projects viable and affordable, the ISA has adopted an aggregation model to assess demand from various countries to reduce system costs substantially. The ISA secretariat proposed a global tendering process for conducting international competitive bidding for design, testing, manufacturing, supply, installation, commissioning, and maintenance services. The Country Missions to nations, namely; Mali, Togo, Niger, Benin, and Uganda, were undertaken with a cumulative demand of 0.1 million solar water pumping systems [7]. ISA has aggregated demand for more than 270,000 solar pumps across 22 countries.

14.4.2 ISA Solar Cooling Initiative (I-SCI)

The ISA Solar Cooling Initiative (I-SCI) has been launched under SSAU to focus on solar cooling technologies to encourage sustainable and energy-efficient cooling technologies to reduce post-harvest food loss. Cooling systems are energy-intensive, and the use of solar cooling technologies reduces the environmental impact. I-SCI is expected to work under the guidance of a pool of public technological research centers from Member countries. For the I-SCI, knowledge support is provided by National Center for Cold-Chain Development (NCCD), India, and the research and academic support is provided by the University of Birmingham, UK.

A pilot project has been under implementation in Nigeria by ISA in collaboration with the Climate and Clean Air Coalition (CCAC). ISA aims to develop associated innovative finance and business models to create integrated cold-chain solutions for different crops and mobilize finance after assessing and aggregating demand for solar cooling and cold-chain systems with the help of stakeholders and partners. The project's objective is to test the business case and monitor the impact of a pilot solar cooling hub in Nigeria. The hub will provide access to cooling to small farmers and demonstrate that cold-chain solutions are powered by solar energy, using low/zero GWP refrigerant gas. The use of climate-resilient cold-chain infrastructure can reduce approximately 19–21 GtCO2e GHG emissions by 2050 [8].

Onset of Covid-19 has led to actions to prevent, protect and provide treatment to the affected population from this dreadful pandemic. In this context, ISA helped to provide 24 × 7 electricity to 500 hospitals across 47 of the least developed (LDC) and Small Island developing (SID) member countries to cold power storage to store vaccines. Through its program called 'ISA Care', efforts were made to solarize these hospitals, one in each district.

14.4.3 Scaling Solar E-Mobility and Storage

Under this program has assessed the Member countries' capacities and needs on solar electric mobility, energy storage, and charging infrastructure using a survey questionnaire. Another benchmarking study has been documenting and presenting an overview of the current state of existing technologies and innovations developed in the world covering all types of solar transportation—road (cars, buses, 2 and 3 wheelers, bicycles), rail, air, and naval—either private or public. Energy storage technologies—batteries (Li-ion, lead-acid), hydrogen, flywheels, thermal, pumped hydropower, and V2X—and solar-powered charging infrastructures such as on-grid and off-grid. The aim is to provide a reference point under which missions of ISA will be planned, and future collaborations with other international agencies will be undertaken.

14.4.4 Scaling Solar Mini-grids

The ISA Secretariat is supported by Deloitte, a global advisory firm, to develop a robust implementation plan for the Solar Mini-grids Program. The secretariat has evolved a Model Mini-Grid Policy [9], which is shared with the National Focal Points. Field visits of diplomatic missions participated by 36 member countries to PV Mini-grid plants under the 'Smart Power Rural Development' Program of Rockefeller Foundation have been undertaken. The petrol pumps, e-government kiosks, and fully solar-operated banks are expected to run on the solar mini-grid system. Demand for more than 10 GW of Solar Mini-grids has been assessed across nine countries and is growing.

14.4.5 Scaling Solar Rooftop

Upscaling of the solar rooftop is undertaken. The ISA secretariat has been working with officials of Peru and Ghana to provide technical support for the preparation of roof top projects. The ISA—Peru Support Expert Group submitted its report on 'Initiating Rooftop Solar PV in Iquitos, Peru' to the Ministry of Energy and Mines, Peru on 7th January 2019 followed by another Report on 'Integrating Rooftop; Utility-Scale PV and Mini-Grid' in Iquitos, Peru 7th February 2019. For Ghana, 'Ghana Rooftop Solar Initiative—Final Report' May 2019 was prepared by the ISA Expert group based on on-site verification and the possibility of implementing 30 MWp rooftop solar under RESCO Model[1] with key recommendations was submitted to the Ministry of Energy, Ghana. The ISA has grouped more than 1 GW of Solar Rooftop across 11 countries.

The ISA Secretariat has proposed to Embassies/Missions in India to install Rooftop solar under RESCO Model. In response, Fiji, Gambia, Ghana, Sudan, Uganda, and Zambia have given their consent. The ISA has also facilitated the installation/display of 2 kWp portable rooftop system with storage (Plug and Play type) developed by GIZ, at NISE Campus.

14.4.6 Large-Scale Solar Power Projects Under Solar Park Concept in Cluster/Groups

Development of large-scale projects under Solar Park Concept among cluster/Group of 121 Prospective Member Countries, including the Island States is a program of five years duration until the year 2024. It has a technology focus for the development of modules, associated accessories, and components. The aim is to plan and design large-scale projects, prepare techno-economic feasibility reports, and detail project reports for meeting the set standards and codes. Activities such as assessment of land, solar resource potential, and demand aggregation in clusters/groups in member countries will be undertaken under various categories to pursue the objectives of the Paris Agreement, 2015. Multiple tools and techniques, surveys, and physical remote-sensing methods will be adopted for the facilitation of technical and financial assistance to public and private entities. An action plan for developing up to 20 GW of solar parks has been launched.

14.4.7 Skill Development and Capacity Building

ISA Solar Technology and Application Resource Center (ISTAR C) supports capacity-building efforts in the ISA member countries through training. It aims to create a skilled workforce for large-scale solar energy applications and research,

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[1] The RESCO model is one of the methods of implementing rooftop solar installations. Under the RESCO model, a Renewable Energy Service Company ("**RESCO**"), (i.e., an energy service company that provides energy to consumers from renewable energy sources), develops, installs, finances, operates and owns the rooftop solar power project.

development, innovation, standardization, and testing in solar energy. ITEC training program is being held in India since 2020. A new cross country M.Tech. course, MBA course in energy management in IIT Delhi, and an undergraduate course for SIDS countries and LDCs from the 2021 academic year have been planned for capacity building of the beneficiaries in the member countries. The ISA—Indian Space Research Organization (ISRO) is developing a software application tool to enable member countries to assess their solar potential [10].

14.4.8 World Solar Technology Summit (WSTS)

ISA held its first World Solar Technology Summit (WSTS) on September 8, 2020, on a virtual platform [11]. The main objective of WSTS was to showcase to the member countries the state-of-the-art and next-generation solar technologies worldwide and to allow key decision-makers and stakeholders to share their perspectives, priorities, and strategic agenda toward a more extensive integration of solar energy. More than 26,000 participants from 149 nations participated in the virtual summit. Federation of Indian Chambers of Commerce and Industry (FICCI), India, was the convener from ISA headquarters. Dr. Michael Stanley Whittingham, Nobel Laureate in Chemistry, delivered the Keynote address in the WSTS participated by many eminent personalities working on advanced solar and disruptive technologies.

Solar technologies have made significant progress and are becoming a viable option for sustainably meeting energy needs. The Summit aimed at deliberating on recent highlights of solar technologies, cost-wise; technology-wise, technology transfers, challenges, and concerns in the field among the stakeholders—leading academic scientists, technology developers, researchers, and innovators. The main objective of WSTS was to showcase to member countries the state-of-the-art and next-generation solar disruptive technologies worldwide. A Global Leadership Task Force on Innovation has been constituted to focus on new Technologies and Innovations in the field of Solar.

14.5 ISA Special Initiatives for Member Countries

14.5.1 Financing Roadmap

A joint mission by the Multilateral Development Banks and Development Finance Institutions has been set up to develop a financing roadmap for financial resource mobilization of USD 1000 billion by 2030. The mission aims to scale up solar investments through enhanced collaborative efforts of ISA with these organizations. ISA has taken the following initiatives for resource mobilization.

(i) The Solar Risk Mitigation Initiative (SRMI) of World Bank (WB) and the Agence Francaise de Développement (AFD) was launched in COP24 to develop bankable solar programs in developing countries [12]. World Bank has committed 337 million USD Risk Mitigation Fund for 23 member countries in the off-grid sector (ROGEP) in Africa in partnership with ISA. Private sector participation is encouraged. The AFD committed to providing financing for solar projects worth 700 million Euros.
(ii) The European Investment Bank (EIB) has started working on a 60 million Euros grant project to create a concessional financial facility and risk mitigation Fund to promote off-grid applications in Africa.
(iii) The Export-Import Bank of India (EXIM Bank) has committed to providing financing for solar projects worth USD 1.4 billion.
(iv) Asian Development Bank has approved a Technical Assistance program of USD 2 million for ISA member countries in South Asia to support solar project preparations.
(v) With ISA's engagement with the private and public corporate sector through the Coalition for Sustainable Climate Action (CSCA), ten public sector organizations in India presented a cheque for 1 million USD each in the third ISA assembly in 2020.
(vi) ISA has mobilized SAARC Development Fund for technical assistance to be implemented jointly by the ISA and Asian Development Bank.

A World Solar Bank has been conceived as a financial agency that would pool resources from around the world and use them to finance the solar power projects in the member countries of ISA, with a capital size expected to be around 10 billion dollars.[2]

14.5.2 OSOWOG

This trans-national electricity grid supplying project was announced by the Prime Minister of India, Mr. Narendra Modi, on the 74th Independence Day of India. The ISA has launched, 'One Sun, One World, and One Grid' (OSOWOG), and has identified program support and action areas [13]. The vision behind the OSOWOG mantra is 'The Sun Never Sets', and it is there on some parts of the earth every 24 h. The ISA Assembly in 2018 has approved this initiative.

A two-day strategic inception workshop was held jointly by International Solar Alliance (ISA), the Ministry of New and Renewable Energy (MNRE), and the World Bank to disseminate the concept of OSOWOG. A Green Grid Initiative as a joint effort of the ISA and Climate Parliament has been launched. It is a stimulant to the member countries to emulate India's GEC and integrate it with OSOWOG. The interconnecting grid between ISA countries would provide an opportunity in terms

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[2] The bank is to be launched at the COP26, United Nations Climate Change Conference to be held in Glasgow in November 2021.

of availability of the solar electricity to countries from one region to other. The Government of Britain has endorsed OSOWOG concept in the COP24.

A three-member consortium has been formed between French state-run power utility firm Électricité de France SA (EDF), France's Application Européenne de Technologies et de Services (AETS), and India's The Energy and Resources Institute (TERI) for creating a road map for ISA's ambitious global grid. India is leading the ISA as a global climate action leader and developing itself as a Green Economy. India has enormous experience of cross-border electricity trade with its neighbors in South Asia.[3] The initiative is to be implemented expeditiously in three phases to support the clean energy transition.

Phase I—Pre-feasibility analysis' of individual Countries' assessment, Demand-Supply Scenario Projections, RE resource potential assessment, and scenario assessment for net-zero by 2050. It would aim to connect grids in West Asia, South Asia, and Southeast Asia to share solar and other renewable energy resources.

Phase II—Key points indicate the political process to choose pilot projects and the timeline for commissioning interlinks. It will aim to connect the first-phase nations with the African pool of renewable sources.

Phase III—The third phase will set up the institutional framework, including draft policy and regulatory guidelines.

A 'Sun Charter' is under preparation. All the implementation partners are expected to develop their roadmap for 2050 with intermediate targets for 2030 and 2040.

14.6 The Way Forward

The Alliance did not go into negotiations initially, but the achievement of its goals necessitates scientific diplomacy tools. Several collaborative programs are taking shape under ISA and their implementation requires close monitoring and diplomacy [14]. At the same time, tariffs for solar energy have fallen tremendously. India has demonstrated that creating a large aggregated market has driven down the prices of LEDs and solar energy. The countries are willing to accept this model, which helped in creating competition among the manufacturers. The ISA is aiming to reduce the cost of technology from specific measures such as,

- Enhancing global demand—which will result in further reduction in the prices of solar energy deployment.
- Promoting standardization—which will make the manufacturing of equipment and other hardware cheaper.
- Increasing investment in research and development—particularly in areas of efficient energy storage systems.

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[3] The Bhutan–India transmission link has a grid capacity of 1200 MW; the India–Nepal one has a capacity of 450 MW, and the India–Bangladesh link has a capacity of 1200 MW.

- Constituting an International Task Force—to structure a common risk mitigation mechanism for new solar projects.

International Solar Alliance (ISA) is a great example that encompasses a common platform for cooperation among solar-rich countries. India's initiatives to scale up, risk reduction, cost reduction, and capacity building with active participation of member states are helping to overcome the challenges and would attract foreign investors, rally investments, and facilitate collaborations, thus putting India at the center of the global clean energy transitions.

References

1. https://isolaralliance.org/
2. Shidore S, Busby JW (2019) The international solar alliance and India's search for geopolitical influence. Energy Strat Rev 26:100385. https://doi.org/10.1016/j.esr.2019.100385
3. Press release. https://isolaralliance.org/uploads/docs/3ea82509578af6cf14d32f6fab2152.pdf
4. file:///E:/C%20Drive%20Data/Downloads/Final%20Text%20of%20the%20International%20Solar%20Alliance%20(1).pdf. Accessed 18 Dec 2021
5. MNRE (2018) Press Information Bureau. https://pib.gov.in/newsite/printrelease.aspx?relid=135794
6. MEA. Media Center. https://www.mea.gov.in/bilateral-documents.htm?dtl/29605
7. https://isolaralliance.org/uploads/docs/7b959ebd678894862d83a41af3a13e.pdf
8. https://isolaralliance.org/work/solarizing-heating-cooling
9. Scaling solar mini grid. https://isolaralliance.org/work/scaling-solar-mini-grids
10. ISA annual report 2020
11. https://currentaffairs.adda247.com/isa-host-world-solar-technology-summit/
12. Bhaskar U (2021) Mint. Retrieved from https://www.livemint.com/industry/energy/isa-to-launch-world-solar-bank-at-global-climate-meet-in-nov-11613582696670.html
13. https://www.business-standard.com/article/current-affairs/one-sun-one-world-one-grid-all-you-need-to-know-about-solar-strategy-120081500417_1.html
14. Goel M (2021) Science diplomacy for South Asian countries: insights & breakthroughs. Springer Nature, p 129. ISBN 978-981-16-3024-8

Bibliography

1. Mezaa C, Lib C, Koodlurc L, Goel M, Khujamberdierve M, Mumtaz T (2013) Energy policy for landlocked countries. In: International science diplomacy workshop on “innovative energy policies for sustainable development”, Trieste
2. Goel M, Tripathi NG (2020) Climate change, covid-19 and cities: societal transformation. Soc Action 70(3):206–215
3. Goswami DY (1996) Solar thermal power technology: present status and ideas for the future. Energy Sources J 20:137–145
4. International Energy Agency (2019) India 2020 energy policy review. Retrieved from https://iea.blob.core.windows.net/assets/2571ae38-c895-430e-8b62bc19019c6807/India_2020_Energy_Policy_Review.pdf
5. Javaid A (2020) Home general knowledge current GK what is ‘one sun, one world, one grid’ (OSOWOG) policy announced by Prime Minister Modi? Jagran Josh. Retrieved from https://www.jagranjosh.com/general-knowledge/one-sun-one-world-onegrid-1598250280-1
6. Goel M (2010) Renewable energy for sustainable development in India and China. In: Asia-Africa development research centre of state council of the PRC. India Energy Forum China Mission, Beijing, 26–30 July 2010
7. https://www.nationalgeographic.org/article/power-sun/
8. myIndiamyGlory (n.d.) Rig Veda described sun’s orbit, attraction of planets 1000s of years before Copernicus. [Online]. Available at https://www.myindiamyglory.com/2021/03/10/rig-veda-described-suns-orbit-attractionof-planets-before-copernicus/
9. Sanchez L (2020) Top 10 microgrid news stories of 2020. [Online]. HOMER Microgrid News. Available at https://microgridnews.com/top-20-microgrid-news-stories-of-2020/
10. https://www.waaree.com/blog/presenting-the-future-of-pv-modules.htm
11. Solarcellcentral.com (n.d.) Early solar history. [Online]. Available at http://solarcellcentral.com/history_page.html
12. Solar ponds—India (2015) [Online]. Available at http://energyprofessionalsymposium.com/?p=7976
13. https://www.irena.org/publications/2019/Nov/Future-of-Solar-Photovoltaic
14. Phadnis H, Kanitkar D (Indo-German Chamber of Commerce, AHK) (2020) Solar heat for industry, India. Solar Payback
15. Henning HM, Glaser H. Solar assisted adsorption system for a laboratory of the University Freiburg. http://www.bine.info/pdf/infoplus/uniklaircontec.pdf
16. Goel M, Tripathi N (2011) ABC of green buildings responsible education, climate change research society. ISBN 978 81-022686-0-6

M. Goel et al., *Solar Energy*, Green Energy and Technology,
https://doi.org/10.1007/978-981-19-2099-8

17. The Economic Times (2019) Solar rooftops: everything you need to know before installing a solar rooftop system
18. Goel M (2015) Innovative solar policies in India for sustainable development. In: CAS-TWAS symposium on green technology for sustainable development (2015 Green Tech), Institute of Process Engineering, Beijing, 22–24 July 2015
19. Ministry of Statistics and Programme Implementation, Govt. of India (2015) Energy statistics 2015