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GROWTH AND DEVELOPMENT OF SOLAR ENERGY IN INDIA AND THE WORLD

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"*Solar power is going to be absolutely essential to meeting growing energy demands while staving off climate change.*" **--- Ramez Naam**

ABSTRACT

Energy and economy are closely related. Energy utilization is associated with varying levels of environmental pollution, affecting climate change. Non-renewable energy causes more environmental pollution than renewable energy, especially solar energy. Energy installed capacities have been increasing. The share of installed capacity in the solar sector increased significantly from 1.45 percent in 2014-15 to 18.51 percent in 2023-24. Energy generation has also been increasing. The share of energy generation in the solar sector increased significantly from 0.42 percent in 2014-15 to 6.69 percent in 2023-24. Energy data for the top six Indian states and the top five countries in the world have been provided. Key incentives for the promotion of solar energy undertaken by the Government of India have been highlighted. India was the fifth-most polluted country globally in 2024. People must be aware, educated, and overcome the challenges of introducing solar energy for its speedy and proper implementation.

Keywords: *Renewable Energy, Non-renewable Energy, Environment, Energy Installed Capacity, Energy Generation.*

JEL Codes: O33, Q01, Q32, Q42, Q43

1. INTRODUCTION

Energy economics is the discipline that studies human utilization of energy resources and energy commodities and the consequences of that utilization. Energy is the lifeblood of the economy, central to almost every economic activity, from manufacturing to transport to schooling to communication, and thus integral to the development of any society. There is a one-to-one association between the pace of energy consumption and the rate of economic growth. Energy leads to economic growth and prosperity, which ensures the enhancement of the economy in terms of higher gross domestic product (GDP) and GDP per capita.

Economic growth and development do not simply depend upon the availability of energy input but on how energy is utilized. Energy is the engine of economic growth since all production and consumption activities require energy as a basic input (Wani et al., 2015).

Economy, Energy, and Environment (EEE or E3) is a cooperating technical assistance foundation helping communities, manufacturers, and manufacturing supply chains adapt and thrive in today's green economy, which is one that results in improved human well-being and social equity while significantly reducing environmental risks and ecological scarcity. In essence, E3 highlights the interconnectedness of economic, energy, and environmental factors, emphasizing the need for sustainable practices and policies that benefit all three aspects. A low-carbon economy (LCE) is an economy that absorbs as much carbon dioxide (CO_2) and greenhouse gas (GHG) emissions as it generates due to human activity. CO_2 and GHG emissions are the dominant causes of observed climate change since the mid-20th century.

The sources of energy are classified into two types: non-renewable (conventional and fossil fuels) and renewable (cleaner). Renewable resources cannot be depleted over time, while non-renewable resources do deplete. Renewable resources include sunlight, water, wind, biomass, and geothermal sources such as hot springs and fumaroles. Non-renewable resources include fossil fuels such as coal, natural gas, petroleum, and nuclear energy. Renewable energy and non-renewable energy are abbreviated as RE and Non-RE, respectively.

New developments in renewable energy have been making headlines and inspiring hope in communities globally. A major disadvantage of non-renewable resources is the pollution of the environment by carbon emissions. The goal of the clean energy transition is decarbonization. Renewable resources provide a cleaner and healthier environment. Renewable resources provide stronger energy security by opening up new opportunities for domestic energy production and consumption, thereby reducing reliance on foreign-sourced energy supplies. For certain types of renewable energy sources, the maintenance and infrastructure costs are minimal.

Regarding costs, renewable energy sources once compared unfavorably to fossil fuels. However, as fossil fuel prices rise, renewable energy has emerged as an affordable alternative energy option. While both clean energy and fossil fuel industries have seen job growth in recent years, growth has been markedly faster in the former. Shifting to renewable energy technologies saves money in the long run, but component costs and upfront costs can be expensive. However, legislation for incentives, tax credits, and various rebates can help offset those costs. Renewable energy power generation is generally location-dependent—solar farms require unobstructed sunlight, hydropower requires water movement, wind farms require open spaces, and geothermal power requires proximity to sources of hot water.

Renewable electricity generation is vulnerable to weather conditions: solar power is susceptible to cloudy days, hydropower to droughts, and wind power to calm days. Due to the intermittent nature of renewable power, batteries are required to store energy during peak production periods for distribution in a controlled, consistent manner during periods of low or non-production. The capacity factor of an energy power plant is the ratio of actual electricity energy produced to the maximum possible energy that could have been produced during a given period. A plant with a capacity factor of 100 percent means it's producing power all of the time. According to U.S. capacity factor by energy source in 2021, the capacity factors of different energy sources are as follows: nuclear (92.7), geothermal (71), natural gas (54.4), coal (49.3), hydropower (37.1), wind (34.6), solar (photovoltaic) (24.6), and solar (concentrating solar-thermal power) (40–50). Those for nuclear and solar (photovoltaic) are the highest and lowest, respectively.

The capacity factors for renewable energy sources are generally lower than those for non-renewable energy sources, and they reduce due to weather conditions. There is an increasing trend in the capacity factors of different energy sources. Supply chain hurdles are hindering the installation of renewable energy projects. Although solar and wind power emit no harmful emissions during power generation, the manufacturing, installation, and transportation of renewable energy equipment often produce greenhouse gas emissions (IBM, 2024)

There are environmental impacts associated with energy sources, particularly fossil fuels, at all stages: generation, transmission, and consumption. To meet the climate targets (SDGs 7 and 13) set out in Paris—"To limit global warming to 1.5°C, greenhouse gas emissions must peak before 2025 at the latest and decline 43% by 2030"—carbon dioxide removal and transitioning to low-carbon energy are absolute musts (Nayak et al., 2024).

Almost all nations have been trying to ensure access to energy for all by 2030 by accelerating electrification and increasing investments in renewable energy sources, but they have been facing some challenges in this respect. Some of those challenges include: (1) reliance on and utilization of a major share of fossil fuel sources for several years, and (2) for shifting towards the utilization of renewable energy sources, the factors of major upfront investment costs, lack of awareness, lack of expertise, and a resistant mindset are major concerns.

1.1. Solar Energy: The Hope of Future

Solar energy has a competitive price compared to other resources but is viewed as a long-term energy solution by many countries. In particularly sunny areas, solar power is the most popular source of energy. Investments in solar energy power plants are becoming increasingly popular due to their superior returns and savings. Solar energy will be a remarkable transition, much like flat-rate telecoms (Brainly, 2020).

In comparison to other energy plants, a solar installation can be built in the shortest period and is easier to maintain. Additionally, setting up solar plants on rooftop installations or in any open space with direct sunlight is all that is required to generate substantial electricity.

Employment in rural areas, especially regarding large-scale solar installations, is flourishing, and the money stays in the community. Solar power companies encourage indirect employment through the supply chain, transport, equipment manufacturing, and material acquisition.

The infrastructure consisting of basic building facilities and installations required to develop solar energy includes a solar power plant to generate power and the electrical grid for power distribution. Solar energy is widely available and unlimited. No air or water pollution is discharged when solar panels are utilized for energy production.

Solar panels are viewed as upgrades, like a renovated kitchen or a finished basement, so purchasing and installing a solar energy system in the house will likely increase home's value.

1.2. Solar Energy vs Other Renewable Energy

Solar Energy vs Wind Energy: While wind power is less costly to generate initially, wind turbines need much more maintenance than solar cells. Furthermore, wind power plants are built in remote areas with little or no proximity to the end user, so transmission lines must be built to bring electricity to the end user.

Solar Energy vs Hydroelectricity: While hydroelectricity is effective, it is generated by large dams, resulting in a high initial installation cost. Moreover, dam construction has the potential to alter an entire ecosystem. Photovoltaic (PV) panels of solar systems have little environmental impact and are much smaller than dams. One of the benefits of solar energy is its adaptability. A land or rooftop installation may be set up easily.

Solar Energy vs Biomass: Solar energy is superior to biomass. Biomass resources take a lot of energy, mainly fossil-based, to harvest, transport to the power station, and require more plant space. Biomass plants take up more space than solar plants. Biomass plants may also have environmental effects (FreyrEnergy, n.d.).

Solar technologies capture the sun's radiation and turn it into useful forms of energy. There are two main types of solar energy technologies: photovoltaics (PV) and concentrating solar-thermal power (CSP). Solar energy has many distinct advantages, such as easy maintenance, long lifetime, and decreasing prices, which still make it the renewable energy of choice for households.

Photovoltaics (PV) Basics: When the sun shines onto a solar panel, energy from the sunlight is absorbed by the PV cells in the solar panel. This energy creates electrical charges that move in response to an internal electrical field in the solar cell, causing electricity in the form of alternating current (AC) to flow.

Concentrating Solar-Thermal Power Basics: Concentrating solar-thermal power (CSP) systems use mirrors or lenses to reflect and concentrate sunlight onto receivers that collect solar energy and convert it to heat, which can then be used to produce electricity or stored for later use. It is used primarily in very large power plants (U. S. Department of Energy, n.d.).

CSP costs are higher due to the advanced technology and materials needed to focus sunlight and store heat. CSP plants flourish in regions with ample open land and high solar irradiation. Although CSP plants typically use more land per megawatt-peak (MWp), the actual electricity production can easily be twice that of a PV plant occupying the same area (Onepointe, 2022).

There are various categories of solar power installations: (a) ground-mounted solar, (b) rooftop solar, and (c) off-grid solar.

Being grid-tied is beneficial because owners don't have to purchase an expensive battery backup system to store any excess energy. Being off-grid means owners are not connected in any way to the grid's power system or utility company. This is appealing because owners are 100 percent self-sustaining in their energy use.

1.3. India as Leading Countries in the World in respect of Adopting Solar Energy

According to the International Trade Administration, India is the third-largest consumer of energy in the world. Furthermore, India is also the third-largest producer and consumer of electricity worldwide, with an installed power capacity of 466.24 GW as of January 31, 2025. In 2024, India surpassed Germany to become the third-largest generator of electricity from wind and solar energy.

India is the world's third-largest electricity consumer for FY 2022-23, with (a) 56.8 percent provided by non-renewable (fossil fuel) sources, where coal provided 49.1 percent, and (b) the rest by renewable sources, where solar, hydro, and wind systems provided 16.1, 11.2, and 10.3 percent, respectively (Ministry of Power, Government of India, 2023).

Today India is one of the biggest importers of energy in the world, and about 85 percent of the total energy and fuels needed are imported from several other countries leading to high expenditure on energy resources amongst all other expenses. With the scope to harness solar energy, there is a huge potential to meet the demand avoiding the dependency on imports. With about 300 clear and sunny days in a year, the calculated solar energy incidence on India's land area is about five quadrillion kilowatt-hours (kWh) per year (or 5 EWh/yr). If harnessed for a year, this energy will surpass India's total fossil fuel energy reserves. Many states in India have already recognized and identified the opportunity solar energy can offer in addition to being an endless power source. In the future, solar energy will greatly meet India's energy demands in multiple sectors like electricity, automobile, manufacturing, and commercial. Theoretically, a small fraction of the total incident solar energy (if captured effectively) can meet the entire country's power requirements (Enphase, 2022).

1.4 Opportunities and Benefits Presented by Solar Energy

Solar energy presents numerous opportunities and benefits, including job creation, reduced energy costs, sustainable development, and various applications like electricity generation, water heating, solar-mumping (Solar pumps use solar energy to draw water from wells and other sources) and agricultural drying. It also contributes to economic growth by fostering innovation and supporting local industries, particularly in areas with high solar potential.

Governments are increasingly implementing policies and incentives to promote solar energy development, including subsidies, tax breaks, and net metering programs.

The solar energy sector offers attractive investment opportunities for both large and small businesses, with potential for high returns and sustainable growth.

The solar industry is constantly evolving, with new technologies and innovations emerging that improve efficiency, reduce costs, and expand the range of solar applications.

Solar energy job creation occurs through various stages of the industry, including manufacturing, installation, maintenance, and related support roles. The sector offers opportunities across diverse skill levels, from technical trades to white-collar positions, fostering economic growth and sustainability.

Solar energy initiatives can significantly empower women by creating economic opportunities, enhancing livelihoods, and promoting financial independence, particularly in rural areas. By providing access to solar technology and training, women can become active participants in the clean energy sector, boosting their skills and earning potential. Women can use their solar skills to start their own businesses, providing solar solutions to their communities, which can generate income and create employment. Empowered women can become leaders in the renewable energy sector, advocating for policies that support women's participation and driving the transition to clean energy.

Solar energy provides access to clean and reliable electricity in remote areas, improving the quality of life for women and their families.

Access to solar lighting reduces the need for kerosene lamps, which are often dangerous and polluting, improving health and safety for women and children.

The shift to solar energy helps reduce reliance on fossil fuels, which contributes to climate change, creating a more sustainable and environmentally friendly future.

The "money multiplier" in solar energy refers to the idea that investing in solar technology can lead to significant financial benefits, including reduced electricity bills, potential earnings from net metering, and increased property value. These savings and earnings can be reinvested, creating a positive feedback loop and effectively multiplying the initial investment. Installing rooftop solar panels can significantly reduce or even eliminate monthly electricity bills by generating householder's own power. For example, a 5KW solar installation might generate enough electricity to offset a significant portion of a household's monthly usage, leading to substantial savings. These savings can then be used to pay off the initial investment, reduce debt, or be reinvested in other areas. Net metering allows the energy users to send excess solar energy back to the grid, and they may receive credits or payments for the energy you've contributed. Those credits can be used to offset future electricity bills or can be converted to cash, further enhancing the financial benefits of solar.

Homes with solar panels are generally considered to be more valuable, making them more attractive to potential buyers. This increased property value can be a significant long-term financial benefit, as it can be realized when the property is sold.

1.5. Challenges involved in solar development in India

While solar energy can be a boon for the Indian energy sector as an alternative source of power generation, there are still many challenges that it faces today, limiting from scaling up. Some of these challenges include:

1. Lack of R&D, modern development facilities, and manufacturing infrastructure impact the development of solar panels, equipment, and inverters to meet complete demand. This friction leads to an increase in imports from countries like China, Germany, etc., thereby increasing the cost of the system.
2. Solar systems require substantial investment in the beginning and have longer payback periods. This investment will burden the flow of investments in other energy sectors and increase the debt. This challenge discourages many people and entities from adopting solar energy.
3. Lack of awareness amongst the general public is one of the key challenges slowing the adoption of solar energy. Education on solar energy, especially in the country's rural areas, should be addressed more actively where the benefits, advantages, and accessibility perks are taught.
4. Some administrative issues, like the ease of land acquisition, government approvals, material supply limits, etc., affect the setup of solar generation plants and thereby lead to delays in development. This issue can be addressed by establishing dedicated government entities working toward solar energy implementation.
5. The overall setup warranty provided by the implementation partner is also one of the challenges that we face today. Many companies today provide limited support and warranty for implementing solar panels and systems, raising concerns for many customers. (Enphase, 2022).

1.6 Solar Energy: Peak Time in a Day, Peak Season in a Year and Variation of Adoptability across States and Regions in India

In India, peak solar generation typically occurs between 10 AM and 3 PM during the sunniest parts of the day. This is because the sun's rays are most perpendicular to the solar panels during this time, maximizing the amount of energy they can capture. While solar panels can still generate power throughout the day, the highest output is usually around midday when the sun is at its highest point.

In India, the peak season for solar generation is typically during the summer months (April-June) due to longer daylight hours and higher sun angles. Solar power generation will generally be highest around noon on sunny days. However, the exact timing and duration of peak generation can vary depending on factors like cloud cover and geographical location.

The adoption of solar energy in India varies significantly across states and between rural and urban regions due to factors like solar irradiance, government policies, infrastructure, and access to finance.

1.7. Objectives, Data and Methodology of the Study

There is a one-to-one correspondence between energy and the economy. Furthermore, energy utilization is associated with varying levels of environmental pollution, affecting climate change caused by CO_2 and GHG emissions. Non-RE causes more environmental pollution than RE, especially solar energy. Therefore, attempts have been undertaken by alliances, nations, communities, and individuals to reduce or eliminate the utilization of Non-RE, preferably in a phased manner, and to increase that of RE, especially solar energy.

The overall objective of the study is to evaluate the trends and share patterns of the energy factors (installed capacity and energy generation) of total energy, RE, Non-RE, and separately of the solar, large hydro, and wind sectors, and compare those of the solar sector with other energy sectors. The shares of small hydro and bioenergy sectors are very small compared to those of the solar, large hydro, and wind sectors. Small hydro and bioenergy have not been considered in the present study.

The study has been performed on (a) all India, and (b) the top Indian states and top countries in the world with respect to RE energy. The share patterns of the energy factors of Non-RE, RE, and separately of the solar sector, large hydro, and wind sectors have been evaluated and compared in the cases of (a) top Indian states and (b) countries with respect to RE in the world.

Secondary data on energy from government-published documents, particularly Ministry of New and Renewable Energy, Government of India, and other sources have been collected and analyzed through MS-Excel, and the results have been presented through tables and texts.

Different statistical tools utilized in the study have been provided below as follows:

A. Compound annual growth rate (CAGR)

$$CAGR = 100 * [\{\frac{Final\ Value}{Beginning\ Value}\}^{1/\text{ time span in years}} - 1]$$

has been utilized to evaluate the growth rates of energy factors.

B. Linear trend equations

$y_t = a + b * t$ where

y_t is the value of the concerned energy variable (factor) at time t, the parameters: ‘a’ and ‘b’ are the intercept and slope respectively estimated by the ordinary least square (OLS) method, have also been constructed to evaluate the growth rates as well as for forecasting the factors. The slope, an absolute figure, indicates the rate of change of the energy factor over each year. The values of R^2 (coefficient of determination or square of coefficient of correlation) have been calculated for each trend equation. Statistical test Student's t tests have been utilized to test the significance of the slopes.

Compound Annual Growth Rate (CAGR) and linear trend are both used to analyze growth over time, but they differ in how they handle the growth process. CAGR assumes growth is compounded annually, meaning returns are reinvested each year, leading to exponential growth. Linear trends assume growth occurs at a constant rate, without any compounding, resulting in a straight-line increase or decrease. CAGR smoothes out year-to-year fluctuations whereas linear trend does not. Linear trends are utilized for the forecasting purposes whereas CAGR are not.

C. Regression equations of energy generation on energy installed capacity

Energy generation = a + b * energy installed capacity where

the parameters 'a' (intercept) and 'b' (slope) to be estimated by ordinary least square (OLS) method along with the values of R^2 (coefficient of determination or square of coefficient of correlation) have been developed.

D. Coefficient of Correlation

Student's t tests have been utilized to test significances of (1) coefficient of correlation, (2) intercept and slope in case of linear trend and (3) regression coefficients in case of regression equation.

The paper is organized in seven sections as follows: 1. Introduction, 2. Review of Literature, 3. RE Energy in India with Special Reference to Solar Sector: Trends since 2014-15, 4. Top Indian States in Renewable Sources of Energy with Special Reference to Solar Sector, 5. Top Five Countries in RE in the World with Special Reference to Solar Energy, 6. Conclusions and Policy Recommendations and 7. Limitations of the Present Study.

2. REVIEW OF LITERATURE

Ramachandra et al. (2011) focused on the assessment of resource potential and variability with respect to solar hotspots in India derived from high-resolution satellite-derived insolation data. NASA SSE (surface meteorology and solar energy) global insolation datasets were derived from a physical model based on the radioactive transfer in the atmosphere along with parameterization of its absorption and scattering properties. The primary inputs to this model include visible and infrared radiation, inferred cloud and surface properties, temperature, perceptible water, column ozone amounts and atmospheric variables such as temperature and pressure measured using diverse satellite instruments. A geo-statistical bilinear interpolation was employed to produce monthly average Global insolation maps for the country detailed with isohels (defined as lines/contours of equal solar radiation) using Geographical Information Systems (GIS). Data analysis revealed that nearly 58 percent of the geographical area potentially represents the solar hotspots in the country. The study evaluated the progress made in solar power generation in the country, especially with the inception of the National Solar Mission (NSM), also termed as 'Solar India'. The organizational aspects of solar power generation, with a focus on existing policy elements, were addressed to probe the actual potential of the identified solar hotspots in meeting the NSM targets. Data and findings were presented through tables and charts.

Sasikala (2011), based on primary and secondary data in a Ph.D. study, tried to (1) study the distribution pattern of electricity and its shortages in India and Tamil Nadu, (2) assess the usage level of solar energy in India and Tamil Nadu, (3) study the socio-economic background of solar users and non-users, (4) study the determining factors behind the adoption of solar energy, (5) perform a cost-benefit analysis for the usage of solar energy, and (6) suggest policy measures for the promotion of solar energy in India and Tamil Nadu. Primary data were collected during the period January to April, 2010 using purposive sampling method. The study utilized cost-benefit analysis, frequency distribution, and regression analysis.

Srivastava et al. (2013) mentioned that solar energy, a clean renewable resource, has tremendous potential that can be harnessed using a variety of devices. With recent developments, it is easily available for industrial and domestic use with the added advantage of minimal maintenance. It can be made financially viable with government tax incentives and rebates. The National Solar Mission (NSM) is a major initiative by the Government of India and the states to promote ecologically sustainable growth while addressing India's energy security challenge. The objective of the National Solar Mission is to promote India as a global leader in solar energy. The National Action Plan on Climate Change points out: "India is a tropical country, where sunshine is available for longer hours per day and in great intensity. Solar energy, therefore, has great potential as a future energy source. It also has the advantage of permitting the decentralized distribution of energy, thereby empowering people at the grassroots level." The study was totally descriptive in nature.

Elavarthi (2014), based on primary and secondary data in a Ph.D. study, tried to (1) interpret and analyze different solar business models available in India, (2) find out when solar power can reach grid parity in all states in India, (3) analyze the performance of different solar power plants at the same location, (4) evaluate the potential of rooftop solar photovoltaics, (5) explore the application of solar power for different sectors, (6) study how to finance solar power projects, and (7) understand employment opportunities in the solar industry. The present study was mainly textual, having some tables and diagrams only.

Jaiswal et al. (2017), based on secondary data on energy power installations in India from government-published reports, provided an overview of solar energy in India through tables and charts only and presented the future potential of different forms of solar energy in India.

Singh et al. (2017), based on secondary energy data, provided an overview of solar energy in India through some tables only and focused on the technical and economic barriers and challenges for the development and utilization of solar energy technology.

Dixit et al. (2018) examined the challenges in the adoption of solar energy in India. For that research paper, a questionnaire survey method was used to identify and analyze the hurdles/issues in the implementation of solar energy in India. For that, the structured questionnaire survey was shared with the professionals, the potential and existing customers of solar energy. The received data were analyzed using relative importance index, relative importance index was applied to prioritize the severity of the factors" and other techniques. Sixteen hurdles/factors were identified for the study, and data was collected from 105 respondents using a convenient sampling technique throughout India, employing a Likert scale (1-5) to calculate the relative importance of the factors. The research findings contribute knowledge and suggestions to policymakers, manufacturers, and local bodies working on the ground to implement solar energy as an alternative energy resource to fossil fuels in India.

Hariprasad (2019) pointed out that solar power systems are now widely available for both industrial and domestic applications, and they have the added advantage of being low-maintenance and became economically feasible as a result of the government tax breaks and rebates. The author discussed the growth of solar power generation in India based on secondary data obtained from government sources through tables and charts only sketching the past of solar power generation in India from 1950 to the present.

Amutha (2020), based on secondary data from government-published reports on renewable energy for the period 2007-08 to 2016-17, presented data in tables and diagrams only, performed trend analysis, and provided annual growth and compound annual growth rates. The study pointed out that India's renewable energy sector was the fourth largest in the world. By expanding renewable energy, India can improve its environment, create new industries and jobs, and move the world towards cleaner, safer, and more affordable energy.

Bharathi et al. (2020) expressed that owing to India's growing economy, energy demand has been increasing, but there is a severe shortage of energy supply. Increasing concern over environmental pollution caused by fossil fuels has triggered the exploration of alternative energy sources, particularly solar energy. An overview of the potential for solar energy harnessing in India, its present status, barriers and challenges, supportive government policies, and future prospects was explored through the analysis of secondary energy data from government publications, presented through textual data, tables and diagrams only.

Sati et al. (2022) tackled solar energy and covered its innovations, advancements, and future prospects; provided a general summary of the world's solar energy capacity, its classification, and advantages, and described pivotal methods for enhancing usability, dependability, and affordability; and discussed potential environmental impacts and ways to mitigate them with new technological advancements and ethical behaviors in future power systems.

Gadhiya et al. (2023) investigated the viability of installing a rooftop solar power plant. Rooftop renewable energy has become popular for residential buildings. The benefit-cost ratio for the owner is 5.61, and the payback period is only 4.45 years.

Ghosh et al. (2023), based on secondary data obtained from different government-published documents and research papers, analyzed data, forecasted trends, and presented findings through tables and diagrams only. They mentioned that solar energy not only addresses the energy demands of people but also has a prominent effect on the nation's socio-economic development. Many countries are currently trying to utilize solar energy as an alternative energy source. India has excellent opportunities for solar energy due to its favorable atmosphere for solar power. The paper looked into the disparity in the use of solar energy across Indian states, attempted to understand the reasons behind such deviations, and proposed measures for the effective implementation of policies in this respect by both the central and state governments. Rural electrification through solar (PV) systems helps rural people enhance their income by extending working hours in the evening and reducing expenditures on liquefied petroleum gas (LPG) and kerosene. Solar energy promotes economic development in rural and urban areas, reduces carbon emissions, and ensures sustainable development.

Patil et al. (2023) reported on the contributions of solar energy in economic growth, sustainable development and social sustainability in India based on both the primary and secondary data through tables and diagrams only.

Saxena et al. (2024) attempted to discuss various policy options for the encouragement of solar PV installation in India. The various incentives and solar tariff scenarios were illustrated based on current trends based on secondary data through tables and diagrams only.

Chand, S. (2025) explored the growth trajectory based on secondary data from government sources through tables and charts only, economic opportunities, challenges, and future potential of solar energy in India, focusing on its role in energy security, job creation, and climate change mitigation.

2.1. Discussions on Some of the Reviewed Literatures

Ramachandra et al. focused on the assessment of resource potential and variability with respect to solar hotspots in India derived from high-resolution satellite-derived insolation data. A geo-statistical bilinear interpolation was employed to produce monthly average Global insolation maps for the country detailed with isohels (defined as lines/contours of equal solar radiation) using Geographical Information Systems (GIS).

The study of Sasikala was based on primary and secondary data tried to study the assess the usage level of solar energy in India and Tamil Nadu, the socio-economic background of solar users and non-users, the determining factors behind the adoption of solar energy, perform a cost-benefit analysis for the usage of solar energy etc. Primary data were collected during the period January to April, 2010 using purposive sampling method. The study utilized cost-benefit analysis, frequency distribution, and regression analysis.

Srivastava et al. mentioned that solar energy, a clean renewable resource, has tremendous potential that can be harnessed using a variety of devices. With recent developments, it is easily available for industrial and domestic use with the added advantage of minimal maintenance. The study was totally descriptive in nature.

Elavarthi, based on primary and secondary data in a Ph.D. study, tried to interpret and analyze different solar business models available in India, to find out when solar power can reach grid parity in all states in India etc. The present study was mainly textual, having some tables and diagrams only.

Dixit et al. examined the challenges in the adoption of solar energy in India. For that research paper, a questionnaire survey method was used to identify and analyze the hurdles/issues in the implementation of solar energy in India. The received data were analyzed using relative importance index, relative importance index was applied to prioritize the severity of the factors" and other techniques.

Amutha based on secondary data from government-published reports on renewable energy for the period 2007-08 to 2016-17, presented data in tables and diagrams only, performed trend analysis, and provided annual growth and compound annual growth rates.

Ghosh et al. based on secondary data obtained from different government-published documents and research papers, analyzed data, forecasted trends, and presented findings through tables and diagrams only.

2.2. Identification of Research Gap

Sixteen literatures including two Ph. D. theses have been reviewed. No study has utilized (a) linear trends and regression equations; coefficients of determination (R^2) and (b) comparisons of shares and trends of solar sector with those of other prominent RE sectors: large hydro and wind. The present study incorporated these aspects and measures the increasing trends of RE and solar sector superseding of the shares of large hydro and wind sector in all India; top Indian states and countries in RE energy. Therefore, the present study claims to be unique and original one.

3. RE ENERGY IN INDIA WITH SPECIAL REFERENCE TO SOLAR SECTOR: TRENDS SINCE 2014-15

In this section, trends and share patterns of all India energy data have been considered. Cumulative all India energy installed capacity (in GW) data since 2014-15 have been presented in the following table (Table 1).

The results of Table 1 reveal that (a) energy installed capacities of total energy, RE, Non-RE, large hydro, wind and solar have been increasing, (b) the shares of installed capacity related to RE, wind and solar sectors have been increasing, but those related to Non-RE, large hydro sectors have been decreasing over the years. The share of installed capacity in solar sector increased significantly from 1.45 percent in 2014-15 to 18.51 percent in 2023-24 with a CAGR as 39.88 percent; while the values of CAGRs for other cases are very low compared to solar sector. The value of slope for solar sector is very high compared to those in case of Non-RE, large hydro and wind sectors. Initially, share of solar installed capacity was very low compared to those of large hydro and wind sectors, but it exceeded that of wind sector in 2020-21 and large hydro in 2021-22.

Table 1: Cumulative All India Energy Installed Capacity (in GW) (Figures in brackets indicate Share Percent) since 2014-15

Year	Sources of Energy					
	Total	RE	Non-RE	Large Hydro	Wind	Solar
2014-15	275.90 (100)	81.22 (29.44)	194.68 (70.56)	41.27 (14.96)	23.44 (8.50)	3.99 (1.45)
2015-16	306.33 (100)	89.87 (29.34)	216.46 (70.66)	42.78 (13.97)	26.78 (8.74)	7.12 (2.32)
2016-17	328.15 (100)	103.04 (31.40)	225.11 (68.60)	44.48 (13.55)	32.28 (9.84)	12.78 (3.89)
2017-18	345.63 (100)	115.94 (33.54)	229.69 (66.46)	45.29 (13.10)	34.15 (9.88)	22.35 (6.47)
2018-19	357.87 (100)	124.81 (34.88)	233.06 (65.12)	45.40 (12.69)	35.63 (9.96)	29.10 (8.13)
2019-20	371.34 (100)	133.96 (36.07)	237.37 (63.93)	45.70 (12.31)	37.74 (10.16)	35.60 (9.59)
2020-21	383.52 (100)	142.01 (37.03)	241.51 (62.97)	46.21 (12.05)	39.25 (10.23)	41.24 (10.75)
2021-22	399.50 (100)	156.61 (39.20)	252.89 (60.80)	46.72 (11.69)	40.36 (10.10)	54.00 (13.52)
2022-23	416.06 (100)	172.01 (41.34)	244.05 (58.66)	46.85 (11.26)	42.63 (10.25)	66.78 (16.05)
2023-24	441.97 (100)	190.57 (43.12)	251.40 (56.88)	46.93 (10.62)	45.89 (10.38)	81.81 (18.51)
CAGR (%)	5.38	9.94	2.88	1.44	7.75	39.88
For Linear Trends						
Intercept	287.72(3.90)	78.79 (2.35)	208.92 (4.17)	42.61(0.44)	25.70 (0.87)	-2.36 (2.90)
Slope	16.65 (0.73)	11.60 (0.44)	5.04 (0.78)	0.57 (0.08)	2.25 (0.16)	8.41 (0.54)
R^2	0.985	0.989	0.858	0.854	0.960	0.968

Source: Government of India (2025).

Note: 1. Figures in brackets corresponding to intercepts and slopes indicate S.E. (standard errors); intercepts (except in case of solar) and slopes are highly positively significant with P-values<0.001

2. Coefficients of determinations (R^2) are very high (near to 1) indicating that trend equations may forecast energy installation capacity with high degrees of accuracy.

Year-wise all India energy generation (in BU) data since 2014-15 have been presented in the following table (Table 2).

Table 2: Year-wise All India Energy Generation (in BU)
(Figures in brackets indicate Share Percent) since 2014-15

Year	Sources of Energy					
	Total	RE	Non-RE	Large Hydro	Wind	Solar
2014-15	1105.38 (100)	190.96 (17.28)	914.42 (82.72)	129.24 (11.69)	33.77 (3.06)	4.60 (0.42)
2015-16	1168.37 (100)	187.16 (16.02)	981.21 (83.98)	121.38 (10.39)	33.03 (2.83)	7.45 (0.64)
2016-17	1236.08 (100)	203.93 (16.50)	1032.15 (83.50)	122.38 (9.90)	46.00 (3.72)	13.50 (1.09)
2017-18	1303.34 (100)	227.94 (17.49)	1075.40 (82.51)	126.10 (9.68)	52.70 (4.04)	25.80 (1.98)
2018-19	1371.68 (100)	261.65 (19.08)	1110.03 (80.92)	134.89 (9.83)	62.04 (4.52)	39.27 (2.86)
2019-20	1383.33 (100)	294.11 (21.26)	1089.22 (78.74)	155.77 (11.26)	64.65 (4.67)	50.13 (3.62)
2020-21	1373.09 (100)	297.55 (21.67)	1075.54 (78.33)	150.30 (10.95)	60.15 (4.38)	60.40 (3.40)
2021-22	1484.36 (100)	322.54 (21.73)	1161.82 (78.27)	151.63 (10.22)	68.64 (4.62)	73.48 (4.95)
2022-23	1617.58 (100)	365.66 (22.61)	1251.92 (77.39)	162.10 (10.02)	71.81 (4.44)	102.01 (6.31)
2023-24	1734.12 (100)	359.89 (20.75)	1374.23 (79.25)	134.05 (7.73)	83.39 (4.81)	115.98 (6.69)
CAGR (%)	5.13	7.29	4.63	0.41	10.57	43.13
For Linear Trends						
Intercept	1097.77 (29.59)	172.84 (7.40)	924.92 (30.67)	123.29 (6.61)	34.27 (2.74)	-7.43 (4.74)
Slope	62.21 (5.54)	21.84(1.39)	40.37 (5.75)	3.44 (1.24)	5.19 (0.51)	12.60 (0.89)
R^2	0.940	0.969	0.861	0.960	0.928	0.962
For Regression Equations of Energy Generation on Energy Installed Capacity						
Intercept	25.55 (110.15)	27.72 (19.40)	-360.57 (337.95)	-92.39 (98.15)	-24.41 (6.70)	-3.90 (1.11)
Slope	3.73 (0.30)	1.86 (0.14)	6.30 (1.41)	5.12 (1.89)	2.29 (0.18)	1.50 (0.04)
R^2	0.951	0.955	0.759	0.658	0.951	0.994

Source: Government of India (2025).

Note: 2.1 Figures in brackets corresponding to intercepts and slopes for linear trends indicate S.E. (standard errors); intercepts except in case of solar and slopes are highly positively significant with P-values<0.001

2.2 Coefficients of determinations (R^2) for linear trends are very high (near to 1) indicating that trend equations may forecast energy generation with high degrees of accuracy.

2.3 Figures in brackets corresponding to intercepts and slopes for regression equations indicate S.E. (standard errors); slopes are highly positively significant with P-values<0.001; intercepts (in cases of wind and solar) are negatively significant with P-values<0.05

2.4 Coefficients of determinations (R^2) for regression equations are very high (near to 1) indicating that regression equations may predict energy generation depending on energy installed capacity with high degrees of accuracy

The results of Table 2 reveal that (a) energy generation of total energy, RE, Non-RE, large hydro, wind and solar have been increasing, (b) the share of energy generation related to solar sector has been increasing, but those related to RE, Non-RE, large hydro and wind sectors have been fluctuating over the years. The share of energy generation in solar sector increased significantly from 0.42 percent in 2014-15 to 6.69 percent in 2023-24 with a CAGR as 43.13 percent; while the values of CAGRs for other cases are very low compared to solar sector. The value of slope for solar sector is very high compared to those in case of large hydro and wind sectors. Initially, share of solar energy generation was very low compared to those of large hydro and wind sectors, but it exceeded that of wind sector in 2021-22 and became very closed to that of large hydro in 2023-24.

3.1. India's Renewable Energy Capacity Achieves Historic Growth in FY 2024-25 and in 30th April, 2025

The Ministry of New and Renewable Energy (MNRE) has reported robust progress in India's clean energy sector for the Financial Year 2024–25. With a record annual capacity addition of 29.52 GW, the total installed renewable energy (RE) capacity in the country has reached 220.10 GW as of 31st March 2025, up from 198.75 GW in the previous fiscal. This performance reflects India's steady advancement towards the target of achieving 500 GW of non-fossil fuel-based capacity by 2030, as part of its commitments under the 'Panchamrit' goals set by Prime Minister Shri Narendra Modi.

Solar Energy Drives Growth: Solar energy contributed the most to the year's capacity expansion, with 23.83 GW added in FY 2024–25, a significant increase over the 15.03 GW added in the previous year. The total installed solar capacity now stands at 105.65 GW. This includes 81.01 GW from ground-mounted installations, 17.02 GW from rooftop solar, 2.87 GW from solar components of hybrid projects, and 4.74 GW from off-grid systems. The growth demonstrates continued uptake of solar energy across utility-scale and distributed categories.

Solar installed capacity (Cumulative) as on 30.04.2025 reached at 107.95 GW including ground mounted solar plant: 82.39 GW, grid connected solar rooftop: 17.69 GW, hybrid projects (Solar Component): 2.89 GW and off-grid solar: 4.98 GW.

Steady Rise in Wind Installations: Wind energy also witnessed sustained progress during the year, with 4.15 GW of new capacity added, compared to 3.25 GW in FY 2023–24. The total cumulative installed wind capacity now stands at 50.04 GW, reinforcing wind energy's role in India's renewable energy mix.

Bioenergy and Small Hydro Power Maintain Momentum: Bioenergy installations reached a total capacity of 11.58 GW, which includes 0.53 GW from off-grid and waste-to-energy projects. Small Hydro Power projects have achieved a capacity of 5.10 GW, with a further 0.44 GW under implementation. These sectors continue to complement the solar and wind segments by contributing to the decentralised and diversified nature of India's energy landscape.

Expanding Pipeline of Clean Energy Projects: In addition to the installed capacities, India has 169.40 GW of renewable energy projects under implementation and 65.06 GW already tendered. This includes 65.29 GW from emerging solutions such as hybrid systems, round-the-clock (RTC) power, peaking power, and thermal + RE bundling projects. These initiatives represent a strategic shift towards ensuring grid stability and reliable supply from renewable sources.

3.2. Key Incentives for Promotion of Solar Energy Undertaken by Government of India

a) **Rooftop Solar Subsidy**: The Ministry of New and Renewable Energy (MNRE) continues to provide subsidies for rooftop solar installations. As of 2024, residential consumers can avail of up to 40 percent subsidy for systems up to 3 kW and 20 percent for systems between 3-10 kW. This subsidy has been a game-changer in making rooftop solar more discounts for homeowners.

To uplift solar acquiring in the residential sector, the Indian government has launched PM Surya Ghar: Muft Bijli yojana. India has set a target of creating **280 GW of solar power capacity by 2030. The nation** has **vast solar potential,** as most of the states of India receive sunshine for more than 300 days a year. To gear up this potential, the Indian government is constantly forming policies and initiatives that encourage the shift to solar among the population. India is determined to **reduce import dependence in the solar sector** and **build domestic manufacturing capabilities.**

The objective of the National Solar Mission (NSM) is to establish India as a global leader in solar energy, by creating the policy conditions for its diffusion across the country as quickly as possible.

b) **Production Linked Incentive (PLI) Scheme**: This initiative focuses to uplift domestic manufacturing of solar panels and to reduce depends on imports. The scheme provides financial incentives to manufacturers based on sales and efficiency of solar modules, which has led to increased production and improved quality of domestic produced panels.

c) **Reduced GST Rates:** The Goods and Services Tax (GST) on solar panels and related components has been maintained at a lower rate of 5 percent to encourage adoption. This reduced tax burden has directly contributed to lowering the overall cost of solar installations.

d) **Accelerated Depreciation:** Companies investing in solar power plants can still benefit from accelerated depreciation, allowing them to deduct a larger portion of the asset's value in the early years of its life. This tax benefit makes solar investments more attractive for businesses.

e) **Net Metering Policies:** While net metering policies vary by state, most regions in India continue to offer favourable net metering arrangements. These policies allow solar system owners to feed excess electricity back into the grid and receive credits, effectively reducing their electricity bills.

4.0 TOP INDIAN STATES IN RENEWABLE SOURCES OF ENERGY WITH SPECIAL REFERENCE TO SOLAR SECTOR

4.1. RE installed capacity

As on 31st March, 2024,

a) In total installed renewable energy, Gujarat, Rajasthan, Tamil Nadu, Karnataka, and Maharashtra were the top five states contributing about 61 percent of the country's total installed renewable energy capacity installation.

b) In the solar energy sector, Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Maharashtra were the top five states contributing 70.76 percent of the country's solar power capacity installation.

c) In case of wind energy sector, Gujarat, Tamil Nadu, Karnataka, Maharashtra, Rajasthan, and Andhra Pradesh were the leading states contributing 93.37 percent of the country's wind power capacity installation.

d) In case of large hydro energy sector, Himachal Pradesh, Uttarakhand, Karnataka, Jammu and Kashmir, Maharashtra and Telangana were the top 6 states contributing 57.15 percent of the country's large hydro power capacity installation.

Cumulative energy installed capacity (in MW) data of top Indian states with significant developments in solar energy sector have been presented in the following table (Table 3).

Table 3: Cumulative Energy Installed Capacity (in MW) of Top Indian States with Significant Developments in Solar Energy Sector (Figures in brackets indicate Share Percent) since 2014-15

State	Sources of Energy					
	Total	RE	Non-RE	Large Hydro	Wind	Solar
Rajasthan	40086.72 (100)	27103.89 (67.61)	12982.83 (32.39)	411.00 (1.03)	5195.82 (12.96)	21347.58 (53.25)
Karnataka	31827.14 (100)	21441.94 (67.37)	10385.20 (32.63)	3689.20 (11.59)	6019.61 (18.91)	8544.68 (26.85)
Gujarat	53945.13 (100)	27461.72 (51.87)	25483.41 (48.13)	1990.00 (3.76)	11922.72 (22.14)	13544.88 (25.58)
Tamil Nadu	39939.50 (100)	22161.62 (55.49)	17777.88 (44.51)	2178.20 (5.45)	10603.54 (26.55)	8211.38 (20.56)
Andhra Pradesh	29154.67 (100)	11029.33 (37.83)	18125.34 (62.17)	1610.00 (5.52)	4096.65 (14.05)	4584.98 (15.73)
Maharashtra	46143.21 (100)	17530.12 (37.99)	28613.09 (62.01)	3047.00 (6.60)	5207.98 (11.29)	6249.67 (13.54)

Source: Government of India (2025).

Shares of RE installed capacities are higher than those of non-RE in Rajasthan, Karnataka, Gujarat and Tamil Nadu. Share of solar power installed capacity is higher than 50 percent only in Rajasthan. Shares of solar power installations are higher than those of large hydro and wind power installations in Rajasthan, Karnataka, Gujarat, Andhra Pradesh and Maharashtra, but that is higher than large hydro power installation in Tamil Nadu.

4.2. RE Generation during 2023-24

a) In total installed renewable energy, Rajasthan, Gujarat, Karnataka, Himachal Pradesh, and Tamil Nadu were the top five states contributing about 56 percent of the nation's total renewable energy generation.

b) In the solar energy sector, Rajasthan, Karnataka, Gujarat, Tamil Nadu, and Andhra Pradesh were the top five states contributing over 75 percent of the country's solar power energy generation.
c) In case of wind power sector, Gujarat, Tamil Nadu, Karnataka, Andhra Pradesh, Rajasthan, and Maharashtra were the leading six states contributing about 93 percent of the country's wind energy generation.
d) In the case of large hydro sector, Himachal Pradesh, Jammu and Kashmir, Uttarakhand, Karnataka and Sikkim were the top five states contributing 62.47 percent of the country's large hydro energy generation.

Year-wise energy generation (in MU) data of top Indian states with significant developments in solar energy sector have been presented in the following table (Table 3).

Table 4: Year-wise Energy Generation (in MU) of Top Indian States with Significant Developments in Solar Energy Sector (Figures in brackets indicate Share Percent) since 2014-15

State	Sources of Energy					
	Total	RE	Non-RE	Large Hydro	Wind	Solar
Rajasthan	116847.23 (100)	48164.86 (41.22)	68682.37 (58.78)	1037.97 (0.87)	8390.67 (7.18)	38365.21 (32.83)
Karnataka	91468.95 (100)	39499.72 (43.18)	51969.23 (56.82)	8913.17 (9.81)	10950.2 (11.97)	15404.09 (16.84)
Gujarat	135398.90 (100)	43039.55 (31.79)	92359.35 (68.21)	4556.33 (3.37)	24794.50 (18.31)	13468.91 (9.95)
Tamil Nadu	123311.63 (100)	33166.59 (26.90)	90145.04 (73.10)	3563.28 (2.89)	16908.08 (3.71)	11737.48 (9.52)
Andhra Pradesh	90081.32 (100)	18837.67 (20.91)	71243.65 (79.09)	1373.19 (1.52)	8644.00 (9.60)	8300.03 (9.21)
Maharashtra	169037.91 (100)	24029.90 (14.22)	145008.01 (85.78)	5264.49 (3.11)	8228.97 (4.87)	5814.13 (3.44)

Source: Government of India (2025).

Shares of energy generation from solar energy sector are higher than those from large hydro and wind energy sector in Rajasthan, Karnataka and Tamil Nadu. But in cases of Gujarat, Andhra Pradesh and Maharashtra, shares of energy generation from solar energy sector are higher than those of large hydro sector.

5.0 TOP FIVE COUNTRIES IN RE IN THE WORLD WITH SPECIAL REFERENCE TO SOLAR ENERGY

Since the global energy data have been accessed from various sources, the figures could not be standardized to the same reference data.

China's solar prowess is surprising. With a massive **710 GW** solar capacity (as of June 2024), the country stands the largest manufacturer of solar energy in the World. China presently publicized plans to develop **1200 GW of solar and wind energy capacity by 2030.**

But reports disclose that the country is on target to reach this by the end of 2024. China is the World highest manufacturer of solar equipment. China has invested over **50 billion US$,** in **new PV supply capacity since 2011** which is ten times larger than the amount invested by the entire Europe in the same industry. **China's share in manufacturing solar panels exceeds 80 percent.** Recently, subsidy-free solar power has become low-cost than coal in China.

With **200+ GW** of installed capacity (as of June 2024), the USA achieves second position in the list of top solar countries.

Germany leads the European countries in renewable energy and achieves the third position in the list of top solar countries. As of 2024, the nation's solar capacity was **90 GW**.

On August, 2024; India's installed solar power capacity reached 89.4 GW. In the first half of 2024, the country added 15 GW of new PV capacity. Further, India overtook Japan to become the third largest solar power producer in 2023.

Japan's total solar installed capacity exceeds **87 GW**. Japan is considered the **fastest growing in terms of promoting Solar PV.** Further, with **45 percent of the World's photovoltaic cells manufactured in Japan**, the nation leads the World in the photovoltaic market.(Ornate Solar, 2024).

Contribution in total RE installed capacity of the World and share of various RE installed capacity (in RE installed capacity) within the respective country up to 31st December, 2023 in top five countries of the World have been provided in the following table (Table 5).

Table 5: Contribution in Total RE Installed Capacity of the World and Share of Various RE Installed Capacity (in RE Installed Capacity) within Respective Country up to 31st December, 2023 in Top Five Countries of the World

Country	Contribution in Total RE Installed Capacity of the World (%)	Share (%) of Various RE Installed Capacity (in RE Installed Capacity)		
		Large Hydro	Wind	Solar
China	37.62	25.49	30.40	41.96*
USA	9.97	21.89	38.43*	36.14
Brazil	5.02	56.63*	15.01	19.30
India	4.55	26.91	25.43	41.55*
Germany	4.32	3.44	41.61	48.96*

Source: Government of India (2025).

**Indicates highest share. Highest shares belonged to wind and large hydro in cases of USA and Brazil respectively, but to solar in cases of China, India and Germany. Share of solar exceeded that of (a) large hydro in case of USA and (b) wind in case of Brazil.*

The shares of solar RE installed capacity (in RE installed capacity) are higher than those of large hydro and wind sectors in China, India and Germany.

Total contribution in total RE installed capacity of the World upto 31st December, 2023 by the abovementioned countries was 61.42 percent.

Contribution in total RE generation of the World and share of various RE sources in the total RE generation within the respective country during 2022 in top five countries of the World have been provided in the following table (Table 6).

Table 6: Contribution in Total RE Generation of the World and Share of Various RE Sources in Total RE Generation within Respective Country during 2022 in Top Five Countries of the World

Country	Contribution in Total RE Generation of the World (%)	Share (%) of Various RE Sources in Total RE Generation		
		Large Hydro	Wind	Solar
China	31.11	49.67*	29.08	16.31
USA	11.37	26.75	45.79*	19.50
Brazil	7.07	71.90*	13.74	5.07
Canada	5.32	88.50*	8.20	1.28
India	4.01	47.48*	20.53	24.73

Source: Government of India (2025).

**Indicates highest share. Highest Shares belonged to wind in case of USA and to large hydro in other cases. Share of solar exceeded that of wind in case of India.*

Total contribution in total RE generation of the World during 2022 by the abovementioned countries was 58.65 percent.

There is a highly positively significant coefficient of correlation between contributions of total RE installed capacity and total RE generation of leading countries in respect of utilization of renewable energy in the world is 0.993 (P-value<0.001).

Top ten countries by nominal GDP as of 1st quarter, 2024 are USA, China, Germany, Japan, India, UK, France, Brazil, Italy and Canada (Investopedia, 2025).

This information indicates strong linkage of energy and economy.

Utilization of energy is very much related to population size and population density.

An outlook of population and economies of the countries China, USA, Brazil, Canada, India and Germany mentioned in the above mentioned two tables (Tables 5 and 6) has been provided in the following table (Table 7).

On the basis of population densities, the world ranks of China, Brazil, India and Germany are 82, 193, 20 and 58 respectively.

Among the leading countries in respect of utilization of renewable energy in the world, there are significantly positive coefficients of correlation (a) 0.553 (P-value<0.01) between population size and RE installed capacity and (b) 0.476 (P-value<0.05) between population size and RE generation.

Table 7: Economies of China, USA, Brazil, Canada, India and Germany

Country	Population Size[a] (in Crores) (World Rank) 2025	Population Density[a] (Population Size per Kilometer Square 2025	GDP (US $)[b] (World Rank) 2025	2025 Projected Real GDP (% Change)[b] 2025	GDP Per Capita[b] (Current Prices) (US $) 2025
China	141.61 (2)	151	$ 19.23 trillion (2)	4.0	$ 13.69 thousand
USA	34.73 (3)	38	$ 30.51 trillion (1)	1.8	$ 89.11 thousand
Brazil	21.28 (7)	25	$ 2.13 trillion (10)	2.0	$ 9.96 thousand
Canada	4.01 (38)	4	$ 2.23 trillion (9)	1.4	$ 53.56 thousand
India	146.39 (1)	492	$ 4.19 trillion (4)	6.2	$ 2.88 thousand
Germany	8.41 (19)	241	$ 4.74 trillion (3)	-0.1	$ 55.91 thousand

Source: [a]Worldometer (2025)
[b]Forbes India (2025) Sourced from IMF Data (as of April 28, 2025)

Among the leading countries in respect of utilization of renewable energy in the world, there are significantly positive coefficients of correlation (a) 0.532 (P-value<0.01) between GDP and RE installed capacity and (b) 0.468 (P-value<0.05) between GDP and RE generation.

The Climate Change Performance Index (CCPI) is an annual report that evaluates the climate protection efforts of 63 countries and the EU, collectively responsible for over 90 percent of global greenhouse gas emissions. The CCPI aims to enhance transparency in international climate politics and allows for a comparison of countries' climate mitigation efforts.

The world's biggest emitter of CO_2 and GHG: China ranks 55th in the CCPI, falling to a very low level. Despite promising plans, trends and measures, China remains heavily dependent on coal and lacks sufficient climate targets.

The US, the second biggest emitter CO_2 and GHG, remains in 57th place in CCPI among the very low performers.

India ranks the 10th in CCPI 2025 among the highest performers. India receives a *high* ranking in the GHG Emissions and Energy Use categories, medium in Climate Policy, and low in Renewable Energy.

The Climate Risk Index (CRI) ranks countries based on the human and economic impact of extreme weather events over a specific period. It assesses how countries are affected by climate-induced disasters, such as floods, heat waves, and cyclones, by considering factors like fatalities, economic losses, and the number of people affected. The CRI is a backward-looking index, meaning it analyzes the consequences of extreme weather events that have already occurred.

The Human Development Index (HDI) is a composite statistic used to rank countries by their level of human development. It measures average achievements in three basic dimensions: health, knowledge, and a decent standard of living. It is calculated by averaging normalized indices for life expectancy, education, and income.

Detailed Explanation of components of HDI:

Health: Measured by life expectancy at birth.

Knowledge: Measured by mean years of schooling and expected years of schooling.

Standard of Living: Measured by Gross National Income (GNI) per capita.

The HDI is calculated as the geometric mean of the normalized indices for each of the three dimensions.

Pollution is the introduction of harmful materials into the environment. These harmful materials are called pollutants. Pollutants can be natural, such as volcanic ash. They can also be created by human activity, such as trash or runoff produced by factories and primarily due to industrial emissions, vehicle pollution, and the widespread use of coal for heating. Pollutants damage the quality of air, water, and land. PM2.5 stands for "particulate matter" that is 2.5 micrometers or smaller in size. These particles are so tiny that we cannot see them with our eyes, but they can go deep into our lungs and even into our blood.

According to the 2024-25 IQAir report, South Asia remains one of the most polluted regions in the world. Bangladesh, Pakistan and India are among the top five most polluted countries. Chad stands as the most polluted countries in the world with the PM2.5 concentration of 91.8 $\mu g/m^3$, followed by Bangladesh, Pakistan, Democratic Republic of the Congo and India. India showed a small improvement, with its PM2.5 level dropping to 50.6 $\mu g/m^3$ from 54.4 in 2023. Pakistan's air quality is still very poor, with a high PM2.5 level of 73.7 $\mu g/m^3$.

The figures for the socio-economic, climatic and environmental indicators: HDI, CCPI, CRI and average PM2.5 concentration (with rank) of the above mentioned six countries have been presented in the following table (Table 8).

Table 8: HDI, CCPI, CRI and Average PM2.5 Concentration (with Rank) of China, USA, Brazil, Canada, India and Germany

Country	HDI 2022[a]	CCPI 2025[b]	CRI for 1993-2022 (Annual Averages)[c]	Pollution Level 2024: Average PM2.5 Concentration ($\mu g/m^3$) (with Rank)[d]
China	0.797	55th	2nd	31.0 (21st)
USA	0.938	57th	13th	7.1 (116th)
Brazil	0.786	28th	101st	14.9 (73rd)
Canada	0.939	62nd	120th	6.7 (119th)
India	0.685	10th	6th	50.6 (5th)
Germany	0.959	16th	48th	9.0 (103rd)

Sources: [a]World Population Review (2025) [b]CCPI (2025) [c]Germanwatch (2025) [d]IQAir (2025)

Among the leading countries in respect of utilization of renewable energy in the world, there are significantly positive coefficients of correlation (a) 0.680 (P-value<0.01) between CCPI and RE installed capacity and (b) 0.430 (P-value<0.05) between CCPI and RE generation.

Among the leading countries in respect of utilization of renewable energy in the world, there are significantly negative coefficients of correlation (a) -0.479 (P-value<0.01) between CRI and RE installed capacity and (b) -0.495 (P-value<0.05) between CRI and RE generation.

Among the leading countries in respect of utilization of renewable energy in the world, no significant associations of HDI and pollution level have been obtained.

Global new investment in renewable power and fuels (not including hydropower projects larger than 50 megawatts, MW) reached a record high of an estimated US $ 622.5 billion in 2023. Investment increased 8.1 percent from 2022, due largely to the global rise in solar photovoltaic (PV) installations. Factors contributing to rising renewable energy investment in recent years include the global energy crisis, as well as alignment across climate change policy ambition, energy security goals and industrial strategies. Together with declining unit costs, this has created a supportive investment environment for renewables. Solar PV and wind power continued to dominate new investment in renewables, with solar PV accounting for 63 percent of the 2023 total and wind power for 35 percent, almost mirroring the shares of 2022. China continued to account for the largest share of global renewable energy investment at 44 percent, followed by Europe (20.9 percent) and the USA (15 percent) (Ren21, 2024).

India is undergoing a transformative shift toward renewable energy, driven by the need to sustainably meet its growing demand for electricity while reducing its dependence on fossil fuels. As one of the fastest-growing economies, the nation has set ambitious targets to ensure energy security, promote environmental health and meet its global climate commitments under the Paris Agreement. This includes a pledge to achieve 500 gigawatts (GW) of renewable capacity by 2030 and reach net-zero carbon emissions by 2070. Solar energy has become a key driver of this transition, supported by initiatives such as the Jawaharlal Nehru National Solar Mission (JNNSM) and policies that encourage investment through tax incentives and subsidies. India's solar energy journey took a significant leap with the introduction of JNNSM in 2010. Driven by the sector's potential and the country's renewable energy goals, this target was soon revised upwards. Solar energy quickly emerged as a key component of India's green energy strategy, supported by a strong policy framework and investment-friendly environment (IBEF, 2025).

India's solar energy sector created significant employment opportunities, with over 238,000 jobs in grid-connected solar PV and around 80,000 in the off-grid sector as of 2023. The renewable energy sector as a whole employed over one million people in 2023, with solar PV and hydropower being the largest contributors. The sector is expected to continue growing, with potential for even more jobs in the coming years (Government of India, 2024).

China's solar energy industry is a major source of employment, with the sector employing an estimated 4.6 million people in the country, primarily in manufacturing and installation of solar panels. China's dominance in solar PV (photovoltaics) manufacturing and installation has led to a significant number of jobs globally, with China contributing a large portion of the global solar jobs market.

In 2023, the USA solar energy industry employed 279,447 workers, representing a 5.9 percent increase from the previous year. This increase included both utility-scale and residential installation segments. The solar industry was a major economic engine, with private investment of over $70 billion in 2024.

In 2023, the solar photovoltaic (PV) industry in Brazil generated roughly 264,000 jobs. The Brazilian solar heating and cooling industry created about 50,700 jobs in the same year. These figures represent a significant increase in employment compared to 2018, when the solar PV industry had 16,600 employees.

The Canadian solar energy industry is experiencing substantial growth, leading to a rise in employment opportunities across various sectors. In 2020, the industry employed approximately 10,000 people annually in construction, manufacturing, operations, and maintenance, with a projected 10 percent annual growth over the next five years. By 2025, the solar industry is expected to support more than 35,000 jobs and displace 15 to 31 million tonnes of greenhouse gas emissions annually.

Reflecting the 104 percent growth in its solar market from 2022 to 2023, Germany's solar workforce became the largest workforce in Europe, with 154,000 solar workers.

India has implemented several policy advancements to boost solar energy adoption, including financial incentives, regulatory reforms, and ambitious targets for renewable energy capacity. Key initiatives like the Jawaharlal Nehru National Solar Mission (JNNSM) and the PM Surya Ghar: Muft Bijli Yojana (PM-SGY) etc are driving solar power generation and distribution.

Public-Private Partnerships (PPPs) play a crucial role in the growth of solar energy in India, combining the government's policy backing with the private sector's capital, technology, and expertise. This model helps accelerate project development, improve efficiency, and unlock India's vast solar potential.

6. CONCLUSIONS AND POLICY RECOMMENDATIONS

In the financial analysis, the cost-benefit analysis of solar panels reveals a compelling case for their adoption. While the initial investment may seem significant, the long-term savings on energy bills, environmental benefits, and potential financial incentives contribute to a positive economic outlook.

The Ministry of New and Renewable Energy (MNRE) is working towards achieving 500 GW of renewable energy capacity by 2030, as announced by the Prime Minister at COP26. As of April 30, 2025, they have installed a total of 51,058.55 MW of wind power, 107,945.61 MW of solar power, and 5,102.05 MW of small hydro power. The ministry also launched the

Green Hydrogen Certification Scheme of India (GHCI) and organized a workshop on opportunities for MSMEs in the green hydrogen supply chain.

The study revealed the following:

a) The installed capacities of total energy, RE, Non-RE, large hydro, wind, and solar have been increasing. The shares of installed capacity related to RE, wind, and solar sectors have been increasing, but those related to Non-RE and large hydro sectors have been decreasing over the years. The share of installed capacity in the solar sector increased significantly from 1.45 percent in 2014-15 to 18.51 percent in 2023-24, with a CAGR of 39.88 percent, while the values of CAGRs for other cases are very low compared to the solar sector.
b) The energy generation of total energy, RE, Non-RE, large hydro, wind, and solar has been increasing. The share of energy generation related to the solar sector has been increasing, but those related to RE, Non-RE, large hydro, and wind sectors have been fluctuating over the years. The share of energy generation in the solar sector increased significantly from 0.42 percent in 2014-15 to 6.69 percent in 2023-24, with a CAGR of 43.13 percent, while the values of CAGRs for other cases are very low compared to the solar sector.
c) In total installed renewable energy, Gujarat, Rajasthan, Tamil Nadu, Karnataka, and Maharashtra were the top five states, contributing about 61 percent of the country's total installed renewable energy capacity.
d) In the solar energy sector, Rajasthan, Gujarat, Karnataka, Tamil Nadu, and Maharashtra were the top five states, contributing 70.76 percent of the country's solar power capacity.
e) In total installed renewable energy, Rajasthan, Gujarat, Karnataka, Himachal Pradesh, and Tamil Nadu were the top five states, contributing about 56 percent of the nation's total renewable energy generation.
f) In the solar energy sector, Rajasthan, Karnataka, Gujarat, Tamil Nadu, and Andhra Pradesh were the top five states, contributing over 75 percent of the country's solar power energy generation.
g) The total contribution to the World's RE installed capacity up to 31st December 2023 by China, the USA, Brazil, India, and Germany was 61.42 percent.
h) The total contribution to the World's RE generation during 2022 by China, the USA, Brazil, Canada, and India was 58.65 percent.
i) India ranks (a) 10th, 6th and 5th in the World rankings with respects of CCPI, CRI and pollution level respectively.

Key incentives for the promotion of solar energy undertaken by the Government of India have been highlighted.

People must be aware of SDG7, urging "affordable, reliable, sustainable and modern energy for all" by 2030, and SDG13, urging action "to combat climate change and its impacts," and the implementations of these goals. To keep ourselves safe to survive, we have to save our motherland: the Earth, the only planet in the Universe that is home to living beings (animals, plants, and microorganisms).

Although governments have proposed and been implementing policies, programs, and incentives for the promotion of solar energy, people must be aware, educated, and ready to overcome any resistance to introducing unfamiliar technology, such as solar energy, for its speedy and proper implementation.

To accelerate solar energy implementation in India, policies should focus on incentivizing investments, streamlining bureaucratic processes. Key recommendations include setting clear targets for solar capacity addition, offering financial incentives like subsidies and tax breaks, and simplifying regulations for grid-connected rooftop solar systems. Additionally, promoting awareness campaigns about the benefits of solar energy and its environmental impact is crucial.

7. LIMITATIONS OF THE PRESENT STUDY

Research on solar energy faces limitations in several areas, including the intermittent nature of solar power, the high initial costs of solar systems, the need for large land areas for solar installations, and challenges in energy storage and grid integration. The manufacturing process of solar panels can have environmental impacts, and the availability of certain materials may be limited. Furthermore, development of awareness and education

Raising awareness and providing education about solar energy are crucial for promoting its adoption and creating a more sustainable future. Education can empower individuals, communities, and businesses to make informed choices about renewable energy, while awareness campaigns can mitigate misconceptions and highlight the benefits of solar power.

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