Review Article

Biomass-Solar Energy: A Comprehensive Review of Sustainable Energy Generation

Abstract:

India is the world's most populous country and plays a crucial role in achieving the United Nations' Sustainable Development Goals by 2030. SDG No. 7 (affordable and clean energy) and climate change reduction goals are essential for sustainable development. This review discusses clean energy potential, obstacles and stimulants, and renewable energy policies in India, focusing on solar and biomass resources. With biomass resources, the nation can generate 130 million tonnes of oil equivalent annually, and it can generate 5,000 trillion kWh of solar energy annually. For the production of renewable energy, biomass resources such as Jatropha, sweet sorghum, cassava, rice, coconut, and agricultural leftovers can be employed. The purpose of this review is to highlight the benefits of using bioenergy to achieve a sustainable energy future through financial incentives, enhanced research, public awareness, social amenities, strategic replenishment, and productive intergovernmental collaborations. Solar thermal and photovoltaic systems offer great possibilities for grid-connected, off-grid, and hybrid installations. Site-specific considerations such as incentives, financing, research, public awareness, government regulations, and private investments influence the techno-economic viability and environmental relevance of solar power and bioenergy for India's sustainable development.

Keywords: Biomass, Bioenergy, Solar energy, Renewable energy, Sustainable energy, Energy policy

1. Introduction:

The rise in the global population has increased demand for energy sources, which varies across countries. Developed nations typically require more energy compared to developing ones. Nowadays, there's a significant focus on renewable energy due to its pollution-free nature, abundance, and cost-effectiveness, with various sources like solar radiation, wind, tidal, biomass, and geothermal energy being harnessed. These sources are environmentally friendly. Over the past two decades, there has been a heightened emphasis on clean energy for sustainable development purposes. On September 25, 2015, the United Nations adopted the Sustainable Development Goals (SDGs), also called the Global Goals, offering a common framework for enhancing global well-being and environmental sustainability. Central to this agenda are the 17 Sustainable Development Goals (SDGs), which demand collective action from both developed and developing nations. These goals underscore the interconnectedness of poverty eradication, improved health and education, reduced inequality, economic advancement, climate action, and the protection of oceans and forests. (UNDP 2015).

In 2021, renewable energy sources such as solar, wind, hydro, biomass, and geothermal accounted for 15% of the total primary energy supply. This represented a small decrease of 0.4% compared to the previous year– due to the COVID-19 pandemic effects. (Global Bioenergy Statistics report- 2023).

The average daily production of oil worldwide in 2022 was 93.9 million barrels (Global Oil Production 1988–2022–Statista report). An overlapping 38% of the participants came from the thirteen present members of OPEC, with roughly 69% coming from the top ten countries (Statista Research Department, 2024). India is now the fourth-largest power consumer in the world, behind the United States, China, and Russia, as a result of recent industrialization and economic growth (Global Energy Statistical Yearbook, 2019a). According to statistics, by 2050, China and India will account for the majority of Asia's energy demand, meaning that the need for energy will only grow from there (EIA, 2019). Meanwhile, India's generation of energy ranks fifth globally (Global Energy Statistical Yearbook, 2019b).According to the International Energy Agency (IEA), once government policies are in place, bioenergy could generate 130 million tonnes of oil equivalent (Mtoe) of useful energy by 2040. The total installed capacity of India has surpassed 3,56,100 MW due to steady increases in energy production (Anon, 2020a). Over the last nine years, the Indian government has added 1,94,394 MW of power generation capacity, making the power sector power-sufficient. In 2023-24, 9,943 MW was added, with 1,674 MW from fossil fuels and 8,269 from non-fossil fuels. Additionally, 7,569 MW of renewable capacity, including large hydro, was added, including solar, wind, biomass, small hydro, and large hydro. The energy requirement and availability in India increased by 8.6% and 7.7% respectively in 2023-24, reaching 11,02,887 MU and 10,99,907 MU respectively. The total electricity generation, including from renewable sources, reached 1176.130 BU, compared to 1092.520 BU in the previous year. The energy shortage at all India levels decreased to 0.3% in 2023-24 (pib-Ministry of Power, 2023). However, the nation's current electricity production infrastructure relies on thermal energy sources (Irfan *et al* 2019a). India generates 57% of its energy from coal alone (Irfan et al., 2019b). Severe environmental risks, such as unpredictable weather patterns, health problems, and global warming, have been brought on by an overwhelming reliance on traditional energy sources (Balakrishnan *et al* 2019).

An overview of biomass resources and bioenergy:

2.1. Biomass resources potential and assessment for energy generation:

Bioenergy is derived from biomass, or the organic matter that makes up plants. The carbon in biomass is taken up by plants during photosynthesis. Modern bioenergy is a potential fuel with almost low emissions since carbon is liberated during combustion and simply returns to the atmosphere when this biomass is used to produce energy. Present-day bioenergy is the world's most abundant renewable energy source, making up over 6% of the world's energy supply and 55% of all renewable energy (IEA, 2023, Tracking Clean Energy Progress, 2023).It also happens to be the fourth most vital renewable energy source globally. Biomass is first divided into feedstocks or conventional and renewable resources. Depending on the type of feedstock, renewable biomass can be further divided into generations. (Bassam & Maliha, 2022). The residue from crops, energy plantations, and municipal and industrial waste are the main discrete sources of biomass energy (Williams *et al* 2014).

2.1.1. Residue of agricultural crop:

India produces an enormous number of residues since it has a vast area of land used for agriculture. These residues hold the potential to serve as biomass fuel for the production of energy (Kumar et al 2015). Agricultural residue is the collective name for all organic materials generated as a by-product of processing and harvesting crops. There are further two more categories for these agricultural residues: primary and secondary residues. Field-based or primary residues are those that are collected in the field

at the time of yield, while processing-based or secondary residues are those that are assembled during processing (Murali et al 2008). Primary residues include rice straw, sugar cane tops, and the like, whereas secondary residues include things like bagasse and rice husk.

Primary residues are utilized in animal feed, fertilizers, etc. As a result, there is less availability for energy applications. On the other hand, secondary residues can be confined and obtained in significant quantities at the yielding site as an energy source. The quantity of residues that are available in India is compiled based on surveys and data collecting (Kumar *et al* 2015).

Agricultural residues are biomass components that are byproducts of agriculture. This comprises rice husks, jute sticks, cotton stalks, coconut shells, wheat and rice straws, and cobs of maize and jowar (Demirbas 2006). A vast range of agricultural residues are available in substantial quantities in many developing nations. Every year, enormous amounts of agricultural plant wastes are produced worldwide and are largely under-utilized. Rice husk, which accounts for 25% of rice by mass, is the most prevalent agricultural residue (Demirbas *et al* 2009).

It was noted that there are numerous competing uses for AR, such as livestock feed and fodder, in addition to its usage in the generation of bioenergy. Furthermore, AR can be used as a fuel source for households and industries (for burning coal, wood, etc.) (Giwa *et al* 2017).

2.1.2. Agricultural feed-stocks-energy plantation:

A variety of crops, including corn, sugarcane, cereals, legumes, rubber, and others, have been utilized to generate biomass energy (Davis et al 2014). There are two types of crop residues used in biomass energy applications: dry and moist biomass. These crops are considered suitable for biomass energy based on factors like calorific value, moisture content, ash content, carbon proportion, etc. (NPC, 1987). These properties are important for converting wet and dry biomass into useful energy. Research shows that crops with a high yield of dry material are particularly good for biomass energy. Currently, prominent biomasses commonly used as energy crops include kadam, babul, bamboo, Julie flora, and Melia dubia (Kumar *et al* 2015).

According to the Ministry of New and Renewable Energy, India generates 200 million tons of agro-processing and domestic waste annually, mostly managed by poor farmers, the unorganized sector, rural workers, and small agro-based industries. This waste is often disposed of inefficiently and at little or no production cost, leading to problems like air pollution from burning leafy waste (Kumar et al., 2015). According to the Ministry of New and Renewable Energy, India generates 200 million tons of agro-processing and domestic waste annually, mostly managed by poor farmers and the unorganized sector, rural workers, and small agro-based industries. Since there are no or low production costs associated with this process, waste is often disposed of inefficiently, leading to problems like air pollution from burning significant quantities of leafy waste (Kumar *et al* 2015).

2.1.3. Forest resources :

Forest resources are also viable sources of biomass for bioenergy generation (Giwa *et al* 2017). Forestry residues are the leftover biomass from forests harvested for timber. Because processing facilities can only use timber of a specific quality, not all biomass material is extracted during the timber harvesting process. As a result,the material that remains after timber harvests can be used for energy generation. Forestry residues include logging wastes, rough and rotten salvageable dead wood, and surplus short pole trees (Haq, 2002).

Forestry residue (FR) is a crucial lignocellulosic material for generating bioenergy. As a wooden biomass left in forests after logging or clearing, FR can pose a fire hazard. Instead of burning it in fields, FR can be converted into products like bio-oil and biochar through pyrolysis (Siwal *et al* 2021).

The forest biomass residues have significant potential for energy production. The wood processing and forest harvesting industries produce over 41 million tons of wood waste annually, which is capable of producing 1.7 GW of energy. Because of the high concentration of sugarcane and forest plantations, the South and Southeast have the greatest potential for producing biomass energy (Ferreira *et al* 2018).

2.1.4. Municipal solid wastes:

The majority of the millions of tons of domestic waste that are collected annually is dumped in open areas. In India, paper and plastic make up the majority of municipal solid waste (MSW), accounting for 80% of the total MSW.

The two methods for converting municipal solid waste into energy are direct combustion and anaerobic digestion. Methane and carbon dioxide are generated on the landfill's sites in a 1:1 ratio by natural decomposition. To produce energy, these gases are extracted from the material that has been stored, cleansed, and swabbed. Then, they are fed into gas turbines or IC engines. The organic part of MSW can be processed anaerobically in high-rate biomass digesters to produce biogas, which is then used to generate steam and electricity (Kumar *et al* 2015).

Municipal solid waste (MSW) includes both organic and inorganic materials from homes and buildings, such as various types of paper, cardboard, scrap wood, food waste, plastic, rubber, glass, metals, and other materials. MSW is highly heterogeneous, with its characteristics and composition depending on the source (Xiao *et al* 2009), season (Horttanainen *et al* 2013), and origin of the waste. Furthermore, in addition to the different regions within a country, MSW characteristics differ for different nations; the physical classification is displayed in Fig. 1 (Siwal *et al* 2021).

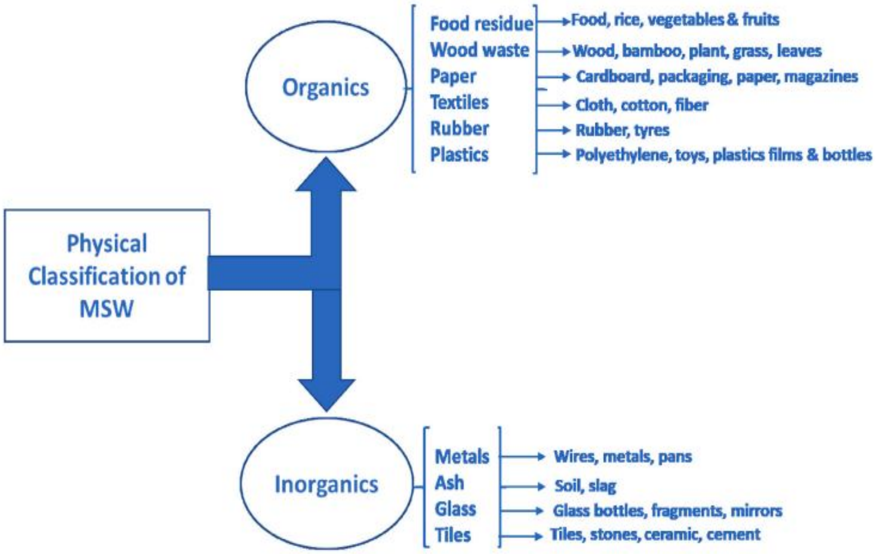


Fig. 1. Physical classification of Municipal solid waste.

2.1.5. Animal wastes:

The primary components of animal waste are organic matter, water, and ash. Animal manure can decompose in both aerobic and anaerobic environments. Stabilized organic materials (SOM) and CO2 are created under aerobic conditions, and additional CH4 is produced under anaerobic conditions. The enormous energy potential in India is made possible by the increased output of animal dung, which makes the potential for CH4 production noteworthy (Kumar *et al* 2015). The production of biogas from cow dung is influenced by many operational variables, including temperature, pH, carbon-nitrogen ratio, and retention period. The production process will slow down and eventually stop at a temperature of 60°C. pH of 7, followed by pH 9, is the optimal level for gas production; pH 4 makes the process excessively acidic. In addition, longer retention times and a higher proportion of cow dung promote better biogas production (Giwa *et al* 2017).

2.1.6. Blends of biofuel and petroleum products:

An additional field of interest for sustainable energy from biomass resources is the combination of biofuels and petroleum products. The adverse environmental impacts of petroleum products can be mitigated by hybrid petroleum-biofuel products (Giwa *et al* 2017).
Biodiesel can be converted from animal and vegetable-based oils as well as oil of microbial origin. Using a chemical process with a catalyst and alcohol, the raw materials are transformed into biodiesel. A biofuel produced from renewable biomass that can replace fossil fuels entirely or in part can also be referred to as biodiesel. It is intended for use in internal combustion engines and, depending on regulations, in various forms of energy generation. It can be used either pure or in different ratios combined with diesel. The blend of 2% biodiesel and petroleum diesel is known as B2, 10% biodiesel is added as B10, and so on, until pure biodiesel, or B100, is reached (Ferreira *et al* 2018).

Bioethanol is an alcohol produced by fermentation, primarily from the carbohydrates found in starchy crops like sugarcane. Additionally, cellulosic biomass—which comes from non-food sources like grasses and trees—is being researched as a feedstock for the synthesis of ethanol. While pure ethanol can be used as car fuel, it is most commonly added to gasoline to boost octane and reduce pollutants. Brazil and the United States both use bioethanol extensively. The present plant design does not allow for fermentation to turn the nin component of plant raw materials into fuel components (Shalaby 2013).

2. Global bioenergy policies:

To meet the 2015 Paris Agreement's climate change commitments, the majority of the nations expanded their usage of bioenergy (Beckman et al., 2018). The more advanced forms of bioenergy, such as bioelectricity, bio-heat, and bioCNG, are being utilized more quickly than the classic forms of biodiesel and biogas, which are being employed in home and transportation applications today. Thus, to guarantee the best possible use of bioenergy resources, regulation is desperately needed. Many nations have well-crafted bioenergy regulatory laws to guarantee robust market competition and the achievement of their goals and mandates globally. Nowadays, the bioenergy policies of many nations are adopting sustainable and renewable resources instead of conventional ones, like municipal solid waste (MSW), forest residues, and agricultural waste or residues. This is because conventional bioenergy resources were based on human edible materials, which leads to issues with food scarcity. For these renewable bioenergy resources to be used to their full potential, a policy framework is also necessary. The modern era of waste-to-energy generation is indicated by the extensive utilization of agricultural waste materials, forest remnants like leaves and branches, urban waste materials, etc. Municipal waste materials comprise 20% organic matter according to currently known technology; yet, because different types of waste materials are mixed, the process of segregating MSW remains difficult (Malinauskaite *et al.,* 2017).

Likewise, agricultural crop residuals hold enormous potential for fulfilling rural area's requirements for bioenergy. Germany may use waste residuals and biogenic resources to satisfy its 13% primary energy requirement. Germany and Russia have enormous potential for producing bioenergy from garbage (Namsaraev *et al* 2018; Brosowski *et al* 2016). Similarly, bioenergy may also be produced from lignocellulosic forest debris (Van Meerbeek *et al* 2019). The enormous demand for bioenergy in China and India may be easily met by excess exports from nations like Brazil. Brazil has a sufficient potential for biomass resources, of which 25% are valuable for export (Welfle, 2017). It's crucial to remember that there is still a ton of unrealized potential for these diverse bioenergy sources. Thus, for effective utilization of the bioenergy resources that are currently available, a worldwide policy framework is needed.

2.3. Bioenergy policy by the Indian Government:

The Government of India is consistently introducing new policies and initiatives while also updating its current ones. There have been three major bioenergy-related projects implemented in 2018: the New National Policy on Biofuels; the Program on Energy from Urban, Industrial, and Agricultural Waste/Residues; and the New National Biogas and Organic Manure Program (NNBOMP). These programs and policies are meant to be updated to address upcoming energy-related issues.

2.3.1. National policy on biofuels — 2018:

India launched its National Policy on Biofuel — 2018 (National Policy on Biofuels, 2018a) against the background of the National Biofuel Policy of 2009. This is a strategically significant initiative that aims to meet the demand for sustainable energy and guarantee the success of developmental schemes like the Clean India Initiative, "Make in India," and skill development. Over the next ten years, the program aims to enhance the use of biofuels in the transportation and energy sectors. Additionally, the program seeks to replace fossil fuels by utilizing, developing, and promoting domestic feedstock for the manufacture of biofuels. In the long run, this helps the country achieve its goals of energy security, mitigating climate change, and creating new job opportunities.

Additionally, the approach would encourage the utilization of innovative technologies in the production of biofuels. By 2030, the policy goal aims to increase the availability of biofuels to achieve the blending requirements, which include 5% biodiesel and 20% ethanol in gasoline. The following initiatives are suggested as a means of achieving this goal:

- Developing novel feedstock for biofuels
- Establishing Second Generation (2G) biorefineries
- Expanding domestic production of both biodiesel and ethanol to ensure ongoing supplies
- Creating an environment that is favorable to the use of biofuels and their integration with conventional fuels.

The country's biofuel production sector could encounter novel opportunities as an outcome of the policy (Kothari *et al* 2020).

To resolve environmental problems like crop burning, India's new policy emphasizes on turning waste—including waste cooking oil and agricultural residues—into biofuels. The primary goals of this initiative are to decrease the import of crude oil by encouraging low-cost ethanol production from waste materials, increase revenue for farmers, and lower emissions through ethanol blending. Additionally, it generates jobs in the supply chain management and biorefinery industries. (Fig. 2) (2018a, National Policy on Biofuels)

Fig.2: Expected Benefits of National Policy on Biofuels - 2018 (National Policy on Biofuels,2018b)

2.3.2. New national biogas and organic manure program (NNBOMP) — 2018:

India possesses 512 million livestock population, of which 300 million are bovine in general, and the livestock sector accounts for 4% of the country's GDP. The MNRE's NNBOMP initiative has multiple goals, including meeting the needs of rural and semi-rural families for lighting, heating, and other modest power requirements, as well as clean cooking fuel. Along with these goals, NNBOMP also aims to increase the production of organically enhanced bio-manure to reduce the need for chemical fertilizers and greenhouse gas emissions to create a more sustainable environment. (Kothari *et al* 2020).

In India, the National Biogas and Organic Manure Programme (NNBOMP) intends to establish 2.55 lakh biogas plants by 2019–20, with an average daily output capacity of 8.40 lakh m3. Plants that produce 1 to 25 m3 of biogas per day are eligible for subsidies from MNRE. This subsidy falls under the category of central financial assistance (CFA), which is organized into three zones in India for optimal implementation. There is also an additional 1600 INR subsidy available for biogas plants based on cattle dung that have a daily capacity of 1 to 15 m3 of biogas. In addition, other incentives can be obtained, including construction, operations, maintenance, and engines that run entirely on biogas. The MNRE approved the standard plant models, which are represented in Fig. and have been chosen based on technical requirements such as feedstock supply and location.

Fixed dome and floating dome plants are the most common forms; for isolated locations, prefabricated digesters are funded (New National Biogas Organic Manure programme, 2018).

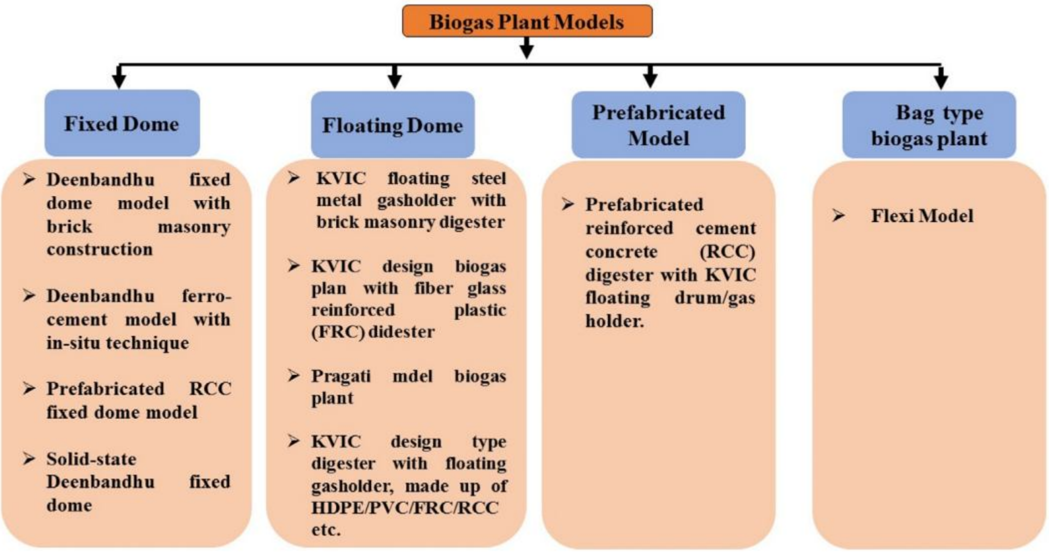


Fig. 3: Ministry of New and Renewable Energy (MNRE) approved model of biogas plants (New National Biogas Organic Manure programme, 2018)

2.3.3. Program on energy from urban, industrial, and agricultural waste/residues:

This program's scope of potential uses is extensive, including the production of biogas and power generation through bio-methanation from industrial, sewage, and agricultural wastes as well as urban sources. It also emphasizes the installation of biomass gasifiers to meet captive power requirements, research and development activities that are promoted, resource assessment, performance evaluation, and technological advancement. The program's goals are to recover energy from urban, industrial, and agricultural wastes in the form of biogas (such as BioCNG) and to encourage the production of power from biomass gasifiers to meet thermal and captive power needs for things like rice mills, village lighting, and water pumping. Furthermore, establishing favorable environmental circumstances to advance, illustrate, and promote the use of wastes and residues for energy recovery within the constraints of the fiscal and financial system is given particular emphasis (New National Biogas Organic Manure programme, 2018).

2.3.4. Contemporary analysis of biofuels policies:

The 2009 National Biofuels policy — was a well-organized program. This policy has a clearly defined preamble, vision, aim, definitions, scope, strategy, and approval process—even though some of the targets have been met since then. It provides methodological examples of the different intervention processes and enabling mechanisms. Similar elaborates are made about quality standards, international cooperation, biofuel import and export, state roles, capacity building, and institutional synergy mechanisms (National Policy on Biofuels, 2009).

2.3.5. Bioenergy development in states and union territories of India:

State government support systems for bioenergy are still in their infancy when compared to solar and wind power, but both the federal and state governments are actively pushing bioenergy through a variety of initiatives. The MNRE, GOI's Biomass Portal of India is a commendable endeavor that provides information on feedstock materials, bioenergy technologies, bioenergy policies about biofuels, and pertinent research publications. The information is updated regularly by the portal. On the other hand, the MNRE portal allows users to upload annual reports and highly regarded technical reports from the US Department of Agriculture Services (USDA), particularly the Global Agriculture Information Network (GAIN) reports on assessments of trade and commodity issues that contain important data about biofuels for different parts of the world (Anon, 2020). Initiatives like these, which disseminate knowledge via a professionally designed website, are highly beneficial for enlightening and educating different bioenergy sector stakeholders.

The MNRE has directly supported the implementation of several bioenergy technology programs, offering financial subsidies such as soft loans for manufacturing and concessional duty/custom-free imports to encourage the use of bioenergy technologies. The success of these schemes and programs in terms of their penetration, however, continues to be low even with government assistance. To support the development of bioenergy technologies in the nation, it would be necessary to remove significant obstacles (Luthra *et al* 2015). Investors seek to invest their funds in sectors where there is substantial demand from the market and funding from the government, not in the riskier bioenergy sector where there is a requirement for a well-established system of support that might result in greater revenue from bioenergy production (Kothari *et al* 2020).

2.4. Biomass energy conversion method and technologies:

The potential of biomass in India makes it evident that a variety of feedstocks are accessible for use in power generation applications as well as in the conversion to biofuels. There are numerous methods for converting biomass, and they vary depending on the kind and amount of biomass feedstock used, the state of the economy, and other factors. The two primary process technologies used to convert biomass to energy are thermo-chemical and bio-chemical/biological. The third method of generating energy from biomass is mechanical extraction combined with esterification, such as in the case of rapeseed methyl ester (RME) biodiesel. The processes involved in thermal conversion include liquefaction, gasification of biomass, combustion, and pyrolysis (Kumar *et al* 2015).

2.4.1. Thermo-chemical conversion:

For the thermo-chemical conversion of biomass, there are three primary methods: incineration or direct burning, gasification, and pyrolysis (Katyal 2007).

Incineration-

Incineration is the oxidation of the flammable substances carried out within the garbage. Incineration is employed as a remedy for a broad variety of trash. Waste is usually an extremely heterogeneous substance, containing mainly organic materials, ores, elements, and H2O. The essential steps of the incineration method are evaporating and degassing, pyrolysis, and gasification. These distinct steps commonly overlay, suggesting that spatial and temporary detachment of those steps while scrap incineration can only be plausible to the bounded range. It is, yet, plausible to change these methods so that decrease contaminant emissions, for example, by adopting models, furnace design, air circulation, and instrument engineering.

Incinerator models consist of three main types: rotating kilns, fluidized beds, and grate incinerators. Depending on the type of waste being used, a trash incinerator mill's concept may change entirely. The chemical composition, physical characteristics, and thermal characteristics of the waste are significant factors that are frequently affected by these unpredictable limitations (Siwal *et al* 2021).

Thermal Gasification-

Thermal gasification is the process of partially oxidizing biomass at high temperatures (usually between 800 and 900 LC) to produce a combustible gas mixture. The low calorific value (CV) gas that is produced can be burned directly or used as fuel for gas engines and gas turbines. The produced gas can also be used as a feedstock (syngas) for the production of chemicals such as methanol (Ganesh and Banerjee, 2001). It is generally acknowledged that the technology for gasification of waste fractions is not as advanced as that of combustion. Gasification, with appropriate future technological developments, could be viewed as a valuable alternative to waste combustion, though there are several drawbacks to this process, including the potential for lower facility costs, better gas quality, and higher overall efficiency (Kaygusuz *et al* 2015).

One concept with significant potential is biomass integrated gasification/ combined cycle (BIG/CC), in which gas turbines convert gaseous fuel to electricity with a high overall conversion efficiency. One major benefit of BIG/CC systems is that the gas is cleaned before being combusted in the turbine, allowing for the use of more affordable and compact gas cleaning equipment due to the smaller volume of gas to be cleaned. High conversion efficiency is guaranteed by the combination of gasification and combustion, resulting in net efficiencies of 40–50% for a plant with a capacity of 30–60 MWel. Syngas generated from biomass are used to make hydrogen and methanol, which are utilized as fuels for various applications, including transportation. Either the hydrogen indirect gasification method or the oxygen blown technique is chosen for producing methanol, and these processes also provide higher value CV gas, which is typically 9–11 MJ¼N m3 (Kumar *et al* 2015).

Pyrolysis-

Pyrolysis is the process of heating biomass to around 500 LC without the presence of air, resulting in the conversion of biomass into liquid (bio-oil or bio-crude), solid, and gaseous fractions. If flash pyrolysis is used, pyrolysis can be used to make bio-oil, allowing for up to 80% efficiency in the conversion of biomass to bio-crude (Kumar *et al* 2015). The volatile portion of biomass produces gases and bio-oils, whereas the stable carbon component is primarily responsible for the solid product known as char. High concentrations of oxygenated molecules are present in dark brown organic liquids known as bio-oils (Jameel *et al* 2017).

This mixture is produced by depolymerizing and breaking down cellulose, hemicellulose, and lignin. It contains elements such as acids, esters, alcohols, ketones, aldehydes, sugars, furans, and phenol (Bridgwater 2012). Depending on the reaction parameters and pyrolysis process, different compounds are produced. It is not good for raw materials or pyrolysis oils to contain water because of its stability, viscosity, pH, abrasiveness, and other characteristics.103 The net energy extracted from the pyrolysis oil decreases with increasing water content (Alper *et al* 2020).

2.4.2. Bio-chemical conversion:

There are two main processes utilized: anaerobic digestion and fermentation, as well as a secondary method based on chemical conversion and mechanical extraction (Kumar *et al* 2015). The primary focus of biochemical transformation is the development of enzymes that bacteria get to regulate the energy stored as a solid fuel (Siwal *et al* 2021).

Fermentation-

Several nations depend on fermentation extensively for the commercial production of ethanol from starch and sugar crops (such as maize and wheat) and sugar crops (such as sugar cane and sugar beet). After the biomass is broken down, enzymes change the starch into sugars, which yeast then ferments into ethanol. Distillation is a concentrated energy process used to purify ethanol; 1000 kg of dried corn yields approximately 450 l of ethanol. The solid residue left behind from this process can be fed to cattle, and the bagasse from the sugar cane can be utilized as fuel in boilers or for further gasification (MNES.In,1996). The conversion of lignocellulosic biomass (such as wood and grasses) has longer-chain polysaccharide molecules, their conversion is more complicated and necessitates the hydrolysis of the resultant sugars by acid or enzyme before they can be fermented to ethanol. Currently, these hydrolysis methods are in the pre-pilot phase (Kumar *et al*. 2015).

Anaerobic digestion-

Anaerobic digestion (AD) converts organic material directly into a gas known as biogas. It is mostly composed of carbon dioxide and methane, with trace amounts of other gases including hydrogen sulfide. Bacteria transform the biomass in an anaerobic environment to create a gas with 20–40% of the lower heating value of the feedstock (McKendry, 2002). AD is a widely utilized method with an established track record in the commercial treatment of organic wastes with moisture contents ranging from 80 to 90 percent. Biogas can be directly utilized in gas turbines and spark-ignition engines (e.g., e.), and by eliminating CO2, it can be upgraded to a higher quality—that of natural gas. A combined heat and power system could be used to collect waste heat from the engine oil, water cooling systems, and exhaust, much like in any other power production system that uses an internal combustion engine as the prime mover (Kumar *et al* 2015).

Composting-

The process of composting/fertilizing, defined as the natural decomposition of large amounts of biodegradable waste under mostly aerobic conditions, transforms biomass into CO2, H2O, heat, and another stable product known as fertilizer. The fertilizer is easy to use, manageable, and safe to use in farming to enhance the soil (Kalyani *et al* 2014). The initial C/N ratio being consumed into an assortment of 30:1, together with the strictly attained and observed wetness and oxygen stages and temps, usually accelerates the composting process. During the fertilization process, three types of microorganisms—fungi, actinomycetes, and bacteria—are abundant (Siwal *et al* 2021).

An overview of solar resources and solar energy:

The issue of rapidly increasing urbanization and energy consumption is widely recognized worldwide. Between 2020 and 2040, an estimated 270 million more people are expected to live in India's cities (IEA, 2019; International Energy Agency, 2021). The capacity for solar power consumption worldwide is expected to increase by 9% annually between 2018 and 2050. The International Renewable Energy Agency (IRENA) has reportedly announced a new strategy. According to research on future photovoltaic energy, by 2050, the world's solar capacity is expected to rise from 480 GW in 2018 to over 8000 Giga-Watt.

“The principal method of delivering solar energy to Earth is through electromagnetic waves”. It is the planet's largest source of carbon-free energy by a wide margin. In just one hour, it strikes Earth with 4.3×1020 J, which is greater than the total energy used on the globe in a year (4.1×1020 J). Infrared radiation (52–55%), visible radiation (42–43%), and ultraviolet radiation (3–5%) make up the majority of solar radiation that reaches the earth's surface. (Duffie et al., 2013). The Earth receives 174 petawatts (PW) of solar radiation (insolation) in the upper atmosphere. The remainder is absorbed by landmasses, seas, and clouds, with around 30% being reflected in space (Vekariya *et al* 2024).

India's energy consumption has almost doubled since 2000, and it still has a lot of room to grow much faster. India's annual energy supply deficit began in 2009 (Overview | Government of India | Ministry of Power, 2022). Approximately 70% of India's electricity is generated by thermal power plants that utilize coal, resulting in significant CO2 emissions (India Energy Outlook 2021 – Analysis - IEA 2021). Due to its abundance, solar energy is the most dependable source for energy security (Amado & Poggi, 2014a). India benefits greatly from solar energy due to its placement in the solar belt, which spans 40°S to 40°N. However, the nation has only put in 66 MWp of solar capacity, which is not very much. About 80% of this capacity is utilized for solar water pumps, home and street lighting systems, and lanterns. There are 2.92 MWp of off-grid and 12.28 MWp of grid-connected solar power plants (SSPs). India's solar energy industry has grown since the National Solar Mission (NSM) was introduced in January 2010. Since other wavelengths of solar energy are suppressed by the atmosphere, solar technologies such as Solar Photovoltaic (SPV) and Concentrated Solar Power (CSP) systems capture wavelengths of solar radiation between 0.29 and 5.5 m. The efficient design of SPV and CSP systems is necessary for power generation, conversion, storage, and distribution because of the variable nature of solar radiation, which is influenced by daily, seasonal, yearly, and topographic factors (Ramachandra *et al* 2011).

3.1.Assessment of solar energy potential for energy generation:

India receives over 300 days of direct sunlight annually, making it a prime location for solar power generation. In India, the land area receives around 5,000 trillion kWh of energy annually, with the majority of its regions receiving solar radiation between 4 to 7 kWh/m^2 per day, approximately 1500 to 2000 hours above the gross energy consumption due to radiation. The quantity of renewable energy produced in India increased by 9.46% in 2020 (Albert & Vanaja, 2020). Less carbon emissions and clean energy for our environment can be produced by solar energy (Kirmani, 2015). India is the world's first country to set up a dedicated ministry for alternative energy sources. To increase the percentage of renewable energy in the nation, the Ministry of New and Renewable Energy (MNRE) was established in 1980. The Indian government, particularly in the years 2000–09 and 2010–19, has demonstrated a strong interest in the advancement of renewable energy, particularly solar energy. The potential for solar energy in the nation is estimated to be 750 GW (MNRE, 2016–17). By 2022, MNRE hopes to raise the capacity of renewable energy to 175 GW, of which 100 GW will come from solar resources alone. The solar business has grown significantly in recent years thanks to government support programs and technological breakthroughs (Raina and Sinha, 2019). India now ranks fifth in the world with 35 GW of cumulative solar capacity because of the development of new solar parks (REN21,2020).

Even with the solar industry's amazing advancements, a sizable population still cannot meet their daily energy needs. When comparing the household energy needs of India, Brazil, Japan, Australia, and Denmark, researchers found that there are significant differences in these countries' energy needs even at the same income level. These differences can be attributed to a variety of factors, including various lifestyles, technologies, and geographic conditions. (Ailawadi*et al* 2006) noted that 40% of Indians lack access to modern energy. (Lensen *et al* 2006) compared household energy needs among these countries.

Determining renewable energy and water resources is necessary for sustainable development to accomplish the goals. The country, whose economy is expanding at the quickest rate in the world, wishes to increase its energy potential. Thus, alternative energy sources such as solar, wind, and hydropower, among others, increase the potential for energy production and will significantly lessen their negative effects on the environment (Hirano and Fujita, 2012). Accordingly, it is necessary to determine the best sites for the installation of photovoltaic (PV) energy resources in terms of their techno-economic and environmental viability (Rajput and Arora, 2017). An essential role is played by the integration of Geographic Information System (GIS) tools, Remote Sensing technology (RS), and the Multi-Criteria Decision Making (MCDM) technique (Habib *et al* 2020). There have been several attempts to investigate the possibilities of multi-spectral remote sensing for urban planning as a significant supplement to traditional techniques of monitoring the urban environment. This was done by utilizing the Terra/ASTER images in conjunction with in-situ spatial data. (Chrysoulakis, 2002). An analysis of the solar potential of the Indian state of Himachal Pradesh, located in the western Himalayas, was conducted using artificial neural networks (ANNs) to model the world's solar radiation. (GSR) prediction method to evaluate any location's solar potential (Yadav and Chandel, 2015). In addition, multi-temporal satellite pictures were used to investigate spatiotemporal urban sprawl and land consumption patterns in the region of the Himalayas to report urban growth on a temporal scale for appropriate urban planning techniques (Diksha and Kumar, 2017). Also, several experts have looked at India's progress with solar energy from different perspectives. For instance, the approaches and prospects of solar power in India (Sharma *et al.* 2012). The concentrating solar power technique was discussed (Ummadisingu and Soni 2011), and the Indian solar industry's degree of progress was contrasted with that of the rest of the globe (Sharma 2011). A study has been carried out to identify solar energy as a viable renewable energy choice for India, analyzing data from four major cities, Mumbai, New Delhi, Chennai, and Bangalore. The research found that solar energy is suitable due to consistent solar irradiation availability throughout the year. MATLAB and RETScreen were employed for data analysis and evaluating the efficiency of PV. The LCA analysis revealed that PV power generation is cheap in India, costing INR 9.27 for 1 kWh, with an average lifetime of 25-30 years. PVs do not require maintenance or operation expenses and require only 0.02 m^2 of land for 1 kWh of electricity production (Irfan *et al* 2019).

To balance the competing and impending energy demands, it is necessary to map and analyze each region's potential for producing solar energy. Previous studies have investigated and utilized geospatial technology to offer valuable contributions to the energy industry (Kumar, 2019). Due to several factors, including rising energy requirements (Redweik *et al* 2013), industrial expansion, faster population growth, rising import costs, improper resource allocation, and poor policy implementation, several developing nations, including India, are facing energy deficits (Inman *et al* 2013). Despite possessing substantial coal reserves, India continues to struggle with resource scarcity, which hinders domestic coal production and slows the pace at which the country needs energy to grow economically (Meisen *et al* 2006).

Over the past few decades, concentrated solar power (CSP) technology has gained increasing attention as a viable option for utilizing solar energy (Yogev *et al* 2013). Worldwide, there are a large number of CSP facilities in operation, and more are being built. Four potential CSP technologies now under consideration seem to have reached a respectable level of technological maturity (Shrimali & Rohra, 2012). These are the linear Fresnel reflector, parabolic dish, power tower, and parabolic trough. The government of India launched the Jawaharlal Nehru National Solar Mission (JNNSM) in January 2010, which gave the country's efforts to create CSP-based solar thermal power generation a significant boost (Sharma, 2014). By 2022, the mission intends to provide a framework of enabling policies for the installation of 20,000 MW of solar power (MNRE, 2010). Finding locations that are ideal for CSP-based solar electricity generation and estimating its overall potential are necessary for such an effort. The discovery of a niche market and a thorough potential assessment of the entire nation would be very beneficial to researchers, policymakers, and project developers (Sharma *et al* 2015).

While many researchers have expressed their opinions about the potential of CSP in the context of India, a recent study (Purohit *et al* 2013) has provided quantitative estimates of the potential for CSP-based power generation in northwest India (the states of Rajasthan and Gujarat). This analysis considers the availability of solar resources and landfills, but it ignores the possibility of wind power generation at some of the places that could be used for solar thermal power. The allocation of wastelands between solar thermal and photovoltaic (PV) power has also not been considered in the study. A different recent study (Mahtta *et al* 2014) uses remotely sensed yearly average GHI and DNI values in a Geographic Information System (GIS) framework to present the district-wise potential of CSP and solar PV in India.

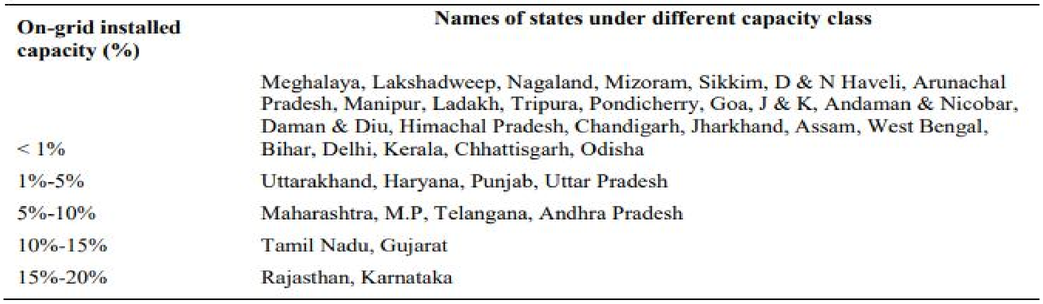
Although this study finds that all categories of wastelands are appropriate for producing solar power, it ignores other factors that can limit the usage of wastelands for solar thermal power generation, such as the potential for wind power to be generated on the same wastelands (Sharma *et al* 2015).

3.2. Analysis of solar energy potential in different sites around India:

India is ranked fifth in the world with an installed capacity of 48556.65 MW for solar power (SP), after China (254354.8 MW), the US (75571.7 MW), Japan (66999.949 MW), and Germany (53783 MW) (MNRE, GoI 2021; IRENA 2021). The contributions from solar roof tops, off-grid systems, and ground-mounted solar power plants (SPPs) are around 41001.49 MW, 6111.06 MW, and 1,444.10 MW, in that order (Table 2). The Indian government is working to increase solar power capacity to meet the aim of 100 GW by 2022, which includes 40 GW from solar rooftops (MNRE GoI 2020-21). The government notes the enormous potential of solar energy, which is 748.99 Gwp (Table 2).

The country of India is made up of 28 states and 8 Union territories (UTs), covering 3.287 million km². The highest on-grid SP installed capacity share is shared by the four states of Rajasthan (9229.8 MW), Karnataka (7483.4 MW), Gujarat (6116.85 MW), and Tamil Nadu (4757.76 MW); the lowest shares are shared by Lakshadweep (0.75 MW) and Meghalaya (0.19 MW) (Fig. 4 & Table 2). If the states were ranked according to installed capacity, only Rajasthan and Karnataka would rank in the top 15-20%, followed by Tamil Nadu and Gujarat (10–15%), Maharashtra, M.P., Telangana, Andhra Pradesh (5–10%), Uttarakhand, Haryana, Punjab, and Uttar Pradesh (1–5%), and the remaining hardy states would rank <1% (Table.1).

Table 1: - State-wise contribution in overall installed capacity of Solar Power in India



On-grid installed capacity (%)	Names of states under different capacity class
< 1%	Meghalaya, Lakshadweep, Nagaland, Mizoram, Sikkim, D & N Haveli, Arunachal Pradesh, Manipur, Ladakh, Tripura, Pondicherry, Goa, J & K, Andaman & Nicobar, Daman & Diu, Himachal Pradesh, Chandigarh, Jharkhand, Assam, West Bengal, Bihar, Delhi, Kerala, Chhattisgarh, Odisha
1%-5%	Uttarakhand, Haryana, Punjab, Uttar Pradesh
5%-10%	Maharashtra, M.P, Telangana, Andhra Pradesh
10%-15%	Tamil Nadu, Gujarat
15%-20%	Rajasthan, Karnataka

Table. 2: - India’s State-wise Solar Potential, SP Target, On-Grid, and Off-Grid Solar Power installed Capacity.

S. No.	STATES / UTs	Solar Potential (GWp)	SP target by 2022	On-Grid SP Capacity 2020-21 (as on 30.11.2021)				Off-Grid Solar Power Cumulative Capacity (as on 31.03.2021)					
				Ground Mounted (MW)	Roof Top (MW)	Total (MW)	%	SLS (street)	HLS (No's)	SL (No's)	SPP (KWp)	Solar Pumps (No's)	Electrified Villages (No's)
1	Andaman & Nicobar	0	27	24.63	4.59	29.22	0.06	1135	468	6296	167	5	0
2	Andhra Pradesh	38.44	9834	4146.01	146.36	4292.37	9.11	15795	22972	77803	3815.6	34045	13
3	Arunachal Pradesh	8.65	39	1.27	4.34	5.61	0.01	13741	35065	125581	963.2	22	297
4	Assam	13.76	663	25.67	33.48	59.15	0.13	17384	46879	647761	1605	45	1953
5	Bihar	11.2	2493	138.93	30.55	169.48	0.36	47152	12303	1735227	6800	2813	0
6	Chandigarh	18.27	153	6.34	46.3	52.64	0.11	901	275	1675	730	12	0
7	Chhattisgarh	0	1783	277.14	31.69	308.83	0.66	3730	42232	3311	31372.9	61970	568
8	D & N Haveli	0	449	2.49	2.97	5.46	0.01	0	0	0	0	0	0
9	Daman & Diu	0	199	10.15	30.57	40.72	0.09	0	0	0	0	0	0
10	Delhi	2.05	2762	8.96	200.7	209.66	0.45	301	0	4807	1269	90	0
11	Goa	0.88	358	0.95	17.42	18.37	0.04	707	393	1093	32.72	15	19
12	Gujarat	35.77	8020	4544.37	1572.48	6116.85	12.98	5004	9253	31603	13576.6	11615	38
13	Haryana	4.56	4142	195.8	397.4	593.2	1.26	34625	56727	93853	2321.25	10103	286
14	Himachal Pradesh	33.84	776	25.75	19.29	45.04	0.10	92500	22592	33909	1905.5	46	21
15	J & K	111.05	1155	2.49	22	24.49	0.05	24904	144316	51224	8129.85	39	349
16	Jharkhand	18.18	1995	19.05	34.51	53.56	0.11	13916	9450	790515	3769.9	5051	700
17	Karnataka	24.7	5697	7145.05	338.35	7483.4	15.88	5069	52638	7781	7854.01	7496	30
18	Kerala	6.11	1870	150	156.3	306.3	0.65	1735	41912	54367	16078.39	818	607
19	Ladakh	0	0	6	1.8	7.8	0.02	0	0	0	0	0	0
20	Lakshadweep	0	4	0.75	0	0.75	0.00	4465	600	5289	2190	0	0
21	M.P	61.66	5675	2431.88	160.14	2592.02	5.50	14258	7920	529101	3654	25047	577
22	Maharashtra	64.32	11926	1646.24	860.57	2506.81	5.32	10420	3497	239297	3857.7	11315	340
23	Manipur	10.63	105	0	6.36	6.36	0.01	22367	24583	9058	1580.5	40	240
24	Meghalaya	5.86	161	0	0.19	0.19	0.00	5800	14874	40750	2004	19	149
25	Mizoram	9.09	72	0.1	1.43	1.53	0.00	10117	12060	107217	3864.6	37	20
26	Nagaland	7.29	61	0	1	1	0.00	15125	1045	6766	1506	3	11
27	Odisha	25.78	2377	383.56	21.66	405.22	0.86	17955	5274	99843	2191.51	9661	1614
28	Pondicherry	0	246	0.8	11.07	11.87	0.03	417	25	1637	121	21	0
29	Punjab	2.81	4772	828.58	222.51	1051.09	2.23	43448	8626	17495	2066	5689	0
30	Rajasthan	142.31	5762	8617.78	612.02	9229.8	19.59	7114	187968	225851	30449	56819	382
31	Sikkim	4.94	36	0	2.76	2.76	0.01	504	15059	23300	850	0	13
32	Tamil Nadu	17.67	8884	4424.15	333.61	4757.76	10.10	40324	298641	16818	13052.6	6447	131
33	Telangana	20.41	0	3822.32	209.74	4032.06	8.56	2208	0	12000	7450	424	0
34	Tripura	2.08	105	5	4.41	9.41	0.02	6887	32723	288941	867	214	842
35	Uttar Pradesh	22.83	10697	1731.5	258.78	1990.28	4.22	291392	235909	2351205	10638.31	31609	335
36	Uttarakhand	16.8	900	277.78	262.71	540.49	1.15	34218	91595	163386	4059.53	26	594
37	West Bengal	6.26	5336	100	51	151	0.32	15605	145332	17662	1730	653	1179
38	Others*	0.79	0	0	0	0	0.00	9150	140273	125797	23885	4621	0
	Total	**748.99**	**99534**	**41001.49**	**6111.06**	**47112.55**	**100**	**830373.00**	**1723479.00**	**7948219.00**	**216407.67**	**286830.00**	**11308.00**

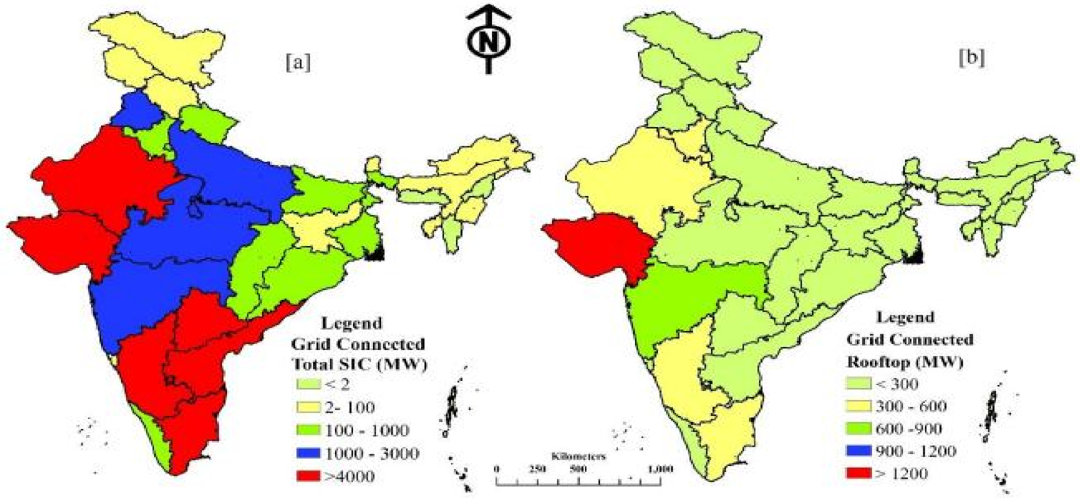


Fig. 4. [a] Shows state-wise total solar installed capacity and [b] shows grid-connected rooftop solar installed capacity up to 30th Nov 2021 according to available data of MNRE.

The PVOUT (photovoltaic electricity production) averages for India are 1.37–6.03 kWh/kWp daily (Fig. 2a) and 500.8–2205 kWh/kWp yearly (Fig. 6b). These figures are similar to the solar radiation received by tropical and subtropical nations (Global Solar GIS). India's solar energy falls into eight primary types, with variations across different regions (Fig. 5). With annual worldwide sun radiation between 1942 and 2159 kWh/m2, Gujarat, western and southern Rajasthan, eastern MP, Maharashtra, Karnataka, Telangana, Tamil Nadu, Andhra Pradesh, and Ladakh have the maximum solar radiation in the nation. The remaining states and union territories, which include parts of Uttarakhand, Himachal Pradesh, Jammu and Kashmir, Maharashtra, Bihar, Andhra Pradesh, Tamil Nadu, Telangana, Mizoram, Assam, and Nagaland, as well as Haryana, Madhya Pradesh, Uttar Pradesh, Chhattisgarh, Chandigarh, Orissa, Andhra Pradesh, eastern West Bengal, and Kerala, also receive a comparatively large amount of solar radiation (1.724–1941 kWh/m^2) (Singh *et al* 2022).

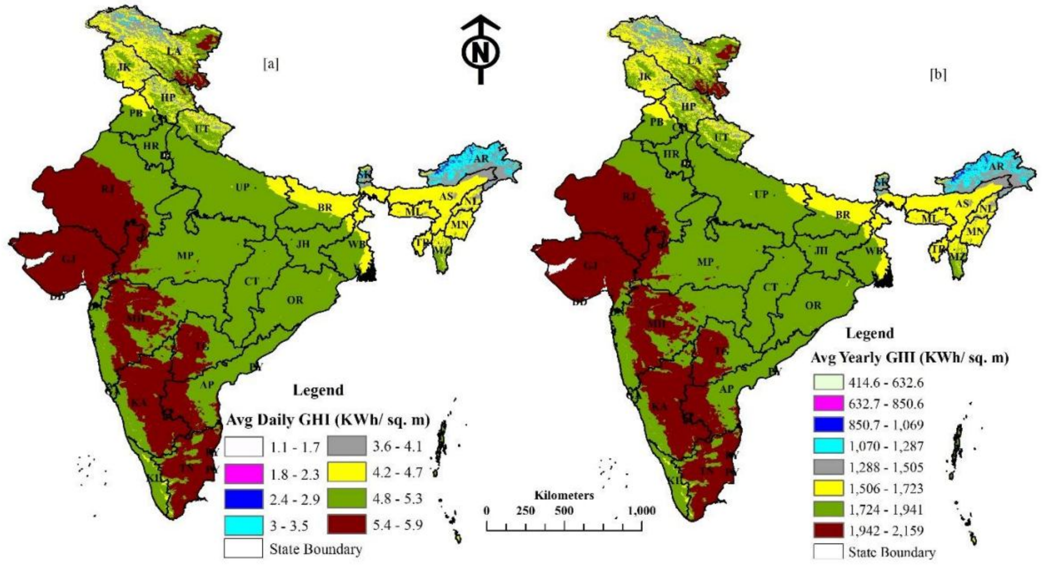


Fig. 5: [a] Illustrates the average daily Global Horizontal Irradiation (GHI) in kWh/m2, and [b] illustrates the average annual Global Horizontal Irradiation (GHI) in kWh/m2.

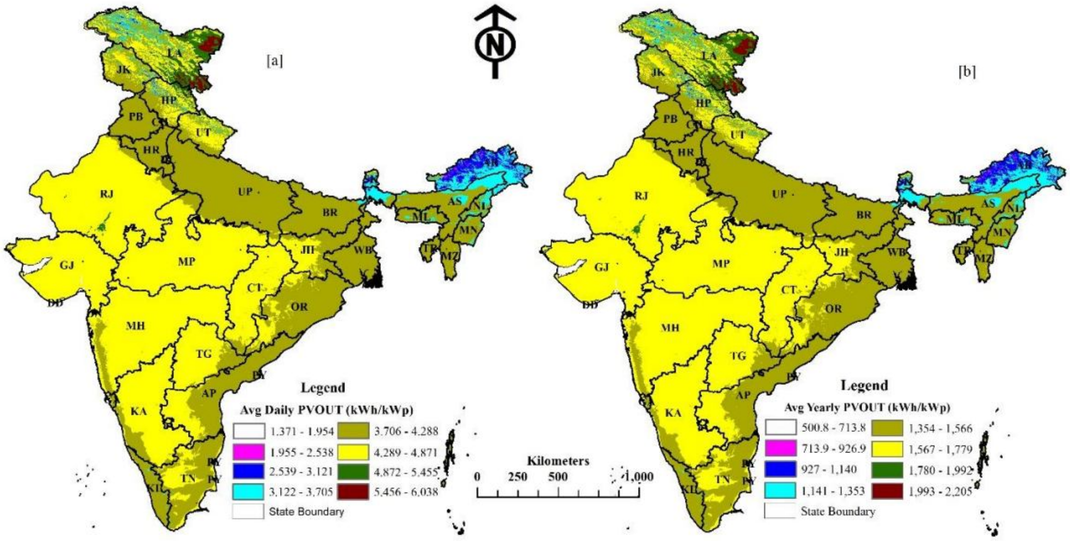


Fig. 6: [a] Displays the average daily Potential Photovoltaic Electricity Production (PVOUT) in kWh/kWp, and [b] displays the average annual Potential Photovoltaic Electricity Production (PVOUT) in kWh/kWp.

3.3. The economic and environmental analysis of solar energy and hybrid systems:

The distribution of large-scale power generation technology is the only way to fully utilize the potential of the identified solar hotspots in India. Apart from the social and organizational dimensions, this section concentrates on the techno-economic aspects of solar power technologies such as SPV and CSP.

SPV-based electricity production: The amount of electricity produced by photovoltaic cells is directly related to the exposure area and the amount of received global insolation. The formula for calculating conversion efficiency is = Po/Pi, where Po denotes the highest power output and Pi the power input under Standard Test Conditions (STC) of 1.5 air mass (AM), 1000 W/m2 global insolation, and 25 ◦C module temperature. The efficiency of SPV technology has significantly increased over the last few decades (Ramachandra *et al* 2011). The majority of SPVs produced worldwide are still first-generation mono and polycrystalline silicon (mc-Si and pc-Si) wafers with 15–22% and 12–15% cell efficiencies, respectively. Si is the primary material used in about 98% of India's SPV cell output, which meets both local and international demand (TERI Press; 2010).

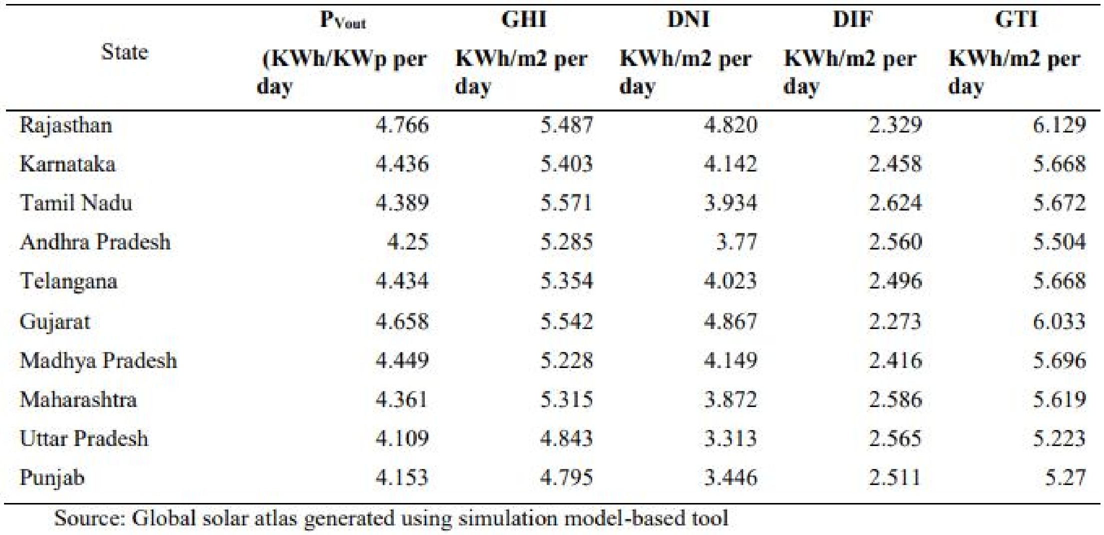
India receives between 2,600 and 3,200 hours of sunshine annually (Mani,1981). Areas with a daily global insolation of 5 kWh/m2 or more are capable of producing an actual on-site output of at least 77 W/m2 at an efficiency of 16%. Therefore, taking into account 2600 sunlight hours annually, even 0.1% of the land area of the identified solar hotspots (1897.55 km2) could provide up to 146 GW of SPV-based power (379 billion units (kWh). This power generation capability would increase significantly if SPV technology becomes more efficient (Ramachandra *et al* 2011).

India's southern regions received the most sun radiation worldwide. For DNI and GHI, the corresponding amounts of potential solar energy for the winter season were 5.304031 kWh/m^2 and 5.098091 kWh/m^2, respectively. The majority of the Southern Peninsula receives more than 4.5 kWh/m^2/day during the winter month of January, with the Western Coast plains and Ghat regions receiving up to 5.5 kWh/m^2/day. In contrast, the Western Himalayas in Northern India receive a minimum of 2.5 kWh/m^2/day. A significant portion of the Indian terrain receives more than 5 kWh/m^2/day in February, whereas the insolation in the Western (Himachal Pradesh, Uttarakhand, Jammu Kashmir) and Eastern (Assam, Arunachal Pradesh, Nagaland) Himalayas remains between 3 and 4 kWh/m^2/day. When the summer heat arrives in April and May, more than 90% of the nation experiences insolation levels above 5 kWh/m^2/day, with the Western dry and Trans-Gangetic plains recording the highest levels at 7.5 kWh/m^2/day. The Eastern Himalayan region receives a minimum of 4.7 kWh/m^2/day of global insolation during this time. June marks the start of the summer monsoon across the nation, and with it comes a notable reduction in global insolation towards the Southern (excluding Tamil Nadu) and North Eastern ranges.

During this time, the lowest recorded value is 3.9 kWh/m2/day. This pattern persists until September as the summer monsoon fades. The northern region of the nation experiences greater values in the range of 5-7 kWh/m2/day and is seldom influenced by this monsoon. The Lower-Gangetic lowlands, the East Coast plains, and the northernmost part of the country receive less than 4 kWh/m2/day of global insolation during the October-November Northeastern monsoon, which originates in Central Asia. The Himalayas function as a barrier to this winter monsoon, allowing only dry winds to reach the Indian mainland. As a result, the Himalayan foothills, lowlands, Central Plateau, and Western dry zones receive above 4.7 kWh/m^2/day. By the end of October, winter had arrived, and the Northern to Western portions of India received less than 4.5 kWh/m2/day. These seasonal fluctuations in global insolation that have been found across the nation are consistent with previous studies (Mani, 1981) that used data from 18 surface solar radiation sites (Ramachandra *et al* 2011).

India has a lot of solar energy potential, but a few challenges are preventing it from being developed further. These challenges can be broadly categorized as trade policy barriers, technological, policy, regulatory, financial, transparent, and accountable hurdles (Irfan *et al* 2020).

Table 3 - Solar power capacity in urban centers of the top 10 states



State	P_{Vout} (KWh/KWp per day	GHI KWh/m2 per day	DNI KWh/m2 per day	DIF KWh/m2 per day	GTI KWh/m2 per day
Rajasthan	4.766	5.487	4.820	2.329	6.129
Karnataka	4.436	5.403	4.142	2.458	5.668
Tamil Nadu	4.389	5.571	3.934	2.624	5.672
Andhra Pradesh	4.25	5.285	3.77	2.560	5.504
Telangana	4.434	5.354	4.023	2.496	5.668
Gujarat	4.658	5.542	4.867	2.273	6.033
Madhya Pradesh	4.449	5.228	4.149	2.416	5.696
Maharashtra	4.361	5.315	3.872	2.586	5.619
Uttar Pradesh	4.109	4.843	3.313	2.565	5.223
Punjab	4.153	4.795	3.446	2.511	5.27

Source: Global solar atlas generated using simulation model-based tool

3.4. Off-Grid SP installed capacity:

In 1992, the government launched the Off-Grid and Decentralized Solar PV Applications Programme (MNRE annual report 2021). This initiative supports rural areas of the nation (Central Financial Assistance) for the installation of solar power plants, solar street lights, and solar study lamps. The greatest number of solar street lights (1723479) and the lowest number, of solar pumps (286830), are shown in Table 1. Nonetheless, small solar power plants currently have a capacity of 216407.7 KWp, which is anticipated to gradually rise (Singh & Diwakar, 2022). Regarding study lamps (Uttar Pradesh > Bihar > Jharkhand > Assam > M.P > Tripura, > Maharashtra > Rajasthan > Uttarakhand), solar pumps (Chhattisgarh > Rajasthan > Andhra Pradesh > Uttar Pradesh > Madhya Pradesh > Gujarat and

Maharashtra), and home lights (Tamil Nadu > Uttar Pradesh > West Bengal > Jammu and Kashmir > and Uttarakhand), the pattern was noticeably different.
plus, off-grid solar power plants (Fig. 7a & Table 1), which are located in the following states: Chhattisgarh > Rajasthan > Kerala > Gujarat > Tamil Nadu > UP > J&K > Karnataka > Telangana > Bihar > Uttarakhand. 11308 villages and hamlets have been reported to be electrified using off-grid solar power. As of March 2021, Assam had the most electrified villages (1953), followed by Odisha (1614), West Bengal (1179), Tripura (842), and Jharkhand (568).

3.5. Social aspects of solar power generation in India:

The ultimate decision about the long-term viability of solar power generation is made by society, even though organizational factors, technological-economic viability, and solar resource potential all play crucial roles. For solar technology to be mobilized in India's fuel-wood-based grassroots economy, awareness of the advantages solar energy offers for the environment and human health is crucial (Ramachandra *et al* 1977). The Indian government has taken steps to disseminate knowledge at the district level. Decentralized rural electrification and management could be facilitated by creating solar micro-grid systems at the village level to meet the electricity needs of a cluster of families through proper fee-for-service models, consumer microfinance, and financial support for energy service providers (Kirubi et al., 2009). In the federal state of West Bengal's Sundarbans, a 345 kWp SPV-based SPP serving 1750 customers is proof of this effective approach (APEIS, 2011). A case study conducted in Sagar Dweep Island (Chakrabarti *et al* 2002) highlights how decentralized solar electrification improved people's health, social life, education, and income generation. Though these events motivate us to shift toward a solar economy, we must eradicate egotistical forces that push the populace and government to pursue unsustainable development paths. To guarantee that solar power generation is embraced by society, a comprehensive strategy encompassing the public, government, academia, media, and international organizations must be implemented (Ramachandra *et al* 2011).

3.6. Indian Government Incentives and Policies:

India's government has launched the Jawaharlal Nehru National Solar Mission (JNNSM) to promote solar energy development and use for power generation and other uses. The mission aims to contribute to India's long-term energy security and ecological security. The mission will be implemented in three stages, leading up to an installed capacity of 20,000 MW by the end of the 13th five-year plan in 2022. The price of solar power will attain parity with grid power at the end of the mission, enabling accelerated and large-scale expansion (Sharma, 2011).

The NTPC Vidyut Vyapar Nigam (NVVN) will be the focal point for grid-connected utility-scale power plants in Phase 1, designated for the purchase of solar power generated by independent producers at fixed rates. The mission includes a major initiative for promoting rooftop solar photovoltaic (PV) applications, with solar tariffs applicable for such installations. The mission will have a focused R&D program to address India-specific challenges in promoting solar energy.

3.6.1. Pradhan Mantri Kisan Urja Suraksha Evam UtthaanMahabhiyaan (PM KUSUM) Yojana – 2018:

Pradhan Mantri Kisan Urja Suraksha Evam UtthaanMahabhiyan (PM-KUSUM) gives farmers sustainable water and energy security by empowering them to become both Urjadata (an energy producer) and Annadata (a food producer), in keeping with the development of solar power in India (MNRE,2022).

The scheme aims to increase solar capacity to 30,800 MW by 2022, with an overall central financial support of Rs. 34,422 crores, including service charges to implementing agencies. There are three components to the Scheme:

- ✔ Component A: The installation of tiny solar power plants with each plant having a capacity of up to 2 MW will yield 10,000 MW of solar capacity.
- ✔ Component B: Installing 20 lakh standalone solar-powered agriculture pumps.
- ✔ Component C: 15 lakh grid-connected agriculture pumps are solarized.

This Yojana is introduced by GOI so that the energy created can be utilized by the farmer to fulfill irrigation needs, and any extra energy that is not needed can be sold to DISCOM. Therefore, boosting farmers' incomes likewise aids in the state's goal of achieving and sustainably reducing carbon dioxide emissions in the atmosphere (Saxena *et al* 2020).

3.6.2. New Solar Power Scheme (for PVTG Habitations/Villages) under PM JANMAN:

The goal of the Pradhan Mantri Janjati Adivasi Nyaya Maha Abhiyan (PM JANMAN) is to implement nine-line ministries with a focus on eleven essential interventions. The Mission encompasses several initiatives, including the implementation of the New Solar Power Scheme (for Particularly Vulnerable Tribal Groups (PVTG) Habitations/Villages), which has been approved for funding outlay of Rs. 515 Cr. This funding will be used to electrify one lakh un-electrified households in PVTG areas, which are spread across 18 states: Andhra Pradesh, Bihar, Chhattisgarh, Gujarat, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Manipur, Odisha, Rajasthan, Tamil Nadu, Telangana, Tripura, Uttar Pradesh, Uttarakhand and West Bengal, and UT of the Andaman & Nicobar Islands. Furthermore, there is a provision under the New Solar Power Scheme for solar lighting in 1500 Multi-Purpose Centers (MPCs) that may receive solar lighting through the New Solar Power Scheme (MNRE, 2024).

3.6.3. Roof Top Solar (RTS) Program:

Rooftop Phase-I of the RTS initiative was introduced on December 30, 2015, when subsidies and incentives were offered to the institutional, social, and residential sectors. For the government sector, achievement-linked incentives were also offered. Rooftop Phase II was initiated in February 2019 to attain a 40,000 MW total capacity by 2022 (MNRE,2022).

3.6.4. Solar mission goals are:

- ✔ To establish a framework of laws that will facilitate the installation of 20,000 MW of solar electricity by 2022.
- ✔ To increase the amount of solar power generated by grid-connected systems to 1000 MW by 2013; by 2017, an extra 3000 MW will have been generated thanks to utilities' required usage of the renewable purchase obligation, which is supported by a preferential tariff. Based on improved and enabled international finance and technology transfer, this capacity can more than double, reaching 10,000 MW installed power by 2017 or more. The lofty goal of 20,000 MW or more by 2022 will depend on how well the first two phases "learn," which, if accomplished, might result in solar electricity that is competitive with the grid. The change could be appropriately scaled up, depending upon the availability of global technology and funding.
- ✔ To establish advantageous circumstances for the capacity to manufacture solar energy, especially solar thermal, for domestic production and market dominance.
- ✔ To encourage off-grid application projects with a target of 1000 MW by 2017 and 2000 MW by 2022.
- ✔ To reach a solar thermal collector area of 15 million square meters by 2017 and 20 million square meters by 2022.
- ✔ By 2022, 20 million solar lighting systems will be installed in rural regions.

The Mission is a deliberate move by India to mitigate the effects of climate change and highlights the government's determination to support solar energy. According to a Greenpeace analysis, that, assuming solar energy replaces fossil fuels, the Jawaharlal Nehru National Solar Mission plan may guarantee a 434 million tons CO2 reduction year by 2050 (Sharma, 2011).

3.6.5. Sun One World One Grid' (OSOWOG) plan 2020:

The One Sun One World One Grid (OSOWOG) plan, which aims to connect solar energy sources across international borders, was recently launched by the Indian government. This phrase is based on the idea that "The Sun Never Sets" and remains constant everywhere, at all times. With this program, the government hopes to bring together more than 140 nations from the far East and far west to forge agreements, start pressing energy policy issues, and lay the groundwork for future international collaboration. With mutual benefit and global sustainability in mind, this will contribute to a significant advancement in the development of a sustainable network of integrated clean energy services that are smoothly transferred. A global grid that is interconnected would allow all nations to pool their renewable energy resources to fulfill peak demand for electricity and to rationalize tariffs (IRE- report, 2010). This will attract developers globally, aid in addressing socio-economic issues, and help all collaborating agencies reduce project costs while increasing productivity and optimizing capacity use (Sharma, 2011).

3.6.6. Incentives offered:

- ✔ The Central Electricity Regulatory Commission (CERC) has declared a preferred rate for solar photovoltaic power of Rs. 18.44 per unit and Rs. 13.45 per unit unit for solar thermal power for 25 years.
- ✔ Zero excise duty on the domestic manufacture of many solar energy devices and systems;
- ✔ NTPC Vidyut Vyapar Nigam will purchase solar power for 25 years at a fixed tariff announced by CERC;
- ✔ Zero or concessional duty applicable on the import of certain specific items;
- ✔ CERC will review the costs every year and fix tariffs accordingly for new projects.

4. Conclusion:

India aims to utilize renewable energy sources to transform its industry and transportation sectors. But rather than relying just on Jatropha, it's important to think about using buses, trains, and airplanes to promote bioenergy, especially biodiesel. Innovations in biotechnology are required to commercialize Jatropha. India ought to encourage the second Green Revolution and study native perennial grasses for the expansion of the bioeconomy. If non-native grass species are used without conducting adequate field research, harm to the environment and the economy may result. India should concentrate on finding more specialized sources from our biological resources for the development of bioenergy and biodiesel feedstock.

Initiatives by the government are required to encourage private enterprise, remove obstacles, and utilize biomass in a variety of ways. Although it applies to other geographic patterns, this analysis focuses on countries in Southeast Asia and EU members. The information is gathered from secondary sources and does not take into account the availability of the power grid or feedstock supply networks in practical situations.

India's solar energy output has expanded dramatically, and it now accounts for about 25% of the country's target of 100GW by 2022. Determining the optimal feedstock for bioenergy is not as important to the nation as sponsoring industrial development and biofuel conversion technology. By 2035, India is predicted to be the country with the second-highest contribution to the world's energy consumption. With the nearly 80% reduction in the cost of photovoltaic (PV) cells, there has been a shift in the production of renewable energy.

India may use bioenergy to achieve a sustainable energy future through financial incentives, enhanced research, public awareness, social amenities, strategic replenishment, and productive intergovernmental collaborations. The government is essential to the growth of renewable energy because it makes sure that plans become reality and fosters an atmosphere that attracts investment. This will support sustainable energy use and lessen drift from rural to urban areas. The production of renewable energy has gained popularity due to factors such as energy crises, rising energy costs, and global warming. For cleaner, more environmentally friendly, and sustainable energy generation, the UN has established SDGs. Leading nations in the increase of renewable energy capacity include Sweden, Germany, China, and the United States. By 2022, India wants to generate 175 GW of renewable energy, with Tamil Nadu, Gujarat, and Karnataka leading the way.

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