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Review Article

Scenario of solar energy and policies in India

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Abstract

Solar power is energy from the Sun that is converted into thermal or electrical energy. China, the USA, and India have the world's richest solar energy sources. India receives solar radiation with an average intensity of 200 MW/km^2 and 250–300 sunny days a year. The solar radiation in India varies from 4 to 7 kWh/m^2/day, with 2300–3200 sunshine hours yearly, depending on the region. Badhla Solar Park, Jodhpur, India, is the world's largest solar plant, with 2.25 GW of installed capacity. Solar energy is the best alternative electricity source used explicitly in the agricultural sector. In the farming sector, the consumption of solar energy has been increasing. The major issues were the installation costs, low availability of technicians, and poor quality of panels. The focus on skill development equips the workforce to drive innovation, efficiency, and sustained growth in the renewable-energy field. With the support of international collaboration and a skilled workforce, India's progress in solar energy development is a boon for the industry.

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Graphical Abstract

Keywords: solar energy; benefits; policies; challenges; achievements

1. Introduction

One-third of global greenhouse gas emissions are attributed to coal, oil, and natural gas use in electricity production. To raise people's standard of living, it is necessary to provide cleaner and more reliable electricity [1]. Various energy sources are used in India's electricity market, including conventional and non-conventional sources. In India, the power generation sector is one of the most developed in the world, using a wide variety of sources such as coal, natural gas, hydroelectricity, nuclear power, wind power, and solar power, as well as agricultural and household waste [2]. Due to population growth, urbanization, and technological advancements, India's electricity demand has increased and is expected to continue to increase in the coming years [3]. Efforts have been made by the Indian government to achieve "Power for All" and to increase the country's capacity [4]. With sustained economic growth driving electricity demand in India, the future of the power sector appears bright [5]. To achieve sectoral decarbonization goals and reduce greenhouse gas emissions, continued policy focus must be placed on the decarbonization of the power sector [6]. A sustainable and efficient electricity system in India requires both intelligent grid models and alternative energy resources, as well as a goal of producing 175 GW of renewable energy. The renewable-energy sector in India has made significant progress. Towards the end of 2020, the country intended to grow 10% of its total installed capacity from renewable resources [7]. Wind energy accounts for ~13% of the total installed capacity, accounting for most of the contribution [8]. In addition to reducing greenhouse gas emissions, improving energy security, and fostering rural and regional development, renewable energy is increasingly emphasized [9]. In addition to biomass, solar, wind, geothermal, and ocean energy, India has been actively researching, developing, and implementing various renewable-energy technologies [10]. As part of its efforts towards renewable energy, the country is also exploring the possibility of producing biofuels, particularly on biogas, biomass-based energy, and microalgae. Despite favorable geology and geography, technological advancements, and suitable regulatory policies, the Indian renewable-energy scenario appears promising [11]. According to the World Energy Council, India had 113 GW of installed renewable-energy capacity as of May 2022, making it the third-largest producer in the world. By 2030, the country intends to generate 500 GW of energy using non-fossil fuel sources [12]. In addition to accounting for over a third of the nation's installed capacity, renewable energy accounts for >40% of the country's power generation. Renewable energy is mainly owned by the private sector in India, with the highest concentration in the western coastal states [13]. Several policy recommendations have been suggested to promote renewable energy and sustainably develop the Indian economy by analysing the country's growth and pattern of renewable energy [14]. As a result of the mismatch between the availability of renewable energy sources and the obligation of obligated entities to meet their renewable purchase obligations, the Central Electricity Regulatory Commission has instituted market-based mechanisms, such as the Renewable Energy Certificate (REC). Investing in renewable energy sources is becoming increasingly attractive due to the downtrend in the cost of power generation from these sources [15]. A typical year in India consists of 250–300 sunny days, with an average solar radiation intensity of 200 MW/km^2. Many methods have been employed to estimate the solar radiation intensity in India, including artificial neural networks (ANNs) [16], Angstrom linear-type correlations [17], and estimates based on the extremes of air temperature [18]. Depending on the region, solar radiation in India ranges between 4 and 7 kWh/m^2/day, and there are 2300–3200 hours of sunlight per year [19]. As India is a tropical country, it receives solar radiation almost all year round, making it an ideal place to generate solar energy [20]. The locations of states such as Andhra Pradesh, Bihar, Gujarat, Haryana, Madhya Pradesh, Maharashtra, Orissa, Punjab, Rajasthan, and West Bengal make them ideal for harnessing solar energy [21]. Solar power projects in the Thar Desert of India have been identified as having the potential to generate 700–2100 GW [22]. Numerous studies have been conducted to discover the world's overall renewable-energy scenario, but all these studies focus on overall renewable-energy scenarios rather than solely on solar energy. This study exclusively focuses on the scenario of renewable energy, especially solar energy in India, as well as significant achievements. This study also focuses on the challenges and opportunities for solar energy in India as it serves as a tool for future research. The result of the study, as well as the hypothesis, expected that the production and consumption of solar energy will increase and that the government and private sector will consider investment in solar energy.

This study exclusively focuses on the scenario of renewable energy, especially solar power, in India, as well as significant achievements. This study also focuses on the challenges and opportunities for solar energy in India, as it serves as a tool for future research.

1.1 Overview of renewable-energy scenario in India

The Government of India has set an objective of adding 175 GW of installed renewable-energy capacity by 2022, with 100 GW coming from solar power, 60 GW from wind power, 10 GW from biomass, and 5 GW from small hydropower plants. Currently, India has 86.75 GW of installed renewable-energy capacity, with 41.10 GW of solar power [23]. A growing demand for electricity and favorable government policies attract foreign investors [24]. Several studies conducted in India, South Asia, and Africa indicate that electricity consumption and government policies significantly contribute to economic growth. According to [25, 26], there is a unidirectional causality between electricity consumption and economic growth in India [27]. The effects of electricity, government spending, financial development, and capital formation on the growth of economies in South Asian countries, including India, are significant [28].

Table 1 shows the capacity of renewable energy in India. The total renewable energy source was 136570.09 MW as of February 2024. Solar energy makes up ~55% of the overall renewable-energy contribution, which means the production and consumption of solar energy are increasing daily. As compared with previous years such as 2020–21, 2021–22, and 2022–23, the production of solar energy has been an increasing trend due to a lot of policies implemented by the Government of India, which mainly focus on the welfare of the people as well as reducing the dependency on the consumption of electricity. Solar energy produced in the manner described above will be used in various fields, including industry, an information technology park, agriculture, etc. Solar water pumps and ponds are used to irrigate fields and store irrigation water, which are the primary applications of solar energy in the agricultural sector [29–32].

1.2 Types of solar photovoltaic system

1.2.1 *Grid-tied (on-grid system)*

Grid-tied or on-grid systems are becoming increasingly popular for renewable-energy applications. These systems allow the integration of renewable energy sources, such as solar photovoltaic

Table 1. Capacity of renewable energy in India (MW). [12]

Sector	2020–21	2021–22	2022–23	Cumulative as of 29 February 2024
Wind power	1503.30	1110.53	2275.55	45 153.67
Solar power	5628.80	12 760.50	12 783.80	75 575.81
Small hydro power	103.65	62.09	95.40	4994.75
Biomass (bagasse) cogeneration	173.37	59.69	0.00	9433.56
Biomass (non-bagasse) cogeneration	97.24	0.00	42.40	828.25
Waste to power	21.00	54.50	25.00	249.74
Waste to energy (off-grid)	20.75	34.66	52.28	334.31
Total	7548.11	14 081.97	15 274.43	136 570.09

Source: Ministry of New and Renewable Energy.

(PV) systems, into the electric power grid. They eliminate the need for energy storage and provide the ability to feed excess power back into the grid. Various topologies and techniques have been developed to improve the performance and efficiency of grid-tied systems. These include the use of multilevel inverters (MLIs) [33], modified W-type 81-level inverters [34], and line commutated converter (LCL) filters [35]. Additionally, the control strategies and power factor correction methods are crucial in optimizing the operation of grid-tied systems [36]. The goal is to ensure stable and efficient power transfer between the renewable energy source and the grid while maintaining grid stability and quality [37].

1.2.2 *Grid-tied with battery backup*

Grid-tied PV–battery power systems can provide battery backup during abnormal grid conditions and improve power quality. Using battery energy storage systems (BESSs) in these set-ups allows load leveling and power factor correction [38]. The control of the voltage source inverters in the systems can maintain power balance and improve power quality under local non-linear loads [39]. Additionally, the BESSs can comply with grid code and fault ride-through (FRT) requirements through a dual control strategy that switches between constant battery current control and continuous direct current (DC)-link voltage control [40]. Integrating BESSs into grid-tied systems can also provide additional services such as frequency regulation, enhancing reliability and generating revenue [41, 42].

1.2.3 *Off-grid system*

Off-grid systems are a solution for areas that lack access to a consistent energy supply from the power grid. These systems use solar panels to convert sunlight into DC, which is stored in batteries. A charge controller regulates the charging and discharging cycles of the battery pack, while an inverter converts the stored DC electricity into alternating current (AC) for appliances and other AC loads [43]. Off-grid solar power systems are cost-effective and efficient for bringing electricity to areas without grid connection [44]. Additionally, off-grid solar PV systems can generate electricity in remote areas, eliminating the need for local generators [45]. To ensure continuous energy production in off-grid areas, a hybrid solution of vertical wind turbines and solar cells can be used [46].

1.3 Largest solar power plants in the world

1.3.1 *Bhadla Solar Park, India*

Bhadla Solar Park was the largest solar park in the world as of the year 2020, with a total investment of ~$1.4 billion [47]. It is part of India's efforts to transition to renewable energy sources—specifically solar power [48]. The park is located in the state of Rajasthan and has a capacity of 6263.71 MW, covering an area of 126.74 km^2 [49]. The project has signed a 25-year power purchase agreement with developers, ensuring the sale of the generated power [50]. However, it is essential to note that the development of solar parks in India has had unintended consequences, such as gender disparities and economic exclusion in rural areas [51]. Bhadla Solar Park is a significant milestone in India's renewable-energy journey, showcasing the country's commitment to sustainable development and reducing reliance on fossil fuels.

1.3.2 *Benban Solar Park, Egypt*

Benban Solar Park is a large-scale solar power plant in Aswan, Egypt. It utilizes solar power tower technology and has a total capacity of 1600 MW AC, producing annual electricity of 3.8 TWh [52]. The park has 7.2 million PV panels and is one of the world's largest solar installations [53]. Microtremors, multichannel analysis, and machine-learning techniques have been applied to accurately map the ground conditions at Benban Solar Park, ensuring the safety and structural integrity of the solar power plant [54]. The park has been found to have stiff ground, with certain regions having more muscular stiffness and damping qualities than others [55]. The location of Benban Solar Park, with outputs of 521 228.8 MWh and a low levelized cost of electricity, has been identified as ideal for the solar power tower plant [56]. The park also reduces greenhouse gas emissions, avoiding almost 1.2 million tons of greenhouse gas annually.

1.3.3 *Tengger Desert Solar Park, China*

Tengger Desert Solar Park, in Zhongwei, China's northwestern Ningxia province, is one of the world's largest solar parks. It has a solar generation capacity of 1.5 GW and covers over 43 km^2 [57]. The China National Grid and Zhongwei Power Supply Co. established the park, supplying power to >600 000 homes [58]. China is the global leader in installed solar capacity, with 32% of the worldwide capacity, and is also the world's largest manufacturer of solar panel technology [59]. The development of the Tengger Desert Solar Park started in 2012 and was commissioned progressively over the 2011–17 period [60]. The park plays a significant role in China's efforts to address challenges in its power sector, such as transmission bottlenecks and problems associated with electric grids [61].

1.3.4 *Kutch Solar Project, India*

The Kutch Solar Project in India focuses on developing and utilizing solar energy in the Kutch region. The project aims to provide electricity to remote areas that do not have access to conventional methods of electricity generation [62]. One aspect of the project involves the construction of a 6000-m^2 solar pond at Bhuj, which is designed to supply process heat and demonstrate the technical and economic viability of solar pond technology in the Indian context [63, 64]. The project also explores the integration of solar stills with greenhouses to address the challenges of water scarcity and salinity in arid areas such as Kutch [65]. The Kutch Solar Project utilizes various computer tools and analysis methods, such as HOMER and the renewable-energy technology (RET) screen, to assess the techno–economic viability of solar PV systems and estimate the reduction in greenhouse gas emissions [66].

1.4 Top five states in solar power in India

1.4.1 *Bhadla Solar Park, Jodhpur*

Bhadla Solar Park, located in Jodhpur, India, was the largest solar park in the world as of 2020 [47] as indicated in Table 2. The project was commissioned in 2017 with a total investment of ~$1.4 billion [67]. The park is part of India's initiative to increase solar power generation, with a target of 40-GW, which has been achieved in 2022 [68]. The park has signed 25-year power purchase agreements with developers, including the National Thermal Power Corporation and the Solar Energy Corporation of India [69]. The region of Jodhpur in Rajasthan is known for its abundant solar energy potential, receiving high annual solar radiation energy. The Indian Institute of Technology, Jodhpur, has also been monitoring and recording the performance of solar PV systems in the area [70].

1.4.2 *Pavagada Solar Park (Shakti Sthala)*

The Pavagada Solar Park, also known as Shakti Sthala, is a large-scale solar energy project in Karnataka, India. The project has implemented innovative land leasing and competitive tendering mechanisms, known as the "Pavagada model," resulting in low-risk returns for investors, low-cost power for state electricity distributors, and new income streams for more prominent landowners [71]. The solar park covers a vast area and is adorned with millions of solar panels, generating carbon-free electricity [72]. The project addresses energy poverty and promotes renewable energy in conflict areas, such as Gaza, by providing clean and safe energy solutions to affected communities [73]. In terms of technical aspects, the solar park incorporates efficient energy conservation and a high degree of automation through solar park lamps and FRT control strategies [74, 75]. Overall, the Pavagada Solar Park represents a significant step towards democratic ownership and control of renewable energy while addressing socio-economic and environmental challenges.

Table 2 shows the solar parks in India. Bhadla Solar Park, Jodhpur, is one of the largest solar parks, followed by Pavagada Solar Park (Karnataka), Charanka Solar Park (Gujarat), Kamuthi Solar Power Park (Tamil Nadu), and Ultra Mega Solar Park (Andhra Pradesh).

2. Materials and methods

An extensive collection of review articles and content analyses were used to gather information on the solar energy scenario in India. Around 100 articles were collected from Springer Link, Research Gate, and Google Scholar sources. The contents of the papers were analysed concisely and necessary data for this study were extracted.

Table 2. Solar parks in India.

State	Total capacity (MW)	Park name
Rajasthan	7737.95	Bhadla Solar Park, Jodhpur
Karnataka	7469.01	Pavagada Solar Park (Shakti Sthala)
Gujarat	5708	Charanka Solar Park
Tamil Nadu	4675	Kamuthi Solar Power Park
Andhra Pradesh	4380	Ultra Mega Solar Park, Kurnool

3. Economic comparison of solar water-pumping systems

Solar water-pumping systems exhibit a significant economic advantage over traditional methods [76], with substantial differences in operational expenses. Solar-powered systems demonstrate superior cost-effectiveness, proving more economical than their diesel counterparts. Particularly in areas that suffer water scarcity, solar-powered systems can be economically viable and efficient [77, 78]. A meticulous cost analysis emphasizes the economic benefits, demonstrating that the operation of the diesel pump is significantly more expensive, at INR (Indian Rupee) 69.14/h. The cost is slightly lower than that of a solar pump (INR 53.79/h). The operational cost of an electric pump is lower than that of a solar pump, which operates at INR 47.76/h. The overall appeal of the solar pump comes with its sustainability and eco-friendliness [79, 80].

The total cost is higher over 20 years when comparing PV systems with diesel engines. The life-cycle cost of the PV system is significantly reduced due to the absence of fuel and replacement expenses—the solar pumping system can be worked in the long run without any issues [81]. Additionally, the payback period—an influential gauge of investment feasibility—is ~4.26 years, stating that the cost of purchasing a PV water-pumping system is justified. The claim is reinforced by the benefit–cost ratio of 1.81 and the internal rate of return of 23.104 13%. These financial measures emphasize the robust economic case for solar water-pumping systems [81].

Research conducted on agricultural applications confirms the economic feasibility of solar-powered irrigation, particularly for crops such as lentils, cotton, soybean, potato, sunflower, strawberry, and mustard, in contrast to diesel-powered irrigation [82]. Solar PV (SPV) pumping systems are economically advantageous due to their annualized life-cycle cost (ALCC), which implies lower costs than those of grid-connected electric and diesel pumps. A 5-horsepower SPV pumping system had an ALCC of INR 56 620, which is notably lower than the alternatives [83].

The economic analyses of PV solar systems demonstrate that they are both cost-effective and suitable for large-scale underground water-pumping systems compared with conventional energy sources. Payback period studies consistently favor PV systems as the most advantageous option [84]. In contrast to its diesel-fueled counterpart, the economic analysis of a 3-kW solar-based irrigation system shows that the solar-powered pump becomes more cost-efficient after the initial period, providing compelling evidence for sustainable and economically effective farming [85]. In conclusion, these extensive economic analyses firmly endorse the adoption of solar-powered water-pumping systems, which offer ecological advantages and significant financial benefits to agricultural producers [86].

4. Policies and initiatives to promote solar energy in Gujarat and India

Due to the country's goal of achieving energy security, India's energy mix can be significantly influenced by renewable energy sources such as solar, wind, biomass, and small hydro. Renewable energy, particularly solar power, has been identified as a significant energy source that can supplement conventional sources and reduce carbon emissions in India [87]. The Indian government's energy initiatives are the foundation of the country's future development, providing a sustainable roadmap for growth and solving significant issues. India's electricity market is based on the Electricity Act of 2003, which includes provisions for privileged tariffs and renewable-energy quotas. The 2005 National Electricity Policy aligns with the overall objective of achieving universal electricity access, which provided a minimum per capita electricity consumption of 1000 kWh to the Indian people by 2012 [85]. A unique solar tariff is included in the Renewable Purchase Obligation (RPO) mechanism, enacted as part of the National Tariff Policy 2006.

The Integrated Energy Policy 2006 sets explicit capacity objectives for producing renewable energy. The National Action Plan on Climate Change 2008 accelerated solar electricity production, setting a 5% RPO for grid procurement and achieving 1% year-on-year growth over 10 years. Financial incentives are given to manufacturing plants under the 2007 Semiconductor Policy, promoting semiconductor production, including solar PV elements. In 2010, the Jawaharlal Nehru National Solar Mission was launched to achieve 100 GW of solar power by 2022, and this target was supported by various initiatives to increase renewable energy and the target was achieved [87].

The tax that was imposed in 2010 through the Clean Energy Cess. Contributions to the National Clean Energy Fund is based on coal consumption, with a value of INR 50 per tonne. The Joint Liability Group for Off-grid Installations and Renewable Energy Certificates 2011 advocates for market mechanisms and inter-state equity in renewable power generation. Residential rooftop solar systems could receive financial support through the Sustainable Rooftop Implementation for Solar Transfiguration of India Scheme in 2017. In the same year, the Pradhan Mantri Sahaj Bijli Har Ghar Yojna was launched to encourage electrification through solar energy, especially in rural areas.

The Kisan Urja Suraksha Evam Utthaanmahabhiyan Yojna, launched in 2018, aimed to provide farmers with financial support and water security through solar solutions. The "One Sun One World One Grid" Plan, implemented in 2021, connects global solar energy supply for sustainability. These programs provide a comprehensive blueprint for India's energy needs, emphasizing sustainability, universal accessibility, and international collaboration. Ongoing efforts must lead to closing implementation loopholes and ensuring effective execution for a future that is genuinely sustainable and energy-efficient. The renewable-energy industry in India has seen several initiatives to enhance its development, resulting in increased adoption rates and improved implementation efficiency. The Surya Mitra Program is a national initiative to develop a skilled technical workforce to manage solar energy projects at various stages, from initial planning and construction to service and maintenance after completion. At the same time, the government made significant progress in promoting cleaner energy by eliminating charges for inter-state power transmissions and damages for solar and wind power projects, providing incentives for a smooth transition to more pristine resources by March 2022 and it has been extended further as well. Moreover, the National Institute of Solar Energy's Rooftop Grid Engineer Course allows students to gain comprehensive knowledge of solar power plants on rooftops connected to the grid. S-WURJA, a simple application created by the National Institute of Wind Energy, is an additional extension to these initiatives. This app, available on both Google Play Store and Apple App Store, provides users with a comprehensive collection of micro-level information on solar and wind energy characteristics, making it incredibly useful for those who are passionate about green energy.

The Faster Adoption and Manufacture of Hybrid and Electric Vehicles program is playing a role in driving the adoption of electric vehicles in smart cities, ultimately contributing to sustainable transportation. State-specific initiatives offer substantial subsidies, making solar rooftops financially feasible and ensuring that any surplus electricity is included in the grid, further supporting the sustainability of renewable-energy practices. Gujarat was the only state in which the Suryashakti Kisan Yojana, launched in 2018, aimed to increase farmers' income two-fold by 2022 through a diplomatic subsidy-sharing model, but it was not achieved. In Gujarat, the Surya Urja Rooftop Yojana, introduced in 2016, had already benefited 200 000 consumers and targeted 800 000 customers by the end of the fiscal year of 2021–22 [88]. The state's dedicated initiatives offer substantial subsidies that make solar rooftops financially feasible and the excess electricity generated is subsequently added to the grid, further supporting the sustainability of renewable-energy practices.

5. Significant achievements

India has achieved notable strides in sustainable and renewable energy, reflecting a conscientious commitment to environmentally responsible practices. A noteworthy initiative in Chhattisgarh involves the collaboration between the Renewable Energy Department and the State Health Department, resulting in the deployment of solar PV systems across 900 healthcare centers. The integration of energy-efficient appliances into these facilities has rendered tangible benefits, catering to the daily needs of 80 000 patients. Furthermore, educational institutions within the state have actively contributed to a broader 50-MW grid power target by incorporating rooftop solar systems. Commendably, cities such as Raipur and Bilaspur have been designated solar cities, signifying a strategic urban commitment to clean energy integration [89]. Maharashtra emerges as a critical player, possessing the highest farm-top solar potential, quantified at an impressive 21.1 GW. Gujarat has implemented the innovative Suryashakti Kisan Yojana, empowering farmers to generate their electric power, contribute surplus energy to the grid, and derive additional income. Additionally, the state has demonstrated environmental stewardship by establishing a 1-MW canal-top solar power plant at the Sardar Sarovar canal, generating 1.6 million units of solar electricity annually and conserving a substantial volume of water from evaporation [87]. Madhya Pradesh, facilitated by investments from the Indian Renewable Energy Development Agency Limited and the World Bank, has successfully commissioned two substantial solar power plants: the 750-MW Rewa ultra-mega solar power plant and the 250-MW Mandsaur solar project. Intriguingly, the state has pioneered the establishment of India's inaugural innovative data room in collaboration with the State Bank of India's technical assistance program [89].

Various regions, including Sunderbans, Bastar, Andaman, Nicobar, and Ladakh, have reaped the benefits of solar energy, fostering power accessibility to >10 000 remote villages. Notable private sector contributions have come from industry leader Infosys, with their Bangalore campus generating 100 million units of electricity, meeting 43% of its energy requirements through solar means. Installing 100-MW solar rooftop plants in Pune, Chennai, and Hyderabad further exemplifies corporate commitment to sustainable energy practices [90].

In the academic and cultural spheres, installations such as the grid-tied solar plant powering the Konark Sun Temple and Konark town in Puri district, Odisha, underscore the multifaceted impact of solar energy. In Bhopal, a critical 750-kW solar power plant addresses the energy needs of a water-pumping station, annually generating 13 000 units and contributing to significant cost savings. Uttar Pradesh's successful implementation of a solar PV rooftop power plant at GAIL's petrochemical complex attests to the viability and impact of renewable-energy projects. Notably, West Bengal's adoption of solar-powered drip irrigation has induced transformative shifts in agricultural practices in remote villages. Kerala boasts a 500-kW floating solar power plant on the Banasura Sagar reservoir. Finally, Tamil Nadu's Chennai Central Railway Station sets an exemplary standard by fulfilling 100% of its daytime energy requirements through a 1.5-MW solar panel installation on platform shelters. These achievements underscore India's commitment to fostering sustainable energy practices across diverse sectors, necessitating ongoing critical evaluation for continual refinement and improvement [90].

6. Challenges and implications

Various challenges that demand careful consideration and strategic planning hinder India's ambitious solar energy plan. Solar project implementation encounters obstacles in funding, land availability for purchase, and solar goods manufacturing, necessitating measures to encourage entrepreneurial activity [91]. The high installation costs and associated transmission and distribution losses of solar power plants pose a significant financial challenge. The complexity of plant set-up approvals, net metering requests, and power purchase agreements adds to project timelines [92]. Also, government-funded outlays are delayed, interfering with the economic incentives intended for stakeholders [92]. This adds to the complexity of solar PV cells and modules, as manufacturers increasingly depend on export markets that offer high prices for their products. Obtaining high-quality inverters and ancillary components from overseas presents one of the primary obstacles. The PV industry requires more funding models and utility arrangements to boost its growth [91]. Insufficient grid connectivity and evacuation infrastructure development have emerged as a pivotal challenge, impeding the growth of solar power in India [16]. Regulatory complexities, including land acquisition, financing, foreign direct investment, and power purchase agreements, introduce bottlenecks into the evolution of the solar market [16, 17]. Harmonizing national roadmaps, policies, and programs to facilitate meaningful solar minigrid deployment in rural areas requires meticulous institutional and local coordination [18, 19].

A major hurdle in the financial system is expensive debt financing, which poses a significant challenge [92]. Systematic issues such as high interest rates, weak capital markets, and the economic instability of distribution companies exacerbate this problem. Low-cost and long-term debt financing provisions are crucial in balancing the levelized cost of energy due to their nature and terms [92]. Financial institutions do not support RETs, and novel financing options are lacking [4, 5, 18, 93–95]. Even though solar modules have decreased in price, the significant initial outlay required to develop solar-based technologies persists as a barrier to broader penetration [96–98]. The competitiveness of the domestic solar module industry is emphasized by factors such as the current capital cost structure and the dominance of module costs [10, 20–22, 99, 100]. A paradigm shift is required to drive the adoption of solar PV, incorporating novel government incentive policies and supply chain innovations [100]. The low capacity utilization factor (CUF) in solar energy installations is a significant issue, as it trails conventional sources such as coal and petroleum, and other renewable sources such as biomass, small hydro, and wind [101]. Despite the often-quoted cost-effectiveness of distributed (residential) solar PV systems, the low CUF leads to higher tariffs [102, 103]. The adoption of solar energy is impeded by the limited knowledge of product information, technology, costs, benefits, potential, operation, and maintenance costs [94, 95]. Social acceptance is critical for successfully implementing solar energy on colossal scales in countries such as India. Increasing awareness, interest, and desire, and taking proactive steps are necessary for consumers to embrace solar energy applications in their everyday lives [102, 103].

India has seen the benefits of solar energy achieved by other countries and policies related to farmers producing solar energy through solar water-pumping systems have been implemented. The Government of India provides many opportunities for people to start businesses related to solar power. The Indian government primarily targets three sectors: manufacturing, services, and agriculture. The Indian government focuses more on rooftop solar energy for manufacturing and service sectors.

The Indian government provides ~60% subsidies to farmers purchasing solar water-pumping systems. Only 40% of the money is contributed by farmers. Many states offer financial support to farmers through the banks to buy solar water-pumping systems, which helps farmers contribute 5–10% of the amount from their pocket. Farmers are selling the surplus electricity to the government through a grid system in many states of India. The government is trying to provide a solar water-pumping system and a drip irrigation system for efficient utilization of water and electricity. Apart from the benefits of solar energy, seasonal changes play a significant role in ruining the production of solar energy. In India, solar energy production through solar water-pumping systems ranges between five and seven units using a one-horsepower solar water-pumping system. Due to climate change, solar energy production has decreased in the rainy season, but agriculture production will not be affected. The climate will ultimately affect solar energy production, which will be used for other sectors such as manufacturing and services.

The awareness about the production and consumption of solar energy was deficient among the people in India. Only people who have a good status in society can get all the benefits that have been provided by the government related to solar energy. The lack of availability of services in the market comes into the minds of consumers, which ensures that they avoid the products. The availability of low-quality products in the markets also influences consumers to avoid purchasing solar-related products.

7. Future outlook

India's renewable-energy goals are being revolutionized through a groundbreaking initiative. The nation has a goal of reaching 500 GW from renewable resources by 2020, which is considered ambitious. As of September 2020, 89.22 GW of solar energy is already operational, 48.21 GW is being implemented, and 25.64 GW is in the bidding process. This potent base allows India to promptly achieve its renewable-energy targets, emphasizing the efficacy of strategic planning and ongoing endeavors. India is committed to reducing its carbon footprint in line with international environmental goals. The country has set a goal of using non-fossil fuel sources for ≥40% of its electricity by 2030. The pledge emphasizes a proactive approach to environmental sustainability and aligns with the broader global efforts to combat climate change. Through various measures, India has taken comprehensive action to attract foreign investment in the renewable-energy sector. The financial feasibility of renewable projects is facilitated, and so are partnerships that aid in the worldwide shift towards cleaner energy [104]. The Ministry of New and Renewable Energy contributes significantly to India's solar energy sector, and has taken an active role in promoting renewable-energy initiatives and creating national programs to encourage renewables.

Given that human capital is critical for sustainable development, the government prioritizes acquiring technical skills and knowledge among the public. The focus on skill development equips the workforce to drive innovation, efficiency, and sustained growth in the renewable-energy field. With the support of international collaboration and a skilled workforce, India's progress in solar energy development is a boon for the industry.

8. Conclusion

In conclusion, the Indian government's strategic regulations have facilitated the growth of solar energy and enabled consumers to become active participants in the energy industry. The country's transition to a sustainable energy economy is aided by the significant decrease in carbon dioxide emissions from solar power, which is also considered climate-friendly. Solar PV systems were initially more expensive to install than traditional alternatives. However, their lower maintenance and operation costs have provided farmers and the general population with a strong incentive for them. Irrigation costs have significantly decreased, and the initial investment in solar power is recouped within 2–3 years. The increasing energy requirements linked to economic development in India have made renewable energy, particularly solar, a crucial factor. The current trend suggests that the existing demand–supply imbalance could result in severe energy deficiency within the domestic and industrial domains. Energy security is facilitated by using renewable energy, which also contributes to meeting the challenge of climate change by decreasing emissions. A sustainable economy and a climate system that is conducive to achieving planetary wellness require adopting renewable energy sources. India has actively researched, developed, produced, and demonstrated diverse renewable-energy technologies in response to the need to move away from traditional petroleum-based energy systems. The country's geology, geography, many customers, and widening energy demand–supply gap make renewable energy a potential growth field. Renewable resources can be efficiently utilized through technological advancement, supportive regulatory policies, tax incentives, and ongoing research and development efforts. Ultimately, considering renewable energy as an option and a part of sustainable and inclusive growth will help India achieve its energy independence. Renewable energy production and consumption, especially solar energy, have been increasing. Farmers are encouraged to adopt solar water-pumping systems through the Suryashakti Kisan Yojana Scheme, especially in Gujarat, with only a 5% contribution by the farmers for purchasing solar water-pumping systems. This successful scheme is expected to extend to other states, in addition to providing drip irrigation systems to ensure the efficient utilization of significant inputs such as electricity and water.

Author contributions

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Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The data underlying this article are available in the article.

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