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THE SUN AND SOLAR ENERGY: IGNITING THE FUTURE



PROF T HARINARAYANA

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Month & Year: April, 2025

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Preface



The ancient inhabitants of the Indian subcontinent correctly recognized the Sun as the ultimate source of sustenance for all life on Earth and revered it as the Sun God. Indeed, the Sun is central to our very existence. Its immense mass exerts a gravitational force that keeps Earth in a stable orbit; without it, our planet would drift aimlessly into the cold, dark void of space. Sunlight drives the process of photosynthesis, which leads to the creation of biomass, including the food that sustains life. This process supports herbivores (such as cows, sheep, goats etc), which in turn are consumed by carnivores (like tigers, lions, hyenas etc). Omnivores, including humans, derive nourishment from both plants and animals. The Sun, therefore, is undeniably the primary source of all nourishment and life.

In addition to providing spatial stability and nourishment, the Sun also provides warmth, making our planet habitable. It is no wonder that many ancient civilizations worshipped the Sun. To Hindus, it is "Surya" or "Aditya"; for the Egyptians, it was "Ra"; the Romans called it "Sol"; the Persians, "Mithra"; and the Chinese, "Xihe." Some interpret the Sanskrit phrases "saptāśva rathamārūḍham" (charioteer of seven horses) and "śvēta padmadharam" (holder of the white lotus) from "Suryāshtam" as references to the seven colours of white light. However, in this remarkable compilation "The Sun and Solar Energy: Igniting the Future", Dr. T. Harinarayana offers a different perspective. He relates these seven to the Sun's electromagnetic spectrum, which includes Gamma rays, X-rays, Ultraviolet rays, Visible light, Infrared radiation, Microwaves, and Radio waves.

India, blessed with abundant sunlight for most of the year, has the potential to harness this clean and sustainable energy source. Although challenges remain, such as the cost and availability of silicon-based solar panels, and managing additional thermal loads, innovative photovoltaic systems are being developed to provide more cost-effective and efficient energy solutions. Moreover, the extra thermal load can be converted into usable energy, mitigating any associated concerns.

Dr. Harinaryana's comprehensive analysis of solar power underscores its significance as a sustainable alternative to fossil fuels, offering humanity a viable path to combat global warming. This concise yet impactful booklet truly embodies the 'power' to shape a cleaner and greener future.

Dr. Ch. Mohan Rao
Chairman-Scientific Advisory Council, ASTC

* CSIR-Distinguished Scientist & Former Director CCMB, Hyderabad

Editor's Vision



The Academy of Science, Technology, and Communication (ASTC) initiated publishing a series of booklets titled "ASTC COMMUNICATIONS" covering various contemporary scientific topics with a view to disseminate the information to a wider section of people. This booklet in the series "The Sun and Solar Energy: Igniting the Future" was authored by Prof. T Harinarayana, Former Chief Scientist of CSIR-NGRI, Hyderabad who has rich experience in all types of renewable energy, more specifically to Solar and Geothermal Energy. Prof Harinarayana's several research findings on solar energy were first of its kind in India and also implemented successfully in the form of National Projects.

With his extraordinary expertise in this field, Prof. Harinarayana narrated an interesting story about Sun and Solar Energy in a very popular way describing the Sun God with His 7 horses symbolically representing seven rays emitting into the space. He described Sun as the centre of energy for all the living beings and listed out several uses of solar energy and its applications in all directions of life with proven examples. The data presented in this booklet are mostly from Prof Harinarayana's personal publications and also from the recent open scientific literature. He concluded that the future of solar energy lies not just in technological advancements but also in the collective will to harness this abundant resource for a cleaner and more sustainable world.

ASTC will continue to publish "ASTC Communications" on diverse scientific topics at regular intervals for the benefit of all. We welcome your feedback and suggestions on these publications.

Dr. R.B.N. Prasad
Chief Editor

Former Chief Scientist & Head, Centre for Lipid Research, CSIR-Indian Institute of Chemical Technology, Hyderabad,
Former President, Oil Technologists' Society of India.

President's Voice



I am delighted to see the publication of "The Sun and Solar Energy: Igniting the Future", a comprehensive work highlighting the immense potential of solar power in driving a sustainable future. The Sun, an enduring source of energy, has sustained life for millennia. Today, harnessing its vast potential is both an environmental imperative and an economic opportunity.

India, endowed with abundant solar resources, has emerged as a global leader in renewable energy adoption. Initiatives such as the National Solar Mission ,have significantly expanded capacity-from large-scale solar parks in Rajasthan and Gujarat to widespread rooftop installations. These achievements reflect the commitment of our scientists, engineers, and policymakers, whose innovations continue to advance renewable energy technologies.

Our vision extends beyond national borders through the One Sun, One World, One Grid (OSOWOG) initiative, championed by the Hon'ble Prime Minister. This ambitious program seeks to create a transnational energy network, promoting equitable access to clean energy worldwide. Through this, India reaffirms its commitment to sustainability and energy security.

This publication arrives at a pivotal moment when awareness of clean energy must reach all sectors of society. I commend the author, Dr. T. Harinarayana, an expert in energy, for compiling valuable insights that will benefit students, professionals, and policymakers alike. ASTC extends its deep gratitude to its Scientific Advisory Council for their academic guidance, and especially to Chief Editor Dr. R. B. N. Prasad for his unwavering commitment in making ASTC Communications accessible through a clear and reader-friendly style.

May this book inspire innovation and strengthen our collective resolve for a sustainable future!

Dr. C. Manikyamba
President, ASTC

*Academy for Science, Technology and Communication (ASTC), Hyderabad

From Secretary's Desk

India's abundant sunshine presents a unique opportunity to lead the world in solar energy. More than just a technological advancement, solar energy represents a transformative movement toward a cleaner, self-reliant future powering homes, industries, and agriculture while safeguarding the environment. Today, thanks to the relentless efforts of our scientists and engineers, solar power is more efficient, accessible, and affordable than ever before.

With strong collaboration between government, industry, and citizens, India's solar sector is experiencing unprecedented growth. Breakthroughs in energy storage technology now ensure uninterrupted, round-the-clock power, making solar a reliable and sustainable choice. Embracing this energy revolution not only reduces costs but also paves the way for a resilient, greener future for generations to come.

The Academy for Science, Technology, and Communication remains committed to bridging the gap between scientific advancements and public understanding. As part of this mission, ASTC Communications publishes insightful booklets that translate complex scientific concepts into accessible knowledge.

With great pride, ASTC presents "The Sun and Solar Energy: Igniting the Future" a comprehensive volume that delves into the science, applications, and innovations shaping the future of solar power. This timely publication highlights India's remarkable progress in solar energy, emerging technologies, and the path forward in clean energy development.

We extend our deepest gratitude to Dr. T. Harinarayana, the esteemed author of this book, for his invaluable contribution and dedication. As a former Chief Scientist at NGRI and former Director of GERMI, Dr. Harinarayana brings a wealth of expertise across various energy domains, with a special focus on solar and geothermal energy. ASTC also expresses sincere appreciation to Dr. R.B.N. Prasad, Chief Editor, for his meticulous refinement of the work. Special thanks are due to the Chairmen and members of the Scientific Advisory Council for their invaluable guidance in shaping this publication.

This book serves as a vital resource for students, professionals, and policymakers, inspiring research, innovation, and decisive action in the field of solar energy.

Let the light of knowledge and the power of the sun guide us towards a brighter tomorrow for everyone.

Sri. C.L. Narasimha Rao
Secretary, ASTC

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The Sun and Solar Energy: Igniting the Future

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Part-I The SUN and Rays

1.1 Introduction

The Sun is the heart of our solar system, a massive, glowing ball of hot plasma that generates energy through nuclear fusion at its core. Composed primarily of hydrogen and helium, the Sun's immense gravitational pull holds the solar system together, anchoring planets, asteroids, comets, and countless other objects in orbit around it. With a diameter of about 1.4 million kilometres, it is 109 times wider than Earth and contains 99.86% of the solar system's total mass. The energy produced in the Sun's core is released as light and heat, which takes about eight minutes to reach Earth, providing the necessary warmth and energy for life to thrive.

The Sun's influence extends far beyond providing light and warmth; it also governs the seasons, climate, and weather patterns on Earth. The solar wind, a stream of charged particles emitted by the Sun, interacts with Earth's magnetic field, creating phenomena such as auroras. The Sun undergoes 11-year solar cycle, during which its magnetic activity fluctuates, leading to variations in solar output and the appearance of sunspots. As a middle-aged star in the main sequence of its life, the Sun has been burning for about 4.6 billion years and is expected to continue doing so for another 5 billion years before evolving into a red giant and eventually ending its life as a white dwarf. The Sun emits 7 primary types of rays. (Fig.1.1). They are briefly described in the following:

1.2 Types of Solar Rays:

Gamma Rays: These rays have the highest energy in the electromagnetic spectrum. They are mostly absorbed by the Earth's atmosphere, preventing them from reaching the surface.

X-rays: These rays have high energy and short wavelengths. Like gamma rays, they are mostly absorbed by the atmosphere, with only a small amount reaching the Earth.

Ultraviolet (UV) Rays: UV rays are classified into three types: UVA- the longest wavelengths, UVB- medium wavelengths and UVC- shortest wavelengths and are the most dangerous, but they are entirely absorbed by the Earth's atmosphere.

Visible Light: This is the portion of the spectrum visible to the human eye, ranging from violet (shorter wavelengths) to red (longer wavelengths).

Infrared (IR) Radiation: They have longer wavelengths than visible light and are perceived as heat. Infrared radiation is divided into 3 types. Near-infrared (NIR): Closest to visible light, mid-infrared (MIR) and Far-infrared (FIR): the longest wavelengths within the infrared spectrum.

Microwaves: These rays have even longer wavelengths than infrared rays and are utilized in communication technologies, such as mobile phones and Wi-Fi.

Radio Waves: These rays have the longest wavelengths in the electromagnetic spectrum and are used for radio, television, and other communication methods.

The visible Sunlight can be harnessed to generate various types of energy through different technologies and processes. Here are the primary methods:

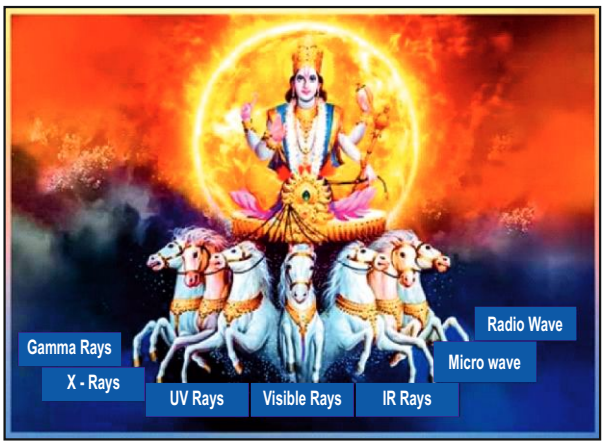


Fig. 1.1 Schematic diagram showing the Sun God with his 7 horses symbolically representing 7 Rays emitting into the space.

1.3 Solar Photovoltaic (PV) System:

Solar PV systems convert sunlight directly into electricity using semiconductor materials, usually silicon. These systems are used in solar panels for homes, businesses, and solar farms. The advantages include scalability, low operational costs, and being a renewable, clean energy source. PV systems can be installed on rooftops or open land.

1.4 Concentrated Solar Power (CSP) Systems:

CSP systems use mirrors or lenses to concentrate sunlight onto a small area, converting it into heat. This heat is then used to produce steam, driving a turbine connected to an electric generator. There are different types of CSP technologies. Parabolic Trough Systems: It uses curved, mirrored troughs to focus sunlight onto a receiver pipe. Solar Power Towers: It uses a large field of mirrors (heliostats) to focus sunlight onto a receiver atop a central tower. Dish/Engine Systems: It is a mirrored dish to focus sunlight onto a receiver at the dish's focal point. CSP is mainly used in utility-scale power plants, with the advantage of incorporating thermal energy storage to provide power even when the sun isn't shining.

1.5 Solar Water Heating system:

It uses sunlight to heat water for domestic, commercial, or industrial use. There are two main types: Active Systems: Uses pump to circulate water or heat-transfer fluid through solar collectors. Passive Systems: It relies on natural circulation and do not require pumps. These systems are commonly used for residential water heating, pool heating, and space heating, offering benefits like reduced energy bills, environmental friendliness, and relatively low costs.

1.6 Solar Thermal Energy for Industrial Processes:

Similar to solar water heating but designed for industrial applications, This method uses solar collectors to generate high-temperature heat for processes like pasteurization, drying, sterilization, and chemical reactions. It is applied in industries like food processing, textiles, and chemical production. The advantages include reducing reliance on fossil fuels, cutting greenhouse gas emissions, and leading to cost savings.

1.7 Solar Architecture:

This approach incorporates passive solar design to reduce energy consumption for heating, cooling, and lighting in buildings. Techniques include- a) passive Solar Heating: the design features that capture and store solar energy to heat buildings, b) the day lighting: using natural sunlight to illuminate indoor spaces, c) natural ventilation Systems: enhancing airflow with solar energy etc. Solar architecture is thus used in both residential and commercial buildings, improving energy efficiency, reducing heating and cooling costs, and increasing indoor comfort.

1.8 Solar Fuel Production:

Solar energy can also be used to produce fuels, such as hydrogen, through processes like solar water splitting (photoelectrochemical cells) or solar thermochemical reactions. Applications include hydrogen production for fuel cells and synthetic fuels for transportation. The main advantages are the production of clean fuels that can be stored and used when needed, thus reducing the dependence on fossil fuels.

1.9 Solar Photovoltaic and Solar Thermal (PVT) Hybrid Systems:

This technology combines photovoltaic and solar thermal methods to generate both electricity and heat from a single system. It is mainly used in residential and commercial buildings where both electricity and hot water are needed. The system offers higher efficiency by utilizing the heat generated by PV panels, which would otherwise be wasted. More details on all aspects of the Sun can be seen from well refereed books (Hughes, 2005; Berman, 2011, Flamini 2014).

Part-II Solar Energy Technology and Its Applications

2.1 Introduction:

It is well known that in this universe of Solar system, Sun is the centre of energy for all living beings. As discussed in Part-I, different rays are being emitted into the space. However, all the Solar rays are not reaching the Earth. Most prominent among the rays reaching the Earth surface known to us are UV, Visible and Infrared, together we called them as Solar radiation. Its spectrum has a large wavelength from nearly 200 nm to as much as 2500 nm. In Fig. 2.1 one can see UV range, visible and infrared with spectral irradiation varying from near zero to 2.5 $W/m^2/nm$).

2.2 About Solar Energy:

Tapping of Solar power can be done in various ways, locations and environments. Here are some key places where solar power can be effectively harnessed. For example,

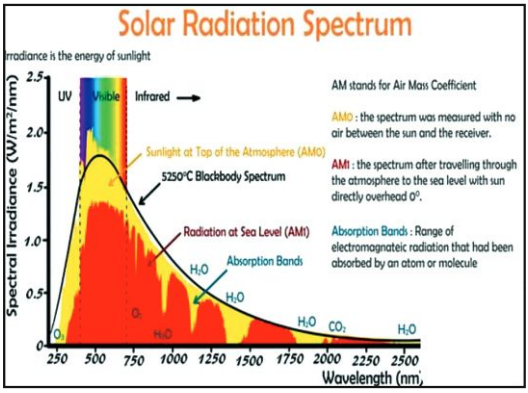


Fig. 2.1 Solar Radiation Spectrum Showing Spectral Irradiance for Different Wavelengths of Rays

a)Rooftops: Residential rooftops, Commercial and industrial buildings, Schools, hospitals, and government buildings (Fig.2.2), **b) Open Fields:** Solar farms or solar parks, **c) Agricultural fields:** using Agri-solar systems (combining solar panels with crop cultivation, **d) Water Bodies:** Floating solar panels on lakes, reservoirs, and other water bodies, Canal-top solar installations, **e) Highways and Infrastructure:** Solar panels along highways, Solar installations as noise barriers and other infrastructure, **f) Urban Areas:** Solar installations on parking lots, Solar trees and streetlights, **g) Remote Areas:** Off-grid solar systems for remote villages and communities, Solar installations for remote industrial operations **h)Hybrid Systems:** Combining solar power with other renewable energy sources like wind and hydro etc. **Solar Energy in Agriculture** is very useful in Solar-powered irrigation systems, Solar dryers and cold storage for agricultural produce. Recent **Innovative Applications** include-Solar panels integrated into building materials, Building Integrated Photovoltaics, BIPV, Solar windows and facades.



Fig.2.2 Different ways of tapping solar energy

2.3 How to Tap Solar Energy:

There are a variety of technologies available today to convert sunlight, that is, the Sun's energy into usable electric power for the mankind. Following are the developed technologies.

Photovoltaic technology: As discussed before, this technology converts energy from the Sun directly into electricity with the help of photovoltaic or Solar cells. Solar cells are usually made of Silicon- a semi conducting material such that when sunlight falls on them, electrons are knocked off, and the flow of this electrons create electricity. Photovoltaic cells in their adoption for use are usually made into flat plates to face the Sun so as to tap as much sunlight as possible hence the name flat-plate Photovoltaic. The most popular photovoltaic technology is the flat-plate photovoltaic panels commonly known as solar panels which are placed mostly on waste lands, rooftops of home buildings to produce electricity. Solar panels are made up of several photovoltaic cells and a number of solar panels put together is called Photovoltaic arrays. Solar cells are also used in small items like watches and calculators.

Concentrating Power technology: It is important to note that the Photovoltaic technology deals with sunlight, while concentrating power technology deals with the Sun's heat. Concentrating power technology harnesses the Sun's energy by concentrating the heat from the Sun with the help of mirrors to a point, where it is then used as a heat source to power steam engines that produce electricity. There are mainly three types of this technology, distinguished by the types of mirrors used and their modes of operation. (Fig.2.3).

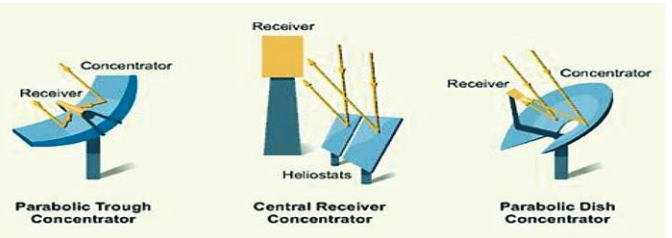


Fig.2.3 Parabolic Trough, Central Receiver, Parabolic Dish

2.4 Parabolic-trough Systems:

This system (Fig.2.4) simply uses several curved (U shaped) mirrors which are long and rectangular. The mirrors are faced toward the Sun such that they focus sunlight on to a pipe which runs down to the centre of the trough and then heats the oil that flows through the pipe. The heated flowing oil then boils water in a steam generator to produce electricity.

Dish/engine systems: The system makes use of a dish-shaped mirror which has a receiver. The mirror is placed facing the sun and it collects the sun's heat and concentrates it to the receiver. The fluid that flows within the engine is heated up through the heat taken by the receiver, which then turns the turbine in the system to generate electricity.

Tower power systems: In this case, a large field of mirrors are used to concentrate sunlight to the top of a tower which produces heat on the receiver. As the receiver receives the heat, it automatically heats up the molten salt inside. It then powers a steam generator that produces electricity.



Fig.2.4 Parabolic-trough Systems Dish/engine Systems Tower Power Systems

2.5 Water Heating Technology

This technology simply uses the Sun's heat to heat the water for homes and offices. This technology usually makes use of flat-plate collectors which are mounted on the roof of buildings. The flat-plate collectors are rectangular boxes that are flat and thin. They have transparent glass on them that allows sunlight to pass through into the box so as to heat the black-coated tubes (the tubes are coated with black paint so that they would absorb heat maximally)

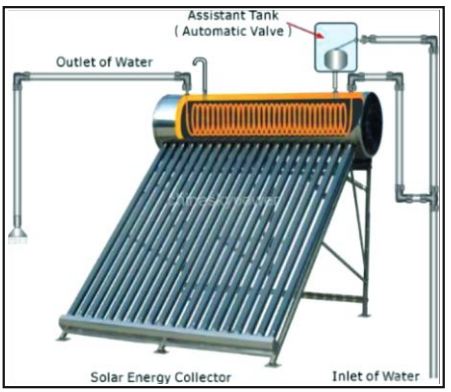


Fig.2.5 Shows Typical water heating systems at Home.

inside which water flows. As the Sun becomes more intense, the water flowing through the tubes (Fig.2.5) get hot and are stored in a tank which is well insulated so that the hotness of the water is retained for a long time.

2.6 Sun's Heat for Space Heating and Lighting in Homes:



Fig.2.6 A Building Designed to Enhance Passive Heating Technology

This technology makes use of special building designs to make best use of the Sun's heat for space heating. The buildings are made in a way that they absorb and retain the maximum heat possible. Some ways of doing this is making the windows of the building face south because the south side of a building always receives the most sunlight, and also making the floor and walls of the building with materials that absorb heat. Apart from space heating, most of such specifically designed buildings also enjoy day-lighting such that the interior of the room is well lit and there will be no need for electricity (Fig.2.6).

2.7 Building Integrated Solar Panels:

Here similar to Roof top, Solar the panels are fixed on all sides of the building - one roof top and 3 or 4 sides of the building as per the shade analysis with respect to its location. This is very economical way of generating power as the panel cost has come down drastically in recent years. This type of buildings are upcoming as this also acts like a decorative glass. As an example, one building is presently generating power economically at Visakhapatnam, A.P., India as can be seen in Fig.2.7. Advantage of this type is two fold – one, generation of solar power and two, reduction of direct heat from the Sun and reducing the usage of cooling systems.

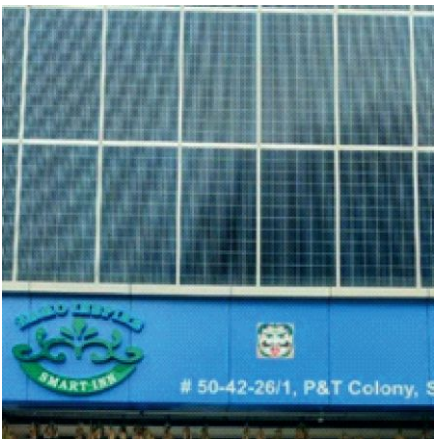


Fig. 2.7

2.8 Process Heat Technology

This technology is used in large industrial buildings for space heating and cooling. The use of special materials to the specific building designs are used to achieve effective heat. The technology can also be designed to provide hot water to be used on a large scale. Fig. 2.8 shows an industrial building with heating technology. More details on all aspects of Solar energy utilization and applications can be seen from Sayigh, 2012; Garg, 2012; Sampaio et al., 2017.

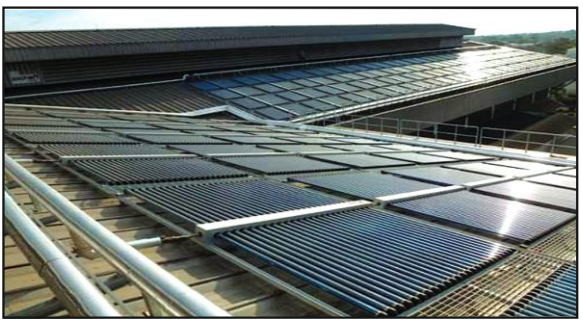


Fig. 2.8

Part-III Recent Research Studies on Solar Energy with Case Studies

3.1 Selection of Optimal Location, an Example from Gujarat:

It is crucial to determine the optimal location before installing a power plant, taking into account various factors. This study focuses on evaluating the geographical, environmental, and economic criteria of the western part of Gujarat, India, which influence the deployment of solar energy as a distributed generation source. The authors have developed an analytic framework using Geographical Information System (GIS) technology (Taye et al., 2013). This framework considers various parameters, including water bodies, agricultural land, forest cover, natural reserves, and wetlands. Additionally, fuzzy logic is applied to evaluate these parameters, helping to identify the best possible sites based on overall suitability. In figure 3.1 Overall Performance index (OPI) is presented which satisfies both environmental objectives and economic feasibility criteria. Circles shown in the figure are the best optimal locations for Solar installations. Such studies can be done in all the states.

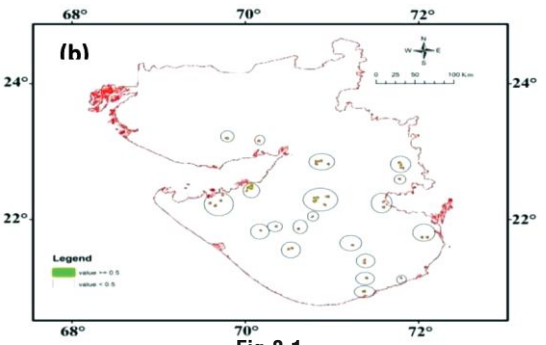


Fig.3.1

3.2 Two layer Solar for Enhancement of Energy at the Same Location:

This research study presents an analysis of near-shade effects using single and two-layer solar panels, modeled for a limited area. The study examined energy generation from a solar panel system on December 20, using a sample area of 756 square meters. The results show that a single-layer solar panel system generated 252 kWh/day, whereas the energy output increased to nearly 445 kWh/day when two layers of solar panels, separated by few meters were used in the same area. This represents an

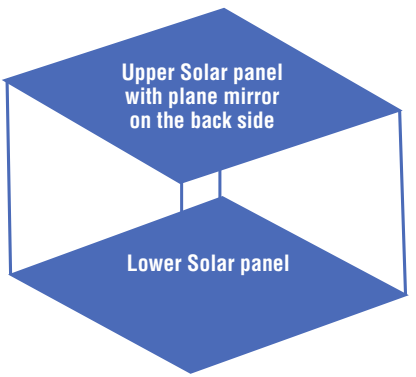


Fig.3.2

increase of over 70% in energy output due to diffused light and also direct sunlight with an angle. The output varies depending on the distance between the two layers of photovoltaic panels. Given the high cost of land in urban areas, this study is particularly significant. The results, which focus on a two-layer PV system with opaque modules as solar energy collectors, are especially applicable to rooftops of houses or small-scale plants. The modeling results are limited to small dimensions but can be extended to an n-layer solar PV panel system of any size. Designing the optimal number of layers should be based on the site location's specific foundations and an analysis of the associated costs. In Fig. 3.2, schematic diagram is shown with two mono-facial Solar panels one above the other.

3.3 Use of Agriculture lands to Generate Solar Power:

This research is based on the energy generation to reach large population. Indian farmers, who have faced challenges without the availability of electrical power, can potentially benefit from integrating solar PV technology into their agricultural practices (Harinarayana and Vasavi, 2014). The present study proposes the use of fertile and cultivated land for solar power generation by installing solar panels on elevated structures, approximately 5 meters above the ground. This approach creates shade on the crops below. The study systematically examines the impact of this shading on the crops through modelling studies, exploring different solar panel design configurations. The goal is to allow crops or plants beneath the solar panels to grow without any reduction in yield. The present idea, if implemented properly, our farmer community will be benefited for his cultivation and also help us to reach our goal of energy security. Another incentive to the farmer is that he can earn by lending his land for power generation. Thus it is a win-win situation for both the farmer and the power industry developer. In figre.3.3, the concept diagram is shown with Solar panels over farmer's agriculture land that helps him to earn double income – one from farming and from selling power to the Government.



Fig.3.3

3.4 Assessment of Solar PV Energy

Promoting solar energy involves identifying regions with high potential for power generation. Solar energy is widely recognized as a highly sought-after energy source for the last 2 decades. While previous studies have created solar energy

potential maps based on solar irradiation, this research focuses directly on solar energy generation, taking into account on various factors. It demonstrates that solar energy generation depends not only on just solar radiation, but on other elements like ambient temperature, wind velocity, weather conditions, and topography also play significant role. The study identifies areas with high and low solar energy potential in India by analyzing solar energy parameters at each grid point (1˚ × 1˚). For a more detailed analysis, data points were refined to 0.25˚ × 0.25˚ , Andhra Pradesh, and Telangana, resulting in a more comprehensive location assessment. The findings show that annual solar energy generation in India ranges from 510,000 KWH to 800,000 KWH per acre. (Fig.3.4a). The lowest energy generation is observed in eastern Arunachal Pradesh and Assam, while the highest in eastern Jammu & Kashmir and Uttarakhand (Harinarayana and Kashyap, 2014; Gajjar et al., 2015).

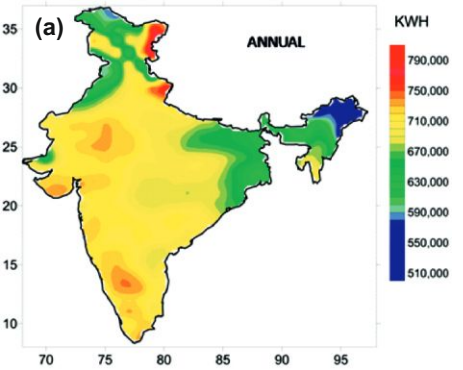


Fig.3.4a Annual solar energy generation potential map for India estimated. Blue colour shows the low energy generation and Red indicates the high energy generation as shown in the Index.

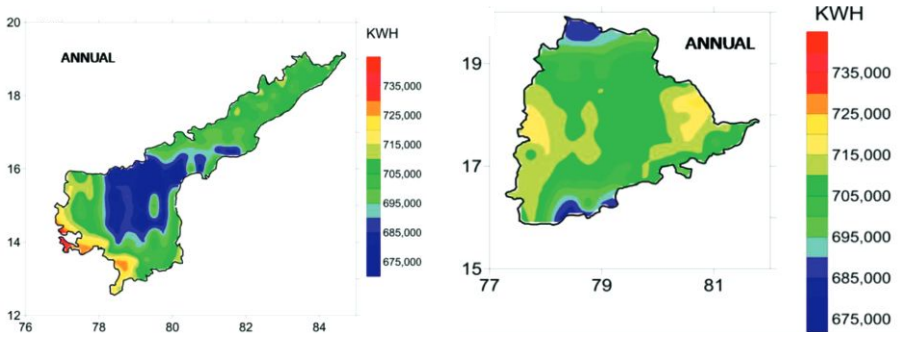


Fig 3.4b Annual solar energy generation map for Andhra Pradesh and Telangana states

In brief, the present research study has been carried out with a focused attention directly on solar energy generation considering various parameters, such as ambient temperature, wind velocity and also other parameters like weather and topographic conditions.

3.5 Assessment of Solar Thermal Energy

As we know, solar PV is well-studied, but Solar thermal installations, particularly concerning energy estimation and performance analysis, are less explored. To

estimate the potential of Concentrated Solar Power (CSP) plants, we simulated a power plant based on a slightly modified 1 MW CSP plant design installed in Gurgaon using Parabolic Trough Collector (PTC) technology. Our model is validated at 18 different solar power plants worldwide by adjusting parameters for plant capacity without major design changes. The deviation between our results and the expected energy generation ranged from 0.4% to 13.7%, with an average deviation of 6.8%. With deviations under 10% compared to actual generation, we extended the modelling studies to cover the entire nation. Our analysis for each grid station at 0.25˚ × 0.25˚ intervals shows that the potential annual output for a 1 MWe solar thermal power plant ranges from 900 to 2700 Mwh (Fig.3.5).

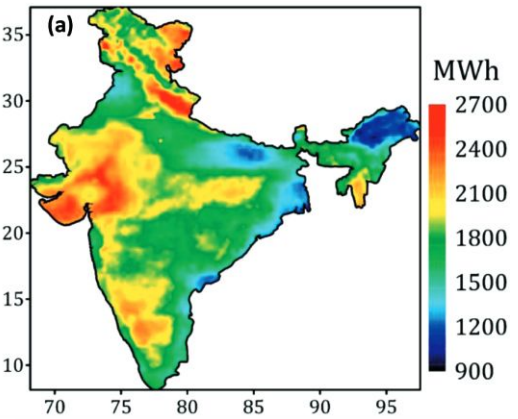


Fig.3.5. Annual solar thermal energy potential map of India per MW

These maps provide a comprehensive solar thermal atlas for India, although further improvements can be made with updated information and data (Bhutka et al., 2016).

3.6 Use of National Highways to Generate Solar Energy

It is known that generating energy with solar photovoltaics typically requires a large land area. Given the rising cost of land, it's essential to use available space efficiently. This study investigates the potential of utilizing the space above national highways by constructing roof structures to install solar panels. This approach avoids additional land costs and enhances energy efficiency by improving vehicle movement and reducing air conditioning needs. It also lowers road repair costs and extends tire life due to shading (Sharma and Harinarayana, 2013).

Our modeling shows that single-layer solar panels on the Ahmedabad-Rajkot highway could produce 104 MW of electricity, equivalent to 163 GWh annually, while the Ahmedabad-Vadodara highway could generate 61 MW, or 96 GWh annually. With double-layer panels, these figures rise to 229 GWh and 140 GWh, respectively (Fig.3.6). Implementing this concept across India could significantly boost power generation, potentially producing several gigawatts of electricity. Additionally, it would offer benefits such as longer road life, job creation, and

reduced CO2 emissions. This concept proposed earlier, is now being accepted by National Highway authority of India – NHAI during 2021.

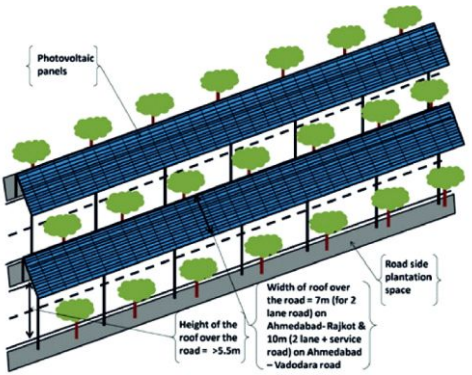


Fig.3.6. Schemaric diagram having a new compact of installation of solar panels on national highways

3.7 Innovative Carbon Research for Solar Energy

Several scientists are exploring how carbon can be used to capture sunlight, aiming to replace more expensive and toxic materials found in traditional technologies. GERMI, PDPU, and CSIR-Institute of Minerals and Materials Technology in Bhuvaneswar have conducted research on two key carbon nanomaterials such as Graphene and Carbon Nanotubes, along with their polymer composites (Fig.3.7). Their work has demonstrated both theoretically and experimentally that these materials can effectively serve as transparent and current-spreading electrodes in thin-film solar cells. Graphene, a new form of carbon with a two-dimensional planar structure, is one of the materials being investigated. This research offers the potential to develop carbon-based solar cells for industrial manufacturing. For more details, refer to the publication by Behura et al., 2014 and Harinarayana (2015).

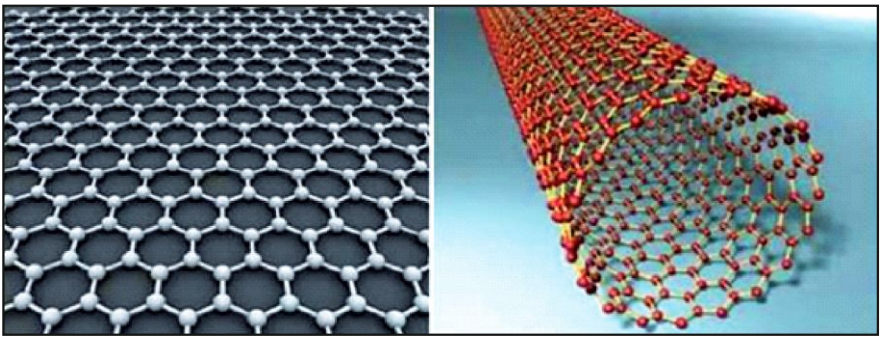


Fig.3.7. Single layer Graphene (left) and Single walled Carbon Nanotube (Right)

3.8 Dissemination of Renewable Energy Data for the Society through APPS

Mobile phone technology and the Internet have revolutionized information technology worldwide. In this context, it is crucial to use these technologies wisely to benefit the society and improve quality of life. A significant amount of data from various modeling studies have been compiled and organized to facilitate further advancements in renewable energy generation. For instance, comprehensive data on Solar PV generation across different states are available from past research (Harinarayana and Jaya Kashyap, 2014). Similarly, data on Solar thermal energy for power generation can be found in previous studies (Bhutka et al., 2016). Wind energy potential across regions in India is also documented in research conducted by the Gujarat Energy Research and Management team (Tank et al., 2016). The following section outlines the procedure for obtaining digital data on Solar PV, Solar thermal, and Wind energy potential, with a particular focus on Solar PV as an example. The solar PV App can be downloaded using the following link

https://drive.google.com/file/d/1nkLTUKu1k5S18zur-hJ4rmZmp0_VW3VX/view?usp=sharing

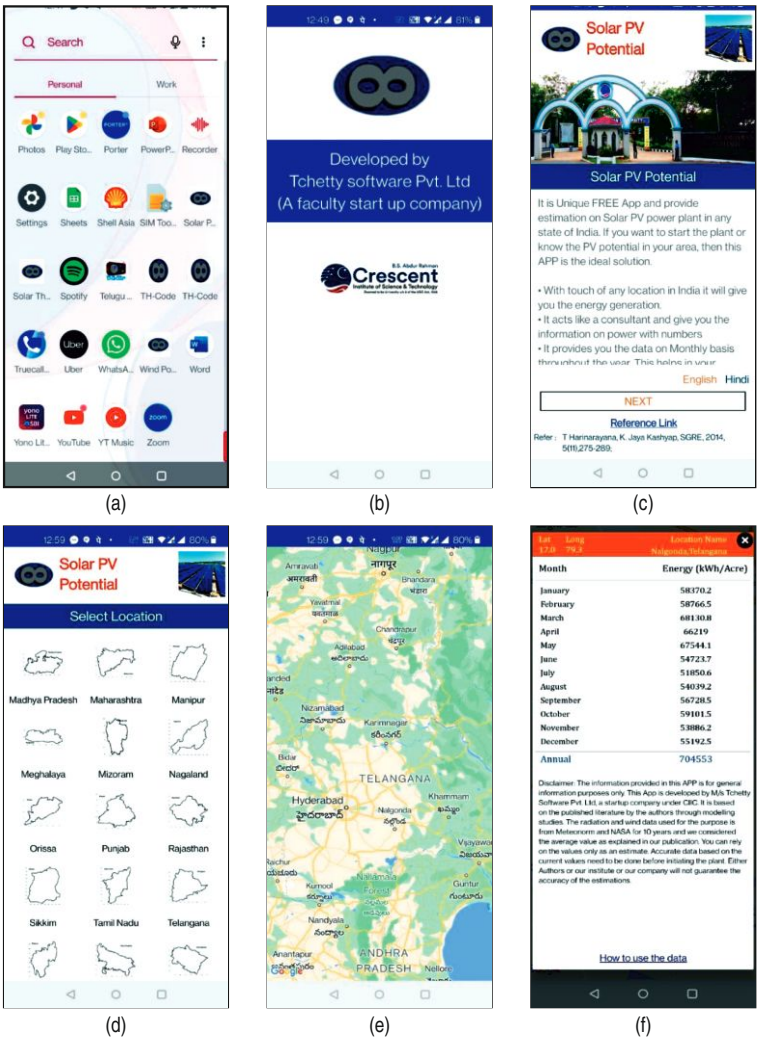
The Solar thermal energy potential data can be obtained using the following link.

https://drive.google.com/file/d/1mZe4TVrH2RT3Hnqb7Unc_k0s3VfPwS_A/view?usp=sharing. Similarly, Wind energy potential digital values can be derived using the following link..

https://drive.google.com/file/d/1nPA8QxopVTdaGcD6A8VtNSSz3NTTcF3d/view?usp=sharing All the three APPs are similar in nature in operation. Accordingly, in the following the use of these apps are explained with one App as an example and related screenshots are provided. It may be noted that as of now these three apps are freely downloadable from the above links for Android phone. IOS platform is also possible. It is now being developed and the work is under progress. After installation of the APPs the Android mobile phone screen should display the APPS as shown below (See Fig.3.8 a-f):

3.9 Hybrid Energy using Solar and Geothermal

It is well established that saving one unit of electrical energy is more beneficial than producing more than two units due to transmission losses and associated costs. One way to reduce power consumption is by using energy-efficient systems. This study analyzes air conditioning systems and proposes an innovative approach using the natural low temperatures of shallow subsurface geothermal cooling (Shahare and Harinarayana, 2015). Our study demonstrates the effective use of heat exchangers through computations, modeling, and laboratory experiments.



(a) (b) (c)

(d) (e) (f)

3.8 (a): Screen Shot showing 3 Apps. **(b, c)** Home Page after Opening the APP, **(d)** Display of Different States after Going the Next Page, **(e)** Display of Telangana Region, **(f)** Digital Data at Nalgonda Region.

We suggest geothermal cooling for 10 months of the year and a solar hot water system for the 2 months of winter (Fig.3.9). This approach can reduce room temperatures from 35°C-40°C to 26°C with minimal electricity use. Conversely, it can increase winter room temperatures from 13°C to 27°C using solar-heated water.

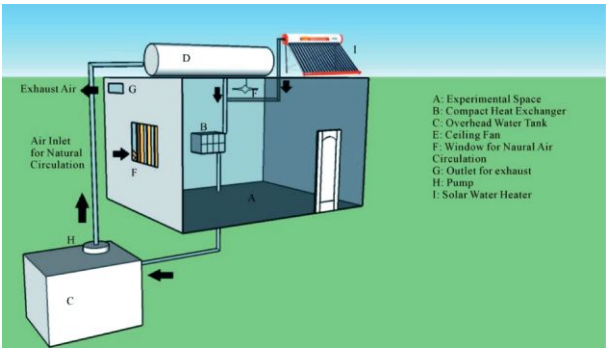
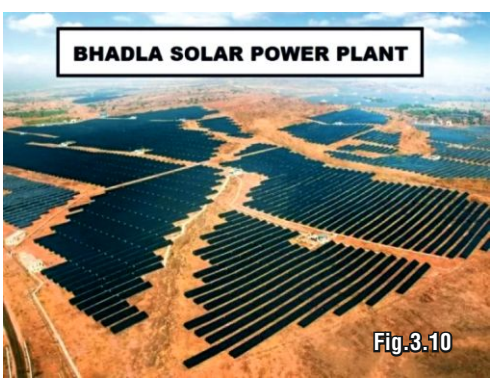


Fig.3.9. Schematic diagram showing the concept used in the present study. Here underground cooled water is pumped to the overhead tank.

Our key finding is that underground water remains nearly at a constant temperature of 26°C despite varying ambient temperatures, making the earth-water heat exchanger suitable for cooling. Our modeling and experimental results show significant temperature reductions at the heat exchanger outlet compared to the ambient temperature. Unlike Air-Earth tube systems, our model maintains air quality by using water as the heat transport medium, avoiding issues with increased moisture content in traditional air-cooling systems. Power consumption is significantly lower with our system. This approach not only supports the "Make in India" initiative but also has potential for job creation. The details of this concept have been filed for a patent (application No. 4574/MUM/2015).

3.10 Grid-Connected Solar and Solar Parks



India is one of the global leaders in grid-connected solar power, with an installed solar capacity of over 70 GW as of 2024. Government of India has launched the Solar Parks Scheme in 2014 to facilitate large-scale solar power generation. Grid-connected solar power plants supply electricity directly to the national grid, reducing dependence on fossil fuels and enhancing energy security. States like Rajasthan, Gujarat, Karnataka, and Andhra Pradesh host some of the largest solar parks in India due to their high solar irradiance. Bhadla Solar Park in Rajasthan (Fig. 3.10), with a capacity of 2,245 MW, is the world's largest solar park

and a key contributor to India's renewable energy targets. Solar parks provide infrastructure support, such as land acquisition and grid connectivity, to developers, facilitating faster deployment of large-scale solar projects.

3.11 Hybrid Solar-wind, Floating Solar and Roof Top Wind Projects

These are emerging trends in India's grid-connected renewable energy sector, optimizing land and water resources. Floating solar power plants are gaining popularity in India as they utilize water bodies like reservoirs, lakes, and canals, reducing land constraints for solar installations. The largest floating solar plant in India (Fi.3.11a) is the 100 MW project at Ramagundam, Telangana, commissioned by NTPC, contributing to clean energy generation. Floating solar panels help in reducing water evaporation and improving panel efficiency due to the cooling effect of water. Rooftop wind energy in India (Fig. 3.11b) is still in a nascent stage, with small-scale vertical-axis wind turbines being tested for urban and industrial applications. Despite its potential, challenges such as low wind speeds in urban areas, cost-effectiveness, and integration with existing power infrastructure need to be addressed for widespread adoption of rooftop wind energy in India. Hybrid renewable energy systems combining wind and solar power (Fig. 3.11c) are being explored to enhance energy generation.



Fig.3.11a



Fig.3.11b



Fig.3.11c

3.12 Innovative Solution for Power Sector

As on 2014, around 28% of power is generated from renewable sources such as hydro, small hydro, wind, solar, and biomass, while non-renewable sources contribute approximately 184 GW, and renewable sources provide around 71 GW. This disparity underscores the urgent need for effective solutions to address the power deficit and meet growing demands (Harinarayana, 2015). If we aim to grow our sectors at an annual rate of 7%, 8%, or 9% over the next decade, the power sector must match this growth rate. By this logic, we would need to generate around 603 GW of electricity by 2024 (Fig.3.12). To achieve this target, it is crucial to start planning and working diligently now. Without proactive measures and aggressive development, reaching this goal will be challenging. In 2015 an innovative solution is provided with quantification to enhance the power generation more on renewable energy without enhancing the power from Non-renewable energy sources.

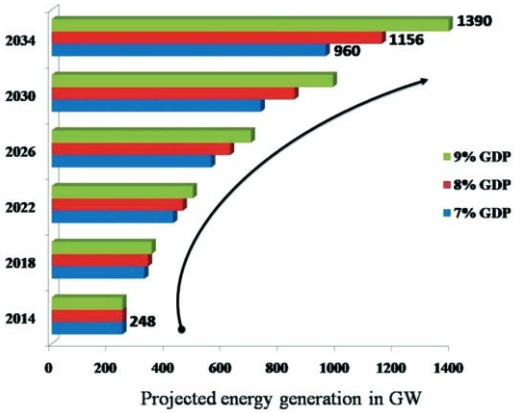


Fig. 3.12 Schematic diagram projecting the expected requirement in the years 2014 to 2034 assuming substantial growth of our Indian economy.

Part-IV Present Status of Solar Energy Generation and Future Direction

4.1 Global Scenario

Solar energy has become a cornerstone of the global transition towards renewable energy, with its adoption accelerating rapidly across the world. As of 2023, the global installed capacity of solar power has surpassed 1,260 GW, generating approximately 1,680 TWh of electricity annually. China leads the way, accounting for nearly a third of the world's solar capacity, followed by the United States, the European Union, and India. These regions have made significant investments in solar infrastructure, driven by a combination of environmental policies, technological advancements, and decreasing costs of solar panels. Countries like Japan, Germany, and Australia also play key roles in the global solar landscape, contributing substantially to the world's renewable energy mix. Emerging markets, including Brazil and Vietnam, are rapidly expanding their solar capacities, reflecting a growing global commitment to reducing carbon emissions and combating climate change. Overall, solar energy is poised to continue its upward trajectory, becoming an increasingly vital component of the global energy portfolio.

Here is a table representing the global solar energy generation scenario. The values include total installed capacity and solar energy generation for the top countries as of 2023:

Country/Region	Total Installed Capacity (GW)
China	392
United States	150
European Union	240
India	70
Japan	75
Germany	65
Australia	30
Brazil	25
Vietnam	16
Rest of World	200
Total (Global)	**1,263**

Table-1: Source: International Energy Agency (IEA) Renewables Market Report

4.2 National Scenario

India has emerged as a global leader in solar energy generation, with its installed capacity reaching approximately 100 GW as of 2023. The country's solar power

landscape is heavily influenced by states like Rajasthan, Karnataka, and Gujarat, which together contribute nearly half of the national capacity. These states benefit from high solar irradiance and vast expanses of land, making them ideal for large-scale solar projects. Other states, including Tamil Nadu, Telangana, and Andhra Pradesh, also play significant roles, driving India's push towards renewable energy. With an annual solar energy generation of around 142 TWh, India is steadily progressing toward its ambitious targets under the National Solar Mission, aiming to reduce carbon emissions and enhance energy security. The rapid expansion of solar infrastructure, supported by government policies, technological advancements, and declining costs, positions India as a crucial player in the global shift towards sustainable energy. India's solar power landscape is dominated by states with high solar irradiance and large available land, such as Rajasthan, Karnataka, and Gujarat. These states have become key players in the country's renewable energy strategy, contributing significantly to the national grid and helping India progress toward its renewable energy targets.

4.3 Status of Andhra and Telangana States

Andhra Pradesh and Telangana are two significant contributors to India's solar energy landscape, reflecting the broader national push towards renewable energy (Table-2). As of 2023, Andhra Pradesh boasts an installed solar capacity of approximately 4.3 GW, generating around 6 TWh annually. The state's strategic location with high solar irradiance and its policies promoting renewable energy investments have driven its growth in solar power. Telangana, with an installed capacity of about 5.5 GW and an annual generation of 7.8 TWh, has also made substantial strides, particularly through the promotion of decentralized solar power and rooftop installations. Both states are leveraging their natural resources and favorable policies to expand their solar infrastructure, contributing significantly to regional energy security and the reduction of carbon emissions. Their efforts align with India's broader renewable energy goals, showcasing the pivotal role that these states play in the country's sustainable energy transition.

Table 2: Solar Energy Generation in Andhra Pradesh and Telangana (2021-2023)

Year	State	Installed Capacity (GW)
2021	Andhra Pradesh	3.5
	Telangana	4.3
2022	Andhra Pradesh	4.0
	Telangana	5.0
2023	Andhra Pradesh	4.3
	Telangana	5.5

Source: MNRE annual reports.

Part-V Summary and Concluding Remarks

The Sun, a massive star at the centre of our solar system, is the primary source of energy for life on Earth. Its core, where nuclear fusion occurs, generates an immense amount of energy that radiates outward in the form of sunlight. This sunlight consists of various forms of electromagnetic radiation, including visible light, ultraviolet (UV) rays, and infrared (IR) radiation. The Sun's energy reaches Earth in the form of solar radiation, which is vital for maintaining the planet's climate and weather patterns. Sun rays are composed of photons, particles of light that carry energy and can be harnessed for various purposes. The ability of the Earth to capture and utilize this energy is foundational to the development of solar power technologies, which convert solar radiation into usable energy, such as electricity and heat. Solar energy is one of the most abundant and sustainable resources available to humanity. It is harnessed through various technologies such as photovoltaic (PV) cells, solar thermal systems, and concentrated solar power (CSP) systems. Photovoltaic cells, commonly known as solar panels, convert sunlight directly into electricity, making them ideal for residential, commercial, and industrial applications. Several portable appliances are also being powered through Solar. Solar thermal systems, on the other hand, use sunlight to heat water or air, which can then be used for heating spaces, powering turbines, or providing hot water. Concentrated solar power systems use mirrors or lenses to focus sunlight onto a small area, generating high temperatures that can drive conventional power generators. Solar energy's versatility is evident in its applications, which range from small-scale uses, like solar-powered calculators and lights, to large-scale solar farms that contribute significantly to national power grids. Additionally, solar energy is employed in desalination plants, space missions, and agriculture, showcasing its broad potential.

Solar energy has rapidly become a key player in the global energy mix, with countries around the world investing heavily in solar infrastructure. As of 2023, global solar capacity exceeds 1,260 GW, generating approximately 1,680 TWh annually. China leads in solar energy production, followed by the United States, the European Union, and India. India has emerged as a major contributor, with an installed capacity of 100 GW and an annual generation of around 142 TWh. Within India, states like Rajasthan, Karnataka, and Gujarat are leading the way, while Andhra Pradesh and Telangana are also significant contributors. Andhra Pradesh, with its installed capacity of 4.3 GW, and Telangana, with 5.5 GW, are leveraging their favorable geographic and climatic conditions to expand their solar footprints. These states are making substantial progress in their solar energy strategies, aligning with national goals to increase renewable energy's share in the overall energy mix.

5.1 Future Directions for Solar Energy

Recent advancements in solar energy research have significantly improved the efficiency and versatility of photovoltaic (PV) technologies. Perovskite solar cells, in particular, have shown remarkable progress, with laboratory efficiencies now exceeding 25%. Researchers are focusing on enhancing the stability and scalability of perovskite cells to make them commercially viable, alongside traditional silicon-based solar cells. Tandem solar cells, which combine perovskite with silicon, are also gaining attention as they have the potential to surpass the efficiency limits of single-junction solar cells. Additionally, innovations in thin-film solar cells, such as organic photovoltaics and quantum dot solar cells, are opening new avenues for lightweight, flexible, and transparent solar panels, broadening the applications of solar energy in various industries. The future of solar energy is promising, driven by continuous technological innovations and increasing global commitment to reducing carbon emissions. Key areas of focus will include enhancing the efficiency and durability of solar panels, developing cost-effective and scalable storage solutions, and integrating solar power into smart grids and other infrastructure. Advances in artificial intelligence and machine learning are expected to optimize solar power generation and distribution, making it more reliable and accessible. Additionally, floating solar farms on water bodies, agrivoltaics (combining agriculture and solar power), and solar-powered transportation are emerging trends that could further expand the applications of solar energy. As governments, businesses, and communities worldwide continue to embrace solar energy, it will play a pivotal role in achieving sustainable development goals and mitigating climate change. The future of solar energy lies not just in technological advancements but also in the collective will to harness this abundant resource for a cleaner and more sustainable world.

Acknowledgements

The contents presented in this report are mostly from my personal publications and also from the open literature made freely available. Sincere effort has been made to refer to all the related literature and it is also possible a few of them might have missed. I duly acknowledge all those scientific contributions and information made available freely in public domain. Thanks are due to Dr. E. Vidyasagar, Director-in-charge, OTBI, Osmania University for his encouragement and my MBA students for helping me to compile all the information in the form of this book.

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Prof T Harinarayana

The author of this book - Prof. T Harinarayana, a retired senior scientist of CSIR-NGRI, Hyderabad has rich experience in all types of renewable energy, more specifically to Solar and Geothermal Energy. With close cooperation and guidance from Govt. of Gujarat, under his leadership as Director, GERMI, 5 MW rooftop Solar project is completed by his Solar team, which is first of its kind in India covering the whole Gandhinagar city with innovative policy. Similarly, there are many research findings that are first of its kind in India. For example, he suggested Agri Solar in the year 2013 is now accepted under Indo-German forum at several locations and greatly helping the farmers. His research suggestion regarding Solar on National highways is now (2024) accepted by the National Highway Authority of India. His release of Solar PV, Solar thermal and wind data through APPs are with innovative ideas. His Solar team has prepared guidelines on the maintenance of a Solar plant along with officials of MNRE, Government of India is now being followed by several Solar engineers. Additionally, his pioneering work in Geothermal energy assessment in Puga, Ladakh region during the years 2006, 2007, has now (2024) gained momentum and ONGC is deeply involved in drilling for possible exploitation of the resource for power generation. E-mail: t.harinarayana Mobile: 9099097528