International Journal of Emerging Science and Engineering (IJESE)
ISSN: 2319–6378 (Online), Volume-13 Issue-10, September 2025

Integrating Solar Energy into Power Grids: India's Path to a Sustainable Energy Future

Sweety Supriya

Abstract: ***India is rapidly advancing towards its ambitious goal of 500 Gigawatt (GW) of non-fossil power capacity by 2030, with solar energy at the forefront of this clean energy transition. Surpassing 100 GW of installed solar capacity by the end of FY 2024-25 demonstrates significant progress in India's renewable energy journey. However, seamlessly integrating this variable energy source into the existing power grid presents complex technical, economic, and regulatory challenges. This article examines the methods and technical hurdles of integrating solar power into the grid, particularly addressing the critical issue of grid stability, which is inherently challenged by the intermittent nature of solar energy production. The rapid expansion of solar power also brings substantial land and cost requirements. The article argues that promoting widespread adoption of rooftop solar is a key solution to these constraints. However, successfully integrating these systems requires a multi-pronged approach to manage variability. Key strategies include flexible grid operations, deploying smart grids and Artificial Intelligence (AI)/Machine Learning (ML) applications, encouraging demand-side participation, and expanding energy storage. By implementing these measures, India can establish a resilient and adaptive grid that effectively manages the inherent variability of solar power, thereby ensuring a reliable, affordable, and sustainable energy supply.***

Keywords: Renewable Energy, Solar Energy, Power Grid, Grid Integration, Grid Balancing, Smart Grid.

Abbreviations:
SDGs: Sustainable Development Goals
COP: Conference of the Parties
NDCs: Nationally Determined Contributions
MNRE: Ministry of New and Renewable Energy
DC: Direct Current
PCU: Power Conditioning Unit
AC: Alternating Current
NSGM: National Smart Grid Mission
AI: Artificial Intelligence
ML: Machine Learning
PM-KUSUM: Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan
IEA: International Energy Agency
GEC: Green Energy Corridor
DSM: Demand Side Management
DR: Demand Response
RDSS: Revamped Distribution Sector Scheme
GEC: Green Energy Corridor
SPV: Solar Photovoltaic
GW: Gigawatt

Manuscript received on 12 August 2025 | Revised Manuscript received on 06 September 2025 | Manuscript Accepted on 15 September 2025 | Manuscript published on 30 September 2025.
*Correspondence Author(s)
Dr. Sweety Supriya*, Department of Electronics, L. S. College, Muzaffarpur (Bihar), India. Email ID: sweety.supriya.lscollege@gmail.com, ORCID ID: 0009-0004-4932-7802

© The Authors. Published by Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP). This is an open-access article under the CC-BY-NC-ND license https://creativecommons.org/licenses/by-nc-nd/4.0/

I. INTRODUCTION

Energy has always been vital for the growth and development of nations. Access to modern energy, especially electricity, is a key driver for improving livelihoods and living conditions. It is also essential for poverty reduction, as a lack of energy directly impedes people's ability to access crucial services, such as healthcare and education, limiting their opportunities to generate income [1]. However, the production and use of energy must not jeopardise the quality of life for present or future generations. It is imperative to ensure that energy consumption does not exceed the carrying capacity of ecosystems, thereby preserving the environment for future generations [2].

Climate change, characterised by rising sea levels, biodiversity loss, and extreme weather events, is a pressing global issue primarily driven by greenhouse gas emissions. To mitigate its impacts, countries worldwide have implemented various strategies to reduce these emissions. The electric power sector, a major contributor to greenhouse gas emissions due to its reliance on fossil fuel-based power plants, has been a focus for environmental action [3].

In 2015, the United Nations emphasized the importance of energy in its global development agenda, introducing it as a key component of the Sustainable Development Goals (SDGs). One of the critical aims of SDGs is to ensure that by 2030, everyone has access to affordable, reliable, and clean energy, contributing to a more sustainable and equitable future. Having access to energy is part of creating a world that is fair, just, and clean [4].

At the Conference of the Parties (COP) 26, held in Glasgow in 2021, the Prime Minister of India stated that India would become net-zero by 2070. India's announcement to achieve net-zero emissions by 2070 and its updated Nationally Determined Contributions (NDCs) to reach 50% of its installed electricity generation capacity from non-fossil sources by 2030 mark a momentous step in the global fight against climate change. This commitment showcases India's leadership in shaping a low-carbon economic development model and contributes to the worldwide battle against climate change [5].

One of the most effective ways to decrease greenhouse gas emissions in the power sector is to transition to renewable energy sources, which include small hydro, wind, solar, biomass, biofuel cogeneration, municipal waste, and other sources approved by the Ministry of New and Renewable Energy (MNRE). Out of these renewable energy sources, solar energy has emerged as the most viable option for several reasons, including its abundance as a renewable

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

energy source and its promise as an inexhaustible source of energy [6]. Moreover, solar energy systems have low operating and maintenance costs, and they can last for decades [7]. These advantages, combined with the decreasing cost of solar technology, have made solar power a desirable option for both residential and commercial applications [8]. Additionally, Government policies have also played an essential role in promoting solar energy adoption through incentives and regulatory support. Reflecting this viability, India's solar capacity has seen a remarkable increase, growing more than 39 times from 2.82 GW in 2014 to 110.9 GW in 2025, with a record 23.83 GW added in 2024–25 [9].

The growth of renewable energy in India has been encouraging so far, but sustaining this momentum in the long run may face several challenges. India would need to generate approximately 5,600 GW of solar capacity and 1,800 GW of wind capacity to achieve its net-zero emission target by 2070. However, scaling up of solar energy to this extent requires significant land acquisition and associated costs. The location of land is essential for establishing a solar project, and competing demand for land from other sectors, such as mining and industries, can further exacerbate the challenge of land acquisition. To partially address these challenges, a distributed solar system, such as a rooftop solar system, is the most crucial solution. Although the Government of India has recognised the importance of such distributed energy sources, this segment has not experienced the same pace of growth as large solar projects [10]. To encourage widespread use of rooftop solar systems, a key mechanism is net metering through grid integration, which enables consumers to receive credit on their electricity bills by supplying solar energy to the grid. The integration of rooftop solar panels with the grid requires automated grid balancing, enabled by recent digital technologies. In view of this background, the present article aims to analyse the methods and technical hurdles of integrating solar power into the grid, particularly addressing the critical issue of grid stability.

A. Trend of Solar Energy Generation in India

Economic growth is crucial for developing countries like India, and energy is a key driver of that growth. However, the relationship between economic growth and energy demand is not always linear. As economies develop, energy demand can fluctuate due to factors such as technological advancements, energy efficiency measures, and evolving consumption patterns [11]. In India, electricity demand has surged in recent years, driven by population growth, industrialization, and technological advancements. India is the world's third-largest consumer of energy. By 2040, India is projected to experience the fastest growth in energy consumption among major economies. However, the country still meets over 75% of its energy demand through coal, oil, and natural gas. This heightened reliance on foreign sources exposes India to fluctuations in global oil prices and potential supply disruptions [12]. Despite its commitment to reducing fossil fuel-based energy generation, the country still has a long way to go in meeting its emission reduction targets. The status of India’s total installed capacity of energy generation by different sources is as follows:

Table I: India's Power Capacity by Source (%) (As on 30 April 2025)

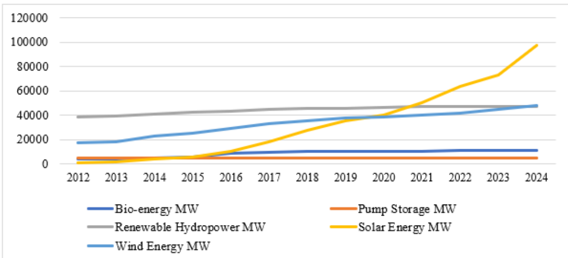
Source	Source-wise Electricity Installed Capacity (%)	Source-wise Electricity Generation Capacity (%)
Coal	46.42	74.58
Oil & Gas	4.39	2.05
Hydro	10.14	6.17
Nuclear	1.86	3.11
Solar	22.85	9.61
Wind	10.81	3.91
Bio Power	2.45	0.33
Small Hydro	1.08	0.24

Source: Ministry of Power & Central Electricity Authority. (https://mnre.gov.in/en/year-wise-achievement/).

The table above shows that India's energy mix comprises a diverse range of electricity generation sources. It is worth noting that two types of electricity generation data are publicly available. The first type of data refers to installed capacity, and the second to generation, as mentioned in the table above. Installed capacity represents the maximum potential power that could be produced if all generators of a particular type were to run continuously at full output. In contrast, electricity generation capacity reflects the actual amount of power delivered to the grid over a period, indicating the real-world contribution of each source.

As of April 2025, the data indicate that coal accounts for the majority of actual electricity generation (74.58%), despite having a lower share of installed capacity (46.42%). This indicates that coal-fired plants operate with a very high capacity factor. Conversely, Solar and Wind energy exhibit a notable difference, with their installed capacity percentages (22.85% and 10.81%, respectively) being significantly higher than their actual generation percentages (9.61% and 3.91%). This gap is due to the intermittent nature of solar panels, which only generate power when the sun shines, and wind turbines, which only generate power when the wind blows, leading to lower capacity factors compared to dispatchable sources.

Suppose we examine the trend of electricity generation capacity in India over the last decade. In that case, it shows a remarkable shift in the renewable energy landscape, with solar energy emerging as the dominant source. Solar capacity witnessed exponential growth, rising from minimal levels in 2012 to approximately 105 GW in 2024, surpassing all other sources. The following figure explains the trend of the generation of electricity from various renewable energy sources:



[Fig.1: India’s Electricity Generation Capacity Growth Trend (Megawatt / MW)]

Source: https://www.irena.org/Energy-Transition/Technology/Solar-energy

The above Figure clearly illustrates the rapid and consistent growth of solar energy capacity in India,

Retrieval Number:100.1/ijese.A105005011125
DOI:10.35940/ijese.A1050.13100925
Journal Website: www.ijese.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

surpassing all other renewable energy sources in recent years and emerging as the dominant contributor to the country's renewable energy mix. Wind energy grew steadily until around 2018, when it then plateaued, reaching approximately 45 GW. Renewable hydropower remained relatively stable, with a modest increase to just under 50 GW, while bio-energy and pump storage showed minimal or stagnant growth throughout the period. This trend highlights India's strategic focus on rapidly deployable and cost-effective solar power, while other renewable sources face various technical, regulatory, or economic challenges.

B. Integrating Solar Power into Grid Systems

The solar production system can broadly be divided into two main categories: off-grid solar systems and grid-connected solar systems. An off-grid solar system comprises several interconnected solar panels that produce electricity, which is then stored in batteries for later use, particularly during the night or when sunlight is unavailable. This provides a straightforward method for utilising solar energy independently, without requiring a connection to the primary power grid.

A grid-connected solar system is one where the solar panels are connected to the primary power grid. This enables the solar panels to work in conjunction with the grid to supply electricity. In grid-connected rooftop or small solar photovoltaic (SPV) systems, direct current (DC) power generated by the SPV panels is converted into alternating current (AC) power by a Power Conditioning Unit (PCU). This AC power is then fed into the electricity grid at appropriate voltage levels, such as 220 kV, 66 kV, 33 kV, or 11 kV for three-phase lines, or 440 V/220 V for three- or single-phase lines. The specific voltage level depends on the capacity of the installed system and the regulatory framework set by the respective state authorities.

The grid-connected system allows electricity to flow back and forth between the solar panels and the grid, depending on the amount of sunlight available and the level of electricity being used. This means that if solar panels generate more electricity than they use, the excess electricity can be sent back to the power grid. Thus, a grid-connected system enables the sale of excess renewable energy production to the grid, thereby incentivising the broader adoption and promotion of renewable energy production and use.

Furthermore, the data indicates that within the renewable energy segment, solar power led the capacity additions in FY 2024–25. This expansion has increased India's overall solar capacity to 110.83 GW as of May 2025. This total encompasses a diverse mix of installations: 84.43 GW from large-scale ground-mounted projects, 18.37 GW from distributed rooftop systems, 3.02 GW from hybrid ventures, and 5.01 GW from off-grid solutions, underscoring the widespread growth of solar energy in both utility and distributed sectors. The details of solar power generation can be seen from the table below:

Table II: Solar Power Capacity Breakdown (as of May 31, 2025)

Category	Sub Category	Installed Capacity (GW)	Proportion of total solar capacity (%)
Grid Integrated	Ground-Mounted Solar Plant	84.43	76.18
	Grid-Connected Solar Rooftop	18.37	16.57
	Hybrid Projects (Solar Component)	3.02	2.72
Sub Total of Grid-Connected Solar		105.72	95.47
Off Grid	Off-Grid Solar	5.01	4.53
Total Solar Capacity		110.83	100

Source: Ministry of New and Renewable Energy, https://mnre.gov.in/en/physical-progress/

This shows that grid-connected solar rooftop installations are a significant and growing component of India's overall solar power capacity. To further increase its share and empower households to generate their own electricity, the Government of India has launched PM Surya Ghar: Muft Bijli Yojana in February 2024. The scheme provides a subsidy of up to 60% of the cost for solar system installation, capped at a maximum system capacity of 3 kW.

While these efforts are driving the expansion of rooftop solar systems across residential, commercial, and institutional sectors, their growth has been somewhat tempered by high upfront costs and existing regulatory challenges in integrating them with the grid. In India, exporting surplus solar electricity to the grid through a standard domestic or commercial electricity connection is not permitted without formal approval under a net or gross metering arrangement. Compliance with regulatory procedures is essential, including registration with the distribution licensee, installation of a bidirectional energy meter, and adherence to technical and safety standards specified by the Central Electricity Authority and respective State Electricity Regulatory Commissions.

Further, in addition to the solar rooftop scheme, the Government of India is actively pursuing a cleaner, more sustainable, and self-reliant energy future through various initiatives aimed at promoting renewable energy, strengthening grid stability, and reducing carbon emissions. Key programs, such as the National Bio-Energy Mission, National Green Hydrogen Mission, and Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM), exemplify the commitment to a clean energy transition.

These schemes have been implemented differently across states, resulting in varied progress in the solar energy sector depending on regional factors such as location, policy support, and infrastructure readiness. The table below presents the state-wise installed capacity of solar energy and the corresponding growth over the last decade.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

Table III: **State-Wise Installed Capacity of Solar Power in India (MW)**

State/ Union Territories	March-14		March-25		Growth During 2014 to 2025	
	Off-Grid Solar Power	Total Solar Power	Off-Grid Solar Power	Total Solar Power	Off-Grid Solar Power	Total Solar Power
Andhra Pradesh	4.13	135.97	88.34	5370	84.21	5234.03
Arunachal Pradesh	1.54	1.57	6.9	14.85	5.36	13.28
Assam	1.42	1.42	9.44	196.54	8.02	195.12
Bihar	1.66	1.66	21.28	328.34	19.62	326.68
Chhattisgarh	15.6	22.7	390.73	1347.04	375.13	1324.34
Goa	0.08	0.08	1.49	56.44	1.41	56.36
Gujarat	10.35	926.75	95.03	18496.66	84.68	17569.91
Haryana	6.42	16.72	969.67	2064.97	963.25	2048.25
Himachal Pradesh	3.04	3.04	34.58	204.26	31.54	201.22
Jammu & Kashmir	7.99	7.99	29.8	74.49	21.81	66.5
Jharkhand	1.16	17.16	85.83	199.87	84.67	182.71
Karnataka	5.86	36.86	39.16	9679.66	33.3	9642.8
Kerala	4.04	4.07	24.93	1538.94	20.89	1534.87
Ladakh		0	0	7.8	0	7.8
Madhya Pradesh	2.78	349.95	102.04	5118.38	99.26	4768.43
Maharashtra	2.07	251.32	1394.37	10687.27	1392.3	10435.95
Manipur	0.83	0.83	6.08	13.79	5.25	12.96
Meghalaya	0.82	0.82	4.07	4.28	3.25	3.46
Mizoram	0.78	0.78	6.39	30.39	5.61	29.61
Nagaland	1.15	1.15	2.17	3.17	1.02	2.02
Odisha	0.78	31.28	42.34	624.44	41.56	593.16
Punjab	4.81	21.66	81.36	1421.43	76.55	1399.77
Rajasthan	26.15	756.25	805.45	28286.47	779.3	27530.22
Sikkim	1.7	1.7	1.92	7.56	0.22	5.86
Tamil Nadu	10.14	108.5	70.4	10153.58	60.26	10045.08
Telangana			8.71	4842.1	8.71	4842.1
Tripura	2.93	2.93	11.34	21.24	8.41	18.31
Uttar Pradesh	24.6	45.68	324.72	3364.07	300.12	3318.39
Uttarakhand	6.7	11.75	20.96	593.07	14.26	581.32
West Bengal	10.6	17.65	13.14	320.62	2.54	302.97
Andaman & Nicobar Islands	0.24	5.34	0.27	29.91	0.03	24.57
Chandigarh	0.81	2.81	0.81	78.85	0	76.04
Dadra & Nagar Haveli and Daman & Diu	0	0	0	48.12	0	48.12
Delhi	0.52	5.67	1.46	313.4	0.94	307.73
Lakshadweep	1.17	1.92	2.52	4.97	1.35	3.05
Puducherry	0.06	0.09	0.18	54.51	0.12	54.42
Others	27.05	27.87	45.01	45.01	17.96	17.14
Total (MW)	**189.98**	**2821.94**	**4742.89**	**105646.49**	**4552.91**	**102824.55**

Source: Ministry of New and Renewable Energy, Government of India. *https://mnre.gov.in/en/year-wise-achievement/#*

The table above provides data on the state-wise installed capacity of solar power from March 2014 to March 2025. The total solar power capacity, encompassing both off-grid and grid-connected installations, has demonstrated exponential growth, escalating from 2,821.94 MW in 2014 to 1,05,646.49 MW by 2025. This represents an increase exceeding 37 times within the decade. Off-grid solar capacity also experienced substantial expansion, rising from 189.98 MW to 4,742.89 MW during the corresponding period.

Among the individual states, Rajasthan exhibited the most substantial growth, augmenting its capacity by over 27 GW to reach 28,286.47 MW by 2025. Gujarat followed with 18,496.66 MW, and Maharashtra with 10,687.27 MW. Notably, states such as Karnataka, Tamil Nadu, Telangana, and Madhya Pradesh also achieved rapid solar adoption, each surpassing the 5 GW installed capacity mark. Telangana, established in 2014, emerged as a significant contributor to solar power generation, reaching 4,842.1 MW. Thus, India's trajectory in solar energy over the past decade underscores a decisive commitment to clean energy transition. However, it is imperative to acknowledge that regional disparities and inconsistent off-grid adoption persist as challenges, necessitating continued focus on policy initiatives and strategic investments.

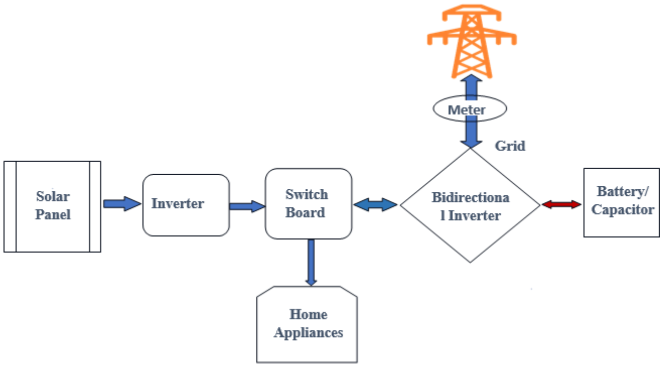
II. THE MECHANICS OF GRID INTEGRATION

In traditional electric utility systems, power flows in a unidirectional manner from power plants to consumers. However, the grid-integrated solar power introduces a bidirectional flow. This means that electricity can not only flow from the grid to consumers but also from solar panels to the grid. Thus, there is a need for bidirectional converters which can operate in both charging and discharging modes [13]. The bidirectional converter takes AC power from the grid. It converts it into DC power during the charging mode, which is then used to charge the energy storage unit (i.e., battery or supercapacitor). This process is used during periods when the grid has excess electricity or when solar energy production is low. During the discharging process, the bidirectional converter receives DC from the energy storage unit and converts it into AC, which is then fed back into the grid. This process is automatically adopted during periods when electricity demand from the

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

grid is high or when solar generation is low, ensuring a stable backup power supply [14].

The system of solar energy integration with the grid can be illustrated through the following diagram:



Source: *Diagram prepared by the author*

The diagram above illustrates a typical grid-tied solar power system, featuring a battery bank and an inverter. This type of system is designed to generate electricity from solar panels, store excess energy in a battery, and connect to the electrical grid for both power supply and grid support. Stepwise detail of the above diagram is as follows:

- **A. Solar Panel: S**olar panels are a core part of the system, which converts sunlight into DC. The efficiency and output of solar panels depend on several factors, including sunlight intensity, panel placement, and regular maintenance.
- **B. Inverter:** An Inverter is another crucial component that converts the DC electricity from the solar panels into alternating current (AC), which is compatible with most household appliances and the grid.
- **C. Switchboard:** The switchboard distributes the AC electricity generated by the solar system to various appliances in the home/premises. It also protects against electrical faults and overloads.
- **D. Bidirectional Inverter:** This type of inverter plays a crucial role in grid-connected systems. It can both charge the battery with electricity from the grid or solar panels and discharge the battery to supply power to the home or feed excess energy back to the grid. This bidirectional capability is essential for optimising the benefits of the system.
- **E. Battery/Capacitor:** The battery/ capacitor stores surplus energy from the solar panels for later use. Batteries provide longer storage durations, while capacitors provide faster discharge rates. The choice of selection between the two depends on the specific needs of the system.
- **F. Bi-Directional Meter:** A special bi-directional meter (or net meter) is installed by the electricity Distribution Company (DISCOM) to measure the amount of electricity consumed by the home/ premise and the amount of electricity fed back to the grid. This meter is crucial for net metering or net billing arrangements.
- **G. Grid:** The system is connected to the grid, allowing for both power supply and grid support. It enables the import of electricity to areas experiencing supply deficits, ensuring stable power access. Conversely, it allows for the export of surplus electricity from areas with excess generation. Thus, grid integration prevents curtailment and maximises their utilisation across the wider grid network. Further, in grid-tied systems, excess energy can be fed back to the grid, potentially earning credits or reducing electricity bills.

III. BALANCING THE GRID: A CENTRAL CHALLENGE WITH RENEWABLE ENERGY

Maintaining a stable and reliable power grid is paramount, requiring constant vigilance to balance electricity supply with demand. Traditionally, power plants are designed not only to generate electricity but also to adjust their output in real-time. Grid operators achieve this delicate balance through a combination of automated systems, manual interventions, and strategic reserves. Generally, “spinning reserve” or “operating reserve” are used to ramp up power generation to meet sudden demand spikes or to compensate for unexpected supply drops, acting like an extra car engine ready to accelerate [15].

However, the growing reliance on variable renewable energy sources such as solar energy has introduced new complexities and challenges to grid stability. These energy sources are unpredictable, as their output depends on changing weather conditions, making precise power forecasting and demand management more challenging [16]. While integrating renewable energy with conventional power plants provides some relief, it does not resolve the issue of intermittent generation. Furthermore, solar energy amplifies these challenges across broader temporal and spatial scales, necessitating faster and more flexible responses from system resources.

To address these challenges, energy storage technologies are emerging as an essential solution [17]. Energy storage systems effectively mitigate the intermittency of renewable sources by storing surplus electricity and releasing it precisely when needed. Thus, it enables grid operators to manage fluctuations in renewable energy output effectively [18].

In this regard, a key document in the Indian context, the "Renewables Integration in India" report, jointly released by the NITI Aayog and the International Energy Agency (IEA) in July 2021, highlights the critical need for states to enhance power system flexibility. To achieve this, the report recommends a multi-faceted approach, encompassing (i) battery storage solutions, (ii) the widespread deployment of smart-meters, (iii) advanced demand forecasting equipment, and (iv) the establishment of inter-regional transfers and cross-border transmission lines. Furthermore, the report introduces both regional and state-level models to evaluate the impact of growing renewable energy shares and the efficacy of these proposed flexibility solutions within India's unique power landscape [19].

A significant emphasis of the aforementioned NITI Aayog's report is placed on prioritising demand-side flexibility. The report explicitly identifies the lack of visibility into rooftop solar systems as an inherent challenge in accurately forecasting electricity demand for electricity distribution companies. Consequently, the report recommends the development of a unified

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

national platform for registering solar pumps and rooftop solar systems across all states, enabling better data collection and sharing.

Complementing these policy recommendations and technical solutions, the Green Energy Corridor (GEC) project stands as a foundational initiative by the Government of India, aimed at enabling the large-scale integration of renewable energy into the national power grid. The GEC's primary objective is to develop a robust transmission infrastructure specifically designed to efficiently evacuate electricity generated from renewable sources, such as solar and wind, particularly from resource-rich regions, and transmit it to high-demand centres across the country. A core goal of the GEC is to enhance the overall stability and reliability of the electricity grid by effectively managing the intermittent nature of renewable energy generation. This is achieved through the implementation of advanced monitoring, forecasting, and control systems, ensuring the seamless absorption of variable renewable power.

Many countries, like Germany and China, offer valuable insights into managing variability through advanced grid flexibility and Demand Response (DR) mechanisms. The DR mechanism primarily encourages customers to reduce their electricity usage during peak hours, thereby easing demand on the grid [20]. Some nations have modernised their grid infrastructure and educated consumers to align their energy usage with renewable energy availability, encouraging greater consumption during surplus periods and load reduction when generation dips. However, in India, Demand Side Management (DSM) is still at a nascent stage but holds significant potential. DSM encompasses initiatives such as DR, Energy Efficiency (promoting energy-saving practices), and Distributed Energy Resources (integrating consumer-owned generation). DSM is not only a tool for energy savings, it is a strategic plan to ensure grid stability, cost-effectiveness, and climate control [21].

IV. THE ROLE OF SMART GRIDS IN GRID BALANCING

Smart Grids are the next generation of power infrastructure, which utilises sensors, software, and digital technologies better to match the supply and demand of electricity in real-time, leading to improvements in the efficiency, reliability, and resilience of the electricity network. The smart grid operates through three interconnected layers that support its intelligent operation and two-way communication of electricity. At the foundation, the Perception Layer gathers raw data from physical devices such as sensors, smart meters, and data acquisition units, which monitor grid parameters and electricity usage. This data is then transmitted through the Network Layer, which serves as a communication backbone which uses various wired and wireless technologies (e.g., Wi-Fi, 5G) to ensure smooth data exchange across the system. At the top, the Application Layer processes and analyses the collected data, utilising sophisticated tools such as big data analytics and machine learning, to provide actionable intelligence for tasks including grid management, demand forecasting, anomaly detection, and consumer interaction. This layered structure ensures efficient data collection, transmission, and analysis, thereby enhancing the smart grid's performance and intelligence [22].

Artificial Intelligence (AI) and Machine Learning (ML) algorithms are key enablers for the practical function of the Smart Grid. These technologies enable real-time data-driven decision-making across various layers of the power grid system. This helps in optimising energy distribution, predicting energy use, quickly detecting faults, and allowing an automated response to changes in energy demand. These capabilities enhance grid balancing and stability, particularly with the increasing integration of variable renewable energy sources, such as solar and wind [23].

ML focuses on developing algorithms and models that enable computers to learn from and identify patterns within large and complex datasets. In the context of smart grids, ML approaches have become increasingly valuable, particularly with the growing integration of renewable energy sources. ML algorithms offer significant potential to optimise power generation, distribution, and consumption. Furthermore, these techniques play a critical role in detecting data anomalies and distortions, as well as maintaining overall system stability [24].

In the Indian context, initiatives under the National Smart Grid Mission (NSGM) and the Revamped Distribution Sector Scheme (RDSS) are actively laying the groundwork for integrating AI/ML technologies into electricity distribution operations. Pilot projects in cities like Bhubaneswar, Chandigarh, and Puducherry have already demonstrated the feasibility of AI-enabled grid automation, demand-side management, and real-time monitoring. While technical developments in solar energy integration are encouraging, certain obstacles remain, spanning environmental, economic, and technical aspects, which must be overcome for widespread adoption [25].

V. CONCLUSION

India has set a highly ambitious target for decarbonising energy, and accordingly, the Government of India is making substantial efforts to achieve this target. One of the essential measures in this direction is to integrate renewable energy into the power grid, encouraging consumers to adopt solar energy systems and helping them reduce their electricity bills through net metering. As of the end of 2024-25, renewable energy constituted only 110 GW, which is approximately 13%of the nation's electricity generation mix. Given India's recent intensified focus on renewable energy, the aforementioned growth in renewable energy represents significant progress. However, this highlights a critical gap that needs to be bridged to achieve the ambitious target of 500 GW of non-fossil capacity by 2030. The monumental growth of renewable energy, led by solar energy, requires significant land and associated costs. One possible solution to this problem is to encourage the widespread adoption of rooftop solar systems by households and businesses. However, integrating these distributed rooftop solar panels into the grid is also constrained by several systemic barriers, including the inherent variability of solar energy, the need for enhanced grid stability, and the complexities of real-time supply and demand balancing. The transition to a decarbonised, reliable power system, therefore, demands a comprehensive,

Retrieval Number:100.1/ijese.A105005011125
DOI:10.35940/ijese.A1050.13100925
Journal Website: www.ijese.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

multi-pronged approach rather than relying on a single solution.

This strategic approach of grid integration and grid balancing involves several key pillars. Firstly, fostering flexible grid operations through advanced forecasting techniques to predict renewable output and demand more accurately, as well as dynamic dispatch to adjust power generation and flow in real-time. Secondly, implementing intelligent infrastructure, such as smart grids, is essential to optimise electricity flow and respond to changes in electricity demand automatically. Thirdly, encouraging proactive participation from consumers and businesses through initiatives such as demand response. Further, pairing renewable energy with advanced storage solutions and smart grid technologies offers a viable and cost-competitive alternative to traditional thermal power. By strategically addressing the barriers above and leveraging digital innovations, India, along with the global community, can pave the way for a sustainable and resilient energy future.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted with objectivity and without any external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

REFERENCES

1. Banerjee, R., Mishra, V., & Maruta, A. A. (2021). Energy poverty, health and education outcomes: evidence from the developing world. Energy economics, 101, 105447. DOI: https://doi.org/10.1016/j.eneco.2021.105447
2. Mulugetta, Y., Ben Hagan, E., & Kammen, D. (2019). Energy access for sustainable development. Environmental Research Letters, 14(2), 020201. DOI: https://doi.org/10.1088/1748-9326/aaf449
3. IPCC (2023). Climate Change: Synthesis Report. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf
4. United Nations (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. New York: United Nations. https://archive.unescwa.org/sites/www.unescwa.org/files/un_resolutions/a_res_69_315_e.pdf
5. P. I. B. (2021). "National Statement by Prime Minister Shri Narendra Modi at COP26 Summit in Glasgow." Government of India. https://www.mea.gov.in/Speeches-Statements.htm?dtl/34466/National+Statement+by+Prime+Minister+Shri+Narendra+Modi+at+COP26+Summit+in+Glasgow
6. Ukoba, K., K. O. Yoro, O. Eterigho-Ikelegbe, C. Ibegbulam, and T. C. Jen. "Adaptation of solar power in the Global South: Prospects, challenges and opportunities." *Heliyon*, 2024. DOI: https://doi.org/10.1016/j.heliyon.2024.e28009
7. IRENA (2025). *Renewable Power Generation Costs in 2024*. https://www.irena.org/Publications/2025/Jun/Renewable-Power-Generation-Costs-in-2024
8. Kavlak, G., J. McNerney, and J. E. Trancik. (2018). "Evaluating the causes of cost reduction in photovoltaic modules." *Energy Policy* 123 (2018): 700-710. DOI: https://doi.org/10.1016/j.enpol.2018.08.015
9. P.I.B. (2025). "India's Energy Landscape Powering Growth with Sustainable Energy". Government of India. https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/jun/doc2025622575501.pdf
10. Mallya, H., D. Yadav, A. Maheshwari, N. Bassi, and P. Prabhakar (2024). *Unlocking India's RE and Green Hydrogen Potential*. https://www.ceew.in/sites/default/files/nexuss-annexure.pdf
11. Dawn, S., P. K. Tiwari, A. K. Goswami, and M. K. Mishra. (2016). "Recent developments of solar energy in India: perspectives, strategies and future goals." *Renewable and Sustainable Energy Reviews* 62 (2016): 215-35. DOI: https://doi.org/10.1016/j.rser.2016.04.040
12. India Energy Outlook (2021). International Energy Agency (IEA). https://www.iea.org/reports/india-energy-outlook-2021
13. Bondalapati, S. R., B. N. Bhukya, G. P. Anjaneyulu, M. Ravindra, and B. S. Chandra. "Bidirectional Power Flow Between Solar-Integrated Grid to Vehicle, Vehicle To Grid, And Vehicle To Home." *Journal of Applied Science and Engineering* 27, no. 5 (2024): 2571-81. DOI: https://doi.org/10.6180/jase.202405_27(5).0014
14. Nwaigwe, K. N., P. Mutabilwa, and E. Dintwa. "An overview of solar power (PV systems) integration into electricity grids." *Materials Science for Energy Technologies* 2, no. 3 (2019): 629-33. DOI: https://doi.org/10.1016/j.mset.2019.07.002
15. Tur, M. R., Ay, S., Erduman, A., Shobole, A., Baysal, M., & Wadi, M. (2017). Impact of Demand-Side Management on Spinning Reserve Requirements Designation. International Journal of Renewable Energy Research, 7(2), 946-953. DOI: https://doi.org/10.20508/ijrer.v7i2.6006.g7075
16. Benti, N. E., M. D. Chaka, and A. G. Semie (2023). "Forecasting renewable energy generation with machine learning and deep learning: Current advances and prospects." *Sustainability*, 15(9), 7087. DOI: https://doi.org/10.3390/su15097087
17. Gür, T. M. (2018). "Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage." *Energy & Environmental Science* 11, no. 10 (2018): 2696-767. https://pubs.rsc.org/en/content/articlelanding/2018/ee/c8ee01419a/unauth
18. Sahoo, S., and P. Timmann.(2023) "Energy storage technologies for modern power systems: A detailed analysis of functionalities, potentials, and impacts." *IEEE Access* 11 (2023): 49689-729. DOI: https://doi.org/10.1109/ACCESS.2023.3274504
19. NITI Aayog (2021) "Renewables Integration in India", Government of India. https://www.niti.gov.in/sites/default/files/2021-08/RenewablesIntegrationinIndia2021-compressed.pdf
20. Dahiru, A. T., D. Daud, C. W. Tan, Z. T. Jagun, S. Samsudin, and A. M. Dobi.(2023) "A comprehensive review of demand side management in distributed grids based on real estate perspectives." *Environmental Science and Pollution Research* 30, no. 34 (2023): 81984-2013. DOI: https://doi.org/10.1007/s11356-023-25146-x
21. Saklani, M., Saini, D. K., Yadav, M., & Gupta, Y. C. (2024). Navigating the challenges of EV integration and demand-side management for India's sustainable EV growth. IEEE Access. DOI: https://doi.org/10.1109/ACCESS.2024.3470218
22. Abrahamsen, F. E., Y. Ai, and M. Cheffena (2021). "Communication technologies for smart grid: A comprehensive survey." *Sensors* 21, no. 23 (2021): 8087. DOI: https://doi.org/10.3390/s21238087
23. Anjana, K. R., & Shaji, R. S. (2018). A review of the features and technologies for energy efficiency of the smart grid. International Journal of Energy Research, 42(3), 936-952. DOI: https://doi.org/10.1002/er.3852
24. Allal, Z., H. N. Noura, O. Salman, and K. Chahine (2024). "Leveraging the power of machine learning and data balancing techniques to evaluate stability in smart grids." *Engineering Applications of Artificial Intelligence* 133 (2024): 108304.

© Copyright: All rights reserved.

DOI: https://doi.org/10.1016/j.engappai.2024.108304
25. Kharche, N. R. (2024). "Emerging Trends." In *Explainable Artificial Intelligence and Solar Energy Integration*, 39. DOI: https://doi.org/10.4018/979-8-3693-7822-9.ch002

AUTHOR PROFILE

Dr. Sweety Supriya is an Assistant Professor of Electronics at L.S. College, Muzaffarpur, Bihar. She holds a PhD in Physics from the Indian Institute of Technology (IIT) Patna, which she completed in 2018. Her research focuses on a range of advanced materials, including polymer nanocomposite dielectrics, energy storage materials, and high-K polymers for flexible electronics. She also specializes in transport phenomena in metal oxides, interfacial science, and ceramic composites.Prior to her current role, Dr Supriya held assistant professorships at the National Institute of Technology (NIT), Nagaland, and the Department of Physics at the University of Delhi. A prolific researcher, she has authored 20 peer-reviewed journal publications and 15 peer-reviewed conference papers. She is currently active in both teaching and research in the field of electronics.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)/ journal and/or the editor(s). The Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP) and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

© Copyright: All rights reserved.