

# Smart Power Grid Evolution in India

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**Abstract** - India's burgeoning population and unwavering commitment to universal electrification necessitate a paradigm shift in its power grid infrastructure. Conventional grids, plagued by inefficiencies and limited integration capabilities, struggle to meet the demands of a rapidly evolving energy landscape. Smart grids, characterized by a robust digital foundation, advanced automation protocols, and bidirectional communication channels, emerge as a potential panacea. This paper delves into the intricate evolution of smart grid technology within the Indian context. It meticulously analyzes the key drivers that propel this transformation, dissects the implemented initiatives aimed at fostering widespread adoption, and rigorously evaluates the potential benefits that accrue to consumers, utilities, and the environment. By critically examining the current state and future trajectory of smart grid development in India, this paper aims to illuminate a path towards a more resilient, efficient, and sustainable energy system.

**Key Words:** Transmission and Distribution (T&D), Artificial Intelligence (AI), Internet of Things (IoT), Advanced Metering Infrastructure (AMI), Renewable Energy, Smart Grids., etc. ...

## 1. INTRODUCTION

India's power sector is at a critical juncture, grappling with numerous challenges that hinder its ability to provide reliable and efficient energy to a growing population and a rapidly industrializing economy. One of the most pressing issues is the high transmission and distribution (T&D) losses, which are among the highest in the world. These losses, often due to outdated infrastructure, theft, and inefficiencies in power delivery, result in significant financial detriments, with losses estimated to be around ₹1.2 trillion (approximately \$16 billion USD) annually. This not only undermines financial stability but also compromises the reliability of power supply.

Another major concern is the limited resilience of the existing grid infrastructure. The traditional grid is vulnerable to various disruptions, including natural disasters, technical failures, and cyber-attacks. This lack of resilience often leads to prolonged outages and instability in power supply, affecting both urban and rural areas. For instance, natural disasters such as the 2019 Cyclone Fani caused extensive damage to the power infrastructure, resulting in prolonged blackouts that affected millions.

Furthermore, the integration of large-scale renewable energy sources poses additional challenges. With India committed to achieving 175 GW of renewable energy capacity by 2022, particularly in solar and wind power, the conventional grid struggles to manage the variable and intermittent nature of these energy sources. Balancing supply and demand, ensuring grid stability, and maintaining power quality are becoming increasingly complex tasks. Conventional grids, characterized by centralized generation and a unidirectional flow of electricity, are not equipped to handle these multifaceted challenges effectively. Their inherent limitations in flexibility, efficiency, and responsiveness underscore the need for a transformative approach to power grid management.

## 1.1 Energy Consumption and Challenges in India

India, as the fourth largest energy consumer globally, is experiencing an unprecedented surge in energy demand, propelled by the rapid growth of its economy. This burgeoning demand for electricity underscores the necessity for substantial advancements in the power sector to sustain economic development, ensure universal access to electricity, and address pressing environmental concerns.

- **Projected Electricity Demand Growth:** Since gaining independence, India has witnessed remarkable progress in the power sector. However, despite these strides, approximately 400 million individuals remain without access to electricity, and hundreds of millions more receive power for only a limited number of hours each day. This disparity highlights the urgent need to enhance the power infrastructure to achieve comprehensive and reliable electrification across the country.

To maintain the momentum of economic growth and to meet the dual objectives of providing electricity to all citizens and adhering to environmental standards, India must explore alternative and non-conventional sources of energy. This strategic shift is crucial for ensuring long-term energy security and sustainability. Integration of Renewable Energy Sources, unlike conventional power generation methods, is characterized by their non-dispatchable nature. This means that there are inherent uncertainties and variability associated with large-scale wind and solar power generation. These fluctuations pose significant challenges for grid stability and reliability. The development of smart grid technology in India is anticipated to play a pivotal role in addressing these challenges. By facilitating the integration of large-scale renewable energy sources, smart grids can

enhance the monitoring and management of the power system. This advanced technology allows for real-time data collection and analysis, enabling more precise control over energy distribution and consumption.

- Enhanced Monitoring and Consumer Participation

Smart grid technology is expected to revolutionize the Indian power sector by providing enhanced monitoring capabilities and fostering greater consumer participation. Through the deployment of advanced metering infrastructure (AMI), the power grid can collect accurate, real-time data on electricity usage, which aids in identifying inefficiencies and optimizing energy distribution. Furthermore, smart grids empower consumers by offering them greater control over their energy consumption. With access to detailed information about their electricity usage patterns, consumers can make more informed decisions, adopt energy-saving practices, and participate in demand response programs. These programs incentivize consumers to reduce their electricity consumption during peak demand periods, thereby contributing to grid stability and reducing the overall strain on the power system.

- Addressing Distribution Sector Issues: The distribution sector in India faces numerous challenges, including high transmission and distribution (T&D) losses, power theft, and aging infrastructure. Smart grid technology addresses these issues by implementing advanced loss detection and management systems. These systems utilize data analytics and machine learning algorithms to identify loss hotspots, allowing utilities to target maintenance and upgrade efforts more effectively. Moreover, smart grids incorporate self-healing capabilities, which enable the power grid to detect and respond to faults automatically. This reduces the duration and impact of power outages, enhancing the overall reliability of the electricity supply.

In the evolution of smart grid technology in India is a critical step towards achieving a resilient, efficient, and sustainable power sector. By integrating advanced technologies, facilitating the adoption of renewable energy sources, and empowering consumers, smart grids hold the potential to transform India's energy landscape, ensuring long-term energy security and supporting the country's continued economic growth.

Transformation of India's Generation Capacity Portfolio in alignment with international development trends, the composition of India's installed generation capacity is undergoing significant transformation. Renewable energy (RE) sources are playing an increasingly important role in the nation's energy portfolio. Currently, approximately 12% of India's total installed generation capacity, equivalent to 29.5 GW, is derived from renewable sources. In terms of

actual energy produced, renewable energy penetration stands at about 6%. The Ministry of New and Renewable Energy (MNRE) has set ambitious targets for the expansion of renewable energy capacities. According to projections by MNRE, by the end of the 12th Five-Year Plan (2012-2017), the installed capacity from renewable sources was expected to reach around 55 GW. Furthermore, by the conclusion of the 13th Five-Year Plan (2017-2022), this capacity is anticipated to increase to approximately 98 GW. The growth trend in renewable energy generation in India is marked by several key initiatives and policies aimed at promoting the adoption and integration of RE sources. This expansion is driven by a combination of technological advancements, policy support, and investment in renewable energy projects.

Category	Details
Solar Energy	Significance: Major contributor to India's renewable energy capacity.
	Projects: Large-scale solar parks, rooftop solar installations.
	Initiative: Jawaharlal Nehru National Solar Mission (JNNSM).
	Target: Deploy 100 GW of solar power by 2022.
Wind Energy	Significance: Critical component of India's renewable energy strategy.
	Resources: Abundant wind resources, especially in Tamil Nadu, Gujarat, and Karnataka.
	Measures: Competitive bidding processes, financial incentives, streamlined approval procedures.
Grid Integration and Smart Grids	Challenges: Variability, intermittency, and grid stability with large-scale renewable integration.
	Solutions: Development of smart grid technologies for real-time monitoring and management to enhance grid reliability.

**Table No.1 Growth Trend in Renewable Generation**

This paper explores the evolution of smart grid technology in India, analysing the driving factors behind its adoption, key initiatives and projects implemented, and the technological advancements that underpin its development. It also examines the potential benefits for consumers, utilities, and the environment, providing a comprehensive overview of how smart grids can transform India's power sector into a more efficient, reliable, and sustainable system.

## 1.2 Smart grids

Smart grids emerge as a promising solution to these challenges, offering a modernized power system with intelligent infrastructure and advanced communication capabilities. Unlike traditional grids, smart grids facilitate bidirectional flow of electricity and data, enabling real-time monitoring, control, and automation of the entire power network. This transformation is driven by the integration of cutting-edge technologies such as the Internet of Things (IoT), artificial intelligence (AI), and advanced metering infrastructure (AMI).

Smart grids promise a more efficient power system by optimizing energy distribution, reducing T&D losses, and improving demand-side management. Enhanced reliability is achieved through real-time fault detection and automated response mechanisms, minimizing the duration and impact of power outages. Additionally, the flexible and adaptive nature of smart grids supports the seamless integration of renewable energy sources, ensuring a stable and balanced power supply.

Moreover, smart grids contribute to sustainability by facilitating the use of clean energy, reducing greenhouse gas emissions, and promoting energy conservation. They empower consumers with greater control over their energy usage and costs, fostering a more engaged and informed user base.

## 2. Smart Grid Evolution

The evolution of smart grid technology in India represents a transformative journey aimed at addressing the inefficiencies and limitations of the traditional power grid. This evolution is characterized by a series of strategic initiatives, technological advancements, and policy interventions designed to modernize India's power infrastructure.

- **Initial Stages and Policy Framework:** The foundation for the evolution of smart grids in India was laid in the early 2000s with the recognition of the need for modernizing the power sector. The Ministry of Power (MoP) and the Central Electricity Regulatory Commission (CERC) played pivotal roles in initiating reforms and setting the stage for smart grid development. Electricity Act, 2003 is landmark legislation aimed to consolidate and improve the efficiency of the power sector. It provided a framework for the restructuring of the sector, encouraged private participation, and promoted competition. National Electricity Policy (NEP), 2005 is emphasized the importance of reliable and quality power supply, recognizing the role of technology in achieving these goals. Integrated Power Development Scheme (IPDS), 2014 is scheme

focused on strengthening sub-transmission and distribution networks, metering of distribution transformers/feeders/consumers, and IT-enabled energy accounting/auditing systems.

- **Smart Grid Vision and Roadmap:** In 2013, India launched its Smart Grid Vision and Roadmap, a comprehensive document outlining the goals, strategies, and milestones for the development of smart grids in the country. The roadmap set ambitious targets for the adoption of smart grid technologies and provided a structured approach for their implementation. Smart Grid Pilots is the Government of India sanctioned 14 smart grid pilot projects across various states to demonstrate the benefits of smart grid technologies and to understand their feasibility and scalability. National Smart Grid Mission (NSGM), 2015 was established to plan and monitor the implementation of policies and programs related to smart grids. It aims to achieve the modernization of India's electricity distribution network by deploying smart grid technologies.
- **Technological Advancements** The evolution of smart grids in India has been driven by the integration of several advanced technologies that enhance the efficiency, reliability, and sustainability of the power system. Advanced Metering Infrastructure (AMI): AMI includes smart meters, communication networks, and data management systems that enable real-time monitoring and control of electricity consumption. By 2020, India had installed over 10 million smart meters under various government programs.
- **Internet of Things (IoT) and Sensors:** IoT devices and sensors are deployed across the grid to collect data on various parameters, such as voltage, current, and power quality. This data is used for real-time monitoring, fault detection, and predictive maintenance.
- **Artificial Intelligence (AI) and Machine Learning (ML):** AI and ML algorithms are employed to analyse large volumes of data generated by smart grids. These technologies help in optimizing energy distribution, detecting anomalies, and improving demand-side management.
- **Energy Storage Systems:** The integration of energy storage systems, such as batteries, is crucial for managing the variability of renewable energy sources. These systems store excess energy generated during periods of low demand and release it during peak demand, ensuring grid stability.

- Key projects in India showcase the benefits of smart grid technologies. Pilot projects in various states demonstrate smart metering, automated demand response, and renewable energy integration. The Green Energy Corridor project facilitates large-scale renewable energy integration into the grid. UDAY, launched in 2015, focuses on improving efficiency of power distribution companies and encourages smart grid adoption.

## 2.1 Benefits and Future Prospects of Smart Grids in India: A Deeper Look

The emergence of smart grid technology in India presents a paradigm shift for consumers, utilities, and the environment. Here's a closer examination of the multifaceted benefits and the promising future landscape:

**Enhanced Efficiency and Sustainability:** Smart grids revolutionize energy distribution by optimizing power flow, minimizing transmission and distribution (T&D) losses, and enabling sophisticated demand-side management strategies. This translates to significant cost savings for all stakeholders. Furthermore, smart grids pave the way for a greener future by facilitating the seamless integration of renewable energy sources like solar and wind. This reduces dependence on fossil fuels, leading to a cleaner environment and a significant reduction in greenhouse gas emissions.

**Improved Reliability and Consumer Empowerment:** Real-time data acquisition and intelligent grid management empower proactive responses to disruptions. Smart grids enable swift detection and rectification of faults, minimizing power outage duration and impact. Consumers benefit from a more reliable and stable power supply. Additionally, smart meters provide them with granular insights into their energy consumption patterns. This empowers them to make informed choices, adopt energy-efficient practices, and ultimately reduce their electricity bills.

- **Future Prospects:** The future of smart grids in India is brimming with potential. Exponential Growth of Smart Metering: The government's ambitious plan to install 250 million smart meters by 2025 signifies a nationwide transformation. This comprehensive coverage will empower consumers across the country and provide utilities with invaluable data for grid optimization.
- **Integration of Distributed Energy Resources (DERs):** The growing popularity of rooftop solar panels, electric vehicles (EVs), and other DERs necessitates the adoption of advanced grid management techniques. Smart grids will need to adapt and evolve to accommodate these new players, ensuring seamless integration and efficient power management.

- **Cyber security Imperative:** As smart grids become increasingly interconnected and data-driven, robust cyber security measures become paramount. Implementing advanced security protocols and fostering a culture of cyber awareness will be crucial to safeguard the integrity and reliability of the smart grid infrastructure.

## 3. Drivers for Evolution of Smart Grid Technology in India

The adoption of smart grids in India is driven by several critical factors that address the inherent challenges of the traditional power grid. These drivers not only aim to enhance the efficiency and reliability of the power system but also to support the country's growing energy demands and sustainability goals. Here is a detailed exploration of these drivers:

### Need to Reduce Transmission and Distribution (T&D) Losses

India experiences significant T&D losses, often exceeding 20%, which is much higher than the global average. These losses are a major concern as they lead to substantial financial losses for utilities and higher electricity costs for consumers. Several factors contribute to these losses, including technical inefficiencies, power theft, and aging infrastructure.

- **Smart Meters and Advanced Metering Infrastructure (AMI):** The deployment of smart meters and AMI is pivotal in reducing T&D losses. Smart meters provide accurate and real-time data on electricity consumption, which helps in identifying discrepancies and areas of loss. AMI enables utilities to remotely monitor and manage the grid, detect anomalies, and take corrective actions promptly.
- **Loss Detection and Management:** Smart grids use advanced data analytics and machine learning algorithms to detect patterns indicative of energy theft or technical losses. By pinpointing loss hotspots, utilities can target maintenance and upgrade efforts more effectively.

### Renewable Energy Integration

India has set ambitious targets for renewable energy capacity, aiming to achieve significant penetration of solar and wind energy in its energy mix. The intermittent and variable nature of these renewable sources poses challenges for the stability and reliability of the traditional grid.

- **Real-Time Grid Monitoring:** Smart grids incorporate sensors and IoT devices that provide real-time monitoring of grid conditions. This

continuous data flow helps in assessing the performance of renewable energy sources and their impact on the grid.

- **Dynamic Control Capabilities:** Advanced control systems in smart grids can dynamically manage the integration of renewable energy. By adjusting the output of conventional power plants and utilizing energy storage systems, smart grids can balance supply and demand, ensuring a stable power supply even with high levels of renewable penetration.
- **Forecasting and Planning:** Smart grids use predictive analytics to forecast renewable energy generation based on weather conditions and historical data. This capability aids in planning and optimizing grid operations, reducing the need for reserve power and enhancing the efficiency of energy utilization.

- **Time-of-Use (TOU) Pricing:** TOU pricing schemes incentivize consumers to shift their electricity usage to off-peak times when demand is lower and electricity is cheaper. Smart meters enable the implementation of TOU pricing by recording consumption patterns in real-time.
- **Demand Response Programs:** Smart grids facilitate demand response programs where consumers are rewarded for reducing their electricity usage during peak demand periods. This not only helps in balancing the grid but also allows consumers to lower their electricity bills.
- **Energy Management Tools:** Smart grids provide consumers with access to detailed information about their energy consumption through mobile apps and web portals. This transparency enables consumers to make informed decisions about their energy use, adopt energy-saving practices, and invest in energy-efficient appliances.
- **Distributed Generation and Net Metering:** Consumers can also participate in distributed generation by installing rooftop solar panels and other renewable energy systems. Smart grids support net metering, where excess energy generated by consumers is fed back into the grid, providing them with credits and promoting decentralized energy production.

### Improved Power Quality and Reliability

The traditional grid often struggles with maintaining consistent power quality and reliability, leading to issues such as voltage fluctuations, power surges, and frequent outages.

- **Voltage Regulation and Stability:** Smart grids employ advanced voltage regulation technologies and power electronics to maintain stable voltage levels across the grid. This reduces the incidence of power surges and sags, protecting sensitive equipment and ensuring consistent power quality.
- **Self-Healing Capabilities:** One of the hallmark features of smart grids is their ability to detect and respond to faults automatically. Self-healing grids use automated switchgear and real-time data to isolate faulty sections and reroute power, minimizing the impact of outages and reducing downtime significantly.
- **Enhanced Monitoring and Maintenance:** Continuous monitoring of grid assets allows for predictive maintenance, where potential issues are identified and addressed before they result in failures. This proactive approach enhances the reliability of the grid and extends the lifespan of infrastructure.

### Consumer Empowerment

Smart grids not only benefit utilities but also empower consumers by providing them with greater control over their energy usage and costs.



Fig -1: Smart grid

### 3. CONCLUSIONS

The evolution of smart grids in India is driven by a combination of technical, economic, and policy factors. By addressing the critical challenges of T&D losses, renewable energy integration, power quality, and consumer empowerment, smart grids offer a pathway to a more efficient, reliable and sustainable power system. The continued support and collaboration among government bodies, utilities, and consumers are essential to realize the full potential of smart grid technologies and to achieve the nation's energy goals.

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