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Review Article

Advanced Metering Infrastructure and Its Role in Building A Smart and Sustainable Power Distribution System: A Comprehensive Review from India's Frame of Reference

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***Abstract** - The Electric Power system is the most complicated network for analyzing and predicting about future trends. Presently, the distribution system in India spreads across a wide geographical area with multifarious networking, which makes it very difficult to understand and control. Advanced Metering Infrastructure (AMI) plays a vital role in mitigating challenges associated with the power distribution system. It provides two-way communication for transmitting crucial data from consumers' smart meters to the utility and vice versa. This paper provides a comprehensive overview of the Advanced Metering Infrastructure and its advantages for the Indian power distribution system. The paper also presents insights into various schemes and initiatives in India that are currently underway to improve the distribution network and examines their current status. Additionally, the paper scrutinizes the implementation challenges of AMI in great detail and recommends mitigation strategies for each of them. The recommendations for mitigation strategies provide a valuable resource for policymakers and stakeholders. Finally, the research trends in AMI discussed in the paper offer valuable insights into the direction of future research from India's frame of reference.*

***Keywords** - Advanced Metering Infrastructure (AMI), Smart grid, Smart meter, Power distribution system, Distribution Company (DISCOM), Mitigation strategies.*

I. Background and Motivation of the Study

India's electrical power system is among the world's largest interconnected systems, with an installed capacity of 410339.23 MW, ranking third globally in terms of generation capacity at 3790.43 MU. The transmission network covers 464795 CKM, with 1151722 MVA (220 KV and above) [1]. The Power System is divided into five interlinked regional grids: North, East, West, South and North-East Grid. The Northern grid is the largest and most heavily loaded, while the North Eastern grid is the smallest and least developed.

Electricity generation in India primarily relies on coal-based thermal power plants, accounting for 57.44% of the total installed capacity. Other energy sources include hydro (11.38%), nuclear (1.65%), wind (10.20%), bio (2.61%), and solar (15.52%). However, India is now focusing on increasing its share of renewable energy, particularly solar and wind power. Despite this progress, India's power distribution system is facing significant challenges. Effective management of the distribution system is essential for delivering electricity to end-users safely, reliably, and cost-effectively.

The distribution network comprises various components, such as substations, feeders, transformers, switchgear, and meters, responsible for managing the flow of electricity. It also ensures that the voltage and frequency remain within acceptable limits. Frequent voltage fluctuations and power outages plague many regions, attributed to aging and inadequate distribution infrastructure. The sector grapples with inadequate investments, leading to outdated and unreliable infrastructure. This financial constraint, coupled with the cross-subsidization of tariffs, which burdens industries and discourages investments, further exacerbates the problem.

Additionally, the distribution transformers are often overloaded, straining their efficiency, increasing losses, and escalating maintenance costs. Accuracy in metering and billing is also an ongoing issue, contributing to commercial losses that demand the adoption of digital metering and enhanced billing systems. Theft of electricity and non-payment of bills continue to be significant challenges, necessitating robust measures to combat these issues.

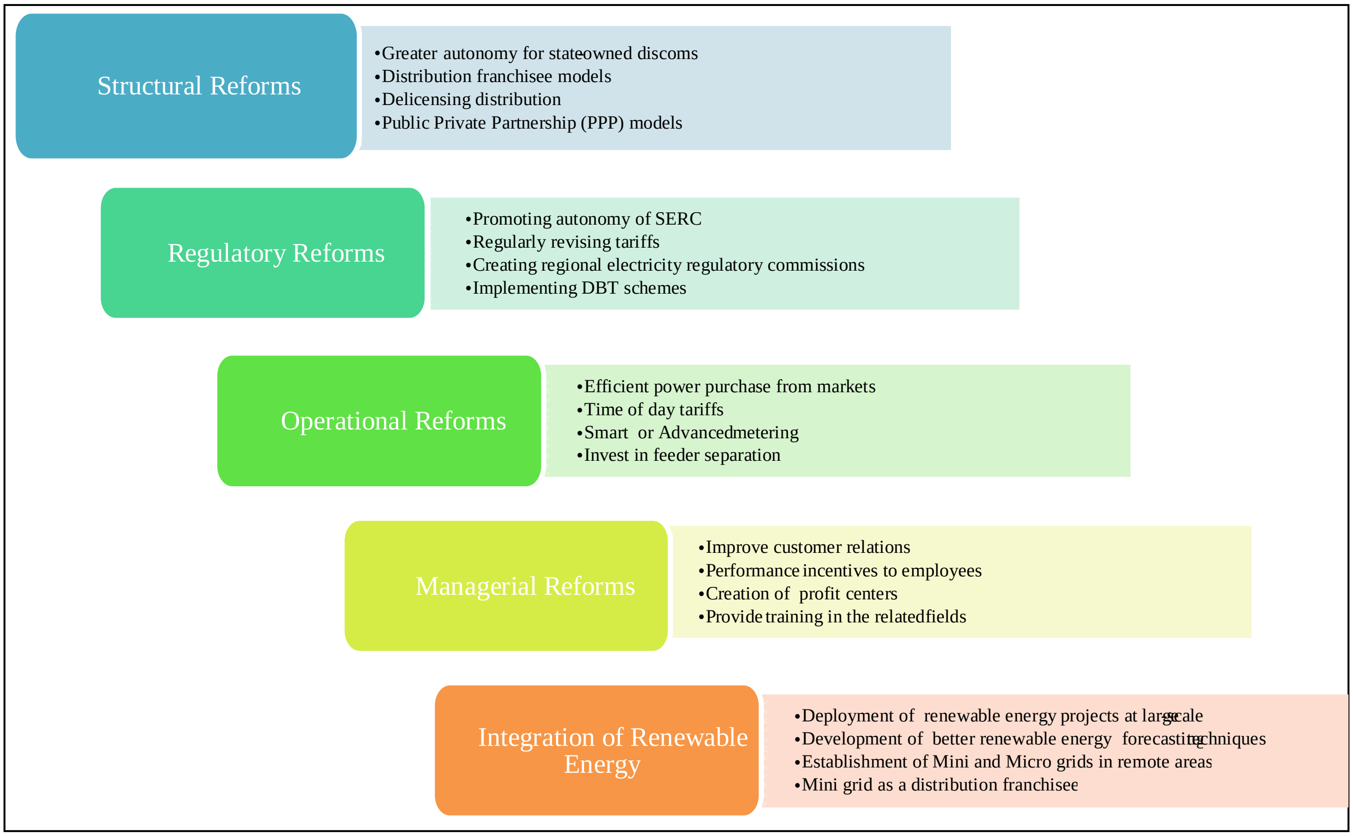


Fig. 1 Summary of major reforms suggested in the NITI Aayog report on the power distribution

Because of this, the majority of power distribution companies (discoms) in India encounter yearly deficits, including Aggregate Technical losses and Commercial losses (AT&C) or Transmission & Distribution losses (T&D). (Refer [2] for an in-depth study on the distribution sector in India). The AT & C and T& D losses are often used interchangeably as both indicate the health of distribution. The only difference between them is that the T&D loss is determined by the difference between the energy input into the T&D network and the sales to consumers, whereas the energy input determines the AT&C loss into the distribution network and the revenue collected from the same [3].

According to the data available on the UDAY website, India's aggregate technical and commercial losses are 17.38%, twice the global average [4]. These accumulated losses hinder the distribution companies from making the necessary investments to provide highly reliable and accountable electrical power. Moreover, the rural electrification effort, while making progress, still faces the task of providing reliable access to electricity in remote areas.

The integration of renewable energy sources, such as wind and solar, into the distribution grid presents technical challenges, including grid stability and power quality concerns. Regulatory complexity and policy inconsistency add to the sector's woes, potentially hindering investment and planning efforts. Addressing these multifaceted problems demands a holistic approach encompassing infrastructure investment, technological upgrades, regulatory reforms, enhanced operational efficiency and revenue collection.

1.1. National Institution for Transforming India (NITI) Aayog Report

The report named "Turning around the power distribution sector" recommends five types of reforms for the upliftment of the power distribution system [5], which is pointed out above in Figure 1 . The reforms mentioned could bring out the utilities from its awful circumstances. Among these reforms, the operational and integration of renewable energy is gaining more fame in the research areas.

1.2. Need for Operational Reforms

Operational reforms in India's power distribution sector are imperative, given the alarming overall AT&C loss figure of up to 17.38 percent. To address these challenges, discoms need to focus on various aspects of their operations. One critical need is to improve billing efficiency through better metering.

This involves achieving 100 percent metering using prepaid or smart meters while also being vigilant about cybersecurity threats. Smart meters are one of the essential parts of AMI technologies that play a pivotal role in this transformation. These meters enable real-time monitoring and data collection, allowing for more accurate billing and reducing losses due to theft or inaccurate readings. Moreover, they empower consumers with real-time consumption information, encouraging energy conservation. Efforts to combat theft and reduce losses can be further enhanced through concerted action by discoms and states.

The implementation of prepaid metering, as successfully seen in Manipur, has proven effective in reducing thefts and increasing revenue collection [5]. Additionally, addressing the issue of default in payments by state government departments and municipal bodies is crucial to improving revenue streams. Investment in distribution infrastructure is another crucial aspect of operational reform.

The revamped central government reform scheme, as announced in the 2021 Budget, provides an opportunity for discoms to upgrade their distribution infrastructure. This investment can significantly reduce technical losses and enhance the reliability of the grid. Subsidized electricity for agricultural use is a common practice in many states, leading to leakages and high losses for discoms.

States like Rajasthan, Andhra Pradesh, Gujarat, Karnataka, and Maharashtra have successfully reduced leakages by segregating feeders for agricultural and non-agricultural use. Furthermore, promoting the use of solar pumps for agriculture can help discoms reduce power procurement costs. Another crucial aspect of operational reform is reconsidering long-term and expensive Power Purchase Agreements (PPAs).

Discoms should refrain from signing new expensive long-term thermal PPAs, especially when low-cost power is available in the market. States like Chhattisgarh, Gujarat, Maharashtra, and Uttar Pradesh have already taken steps to restrict new thermal PPAs. Additionally, where feasible, discoms should explore options to exit expensive and long-term PPAs, thus reducing the overall cost of power procurement.

To further optimize their operations, discoms should implement Time-of-Day (ToD) tariffs, incentivizing changes in demand patterns. Dynamic tariffs, facilitated by Advanced Metering Infrastructure (AMI) and a smart grid, enable real-time pricing adjustments based on supply and demand dynamics. This not only reduces the discoms’ power purchase costs but also helps manage peak loads efficiently, ensuring a more sustainable and reliable power distribution system.

1.3. Advanced Metering Infrastructure (AMI)

AMI is the foundation of the smart grid, an innovative electricity distribution system that utilizes digital technologies to enable bidirectional communication between utility providers and consumers. This communication enables real-time energy distribution system monitoring, analysis, and control. With AMI facilitating two-way communication, consumers can benefit from real-time pricing, demand response programs, and other energy management strategies, empowering them to make informed decisions about their energy usage.

In India, on 28th February 2022, the Central Electricity Authority (CEA) of India amended the CEA (Installation and Operation of Meters) Regulations. The amendment introduced a definition for “Advanced Metering Infrastructure is an integrated system of smart meters, communication networks and data management systems that enables two-way communication between the utilities and energy meters, and the functional blocks of Advanced Metering Infrastructure typically include Head end system, Wide area network, Neighborhood area network, Data concentrator unit, and Home area network [6].”

1.4. Major Components of AMI

AMI comprises hardware and software parts that measure energy use and transmit data about energy, water, and gas usage to utility providers and customers. The main technological elements of AMI [7] are as follows:

1) Smart Meters: These meters come with advanced information and communication technologies, allowing for real-time data transmission in both directions.
2) Communication Networks: AMI requires robust communication networks to transmit data between smart meters and utility companies. These networks can be wireless, cellular, or power line-based. Examples: Power Line Communication, Local Area Network,.etc.
3) Meter Data Management Systems (MDMS): Data collected from smart meters is processed, stored, and managed using advanced data management systems. These systems typically include data analytics tools that provide insights into energy consumption patterns and help utilities optimize their operations.
4) Data Concentrator Unit (DCU): It collects data from multiple smart meters and sends it to the head-end system via the communication network. It also receives commands from the head-end system and sends them to the smart meters.

In general, AMI is a complete system that includes smart meters, a two-way communication network, control center hardware, and applications that collect and transfer energy usage data in real-time. It forms the foundation of the smart grid by enabling two-way communication with customers. The main objectives of AMI are load profiling, energy audits, partial curtailment instead of load shedding, network problem detection, and remote meter reading for accurate data. It is important to note that AMI and Automated Meter Reading (AMR) have a fundamental difference, which can be understood in Table 1.

Table 1. Comparison of AMR, AMR PLUS, and AMI [8]

Functions	AMR	AMR Plus	AMI
One Way Communications	✓	×	×
Full Two-Way Communication	×	×	✓
Outage Notifications	×	✓	✓
Reconnect /Disconnect	×	×	✓
Advanced (Time-Based) Rates	×	×	✓
Distributed Generation and Control	×	×	✓
Remote Metering Programming	×	×	✓
Power Quality and Monitoring	×	×	✓
Home Area Network Interface	×	×	✓
Enhanced Security Compliance	×	×	✓

Table 2. Comparison of conventional energy meter vs Smart meter

Conventional Energy Meter	Smart Meter
An electromechanical device that measures electricity consumption.	An electronic device that records and transmits electricity usage data in real-time to the utility company.
It requires manual reading by a meter reader, which can be time-consuming and prone to errors.	Enables real-time monitoring of electricity consumption, eliminating the need for manual reading or estimation.
It does not allow consumers to monitor their electricity usage in real-time.	Provides consumers with real-time data to help them better understand and manage their electricity usage.
Billing is based on manual readings or estimates, which can be inaccurate.	Enables more accurate billing, as there is no need for manual reading or estimation.
Does not offer advanced features such as power outage detection or time-of-use pricing.	Offers additional features and benefits such as power outage detection, time-of-use pricing, and the ability to connect or disconnect service remotely.
Relatively simple and inexpensive.	More costly to install and maintain.
Does not raise concerns about data privacy and security.	Raises concerns about data privacy and security due to the electronic transmission of usage data.

The common functions in all three technologies are automated monthly readings, tamper reporting, meter diagnostic reporting, and data aggregation. Hence, it can be concluded that AMI offers better functionalities than AMR and AMR Plus and brings more intelligence to energy management.

1.5. Smart Meter

Smart meters are considered the backbone of AMI technologies. It has advanced measuring devices that offer several features, such as the ability to measure power consumption and various electrical characteristics like the three-phase voltage, three-phase current, power factor, Total Harmonic Distortions (THD), etc. [9]. They can also forecast power usage at specific intervals, and due to their potential to distribute the power from the residential grids to homes, they are commonly referred to as smart sockets. The use of smart meters will eliminate the need for meter readers to visit each customer, improving the existing situation of distribution companies in India.

The main challenge is leveraging this vast amount of smart meter data to enhance the effectiveness and sustainability of Demand Side Management (DSM), which is a significant global issue [10] (Refer to Table 2. for a Comparison between Smart and Conventional energy meters).

1.6. International & National Standards for AMI

Several National and International standards have been established for AMI to ensure the system’s interoperability, reliability, and security. Some of the key International and National standards for AMI include the following:

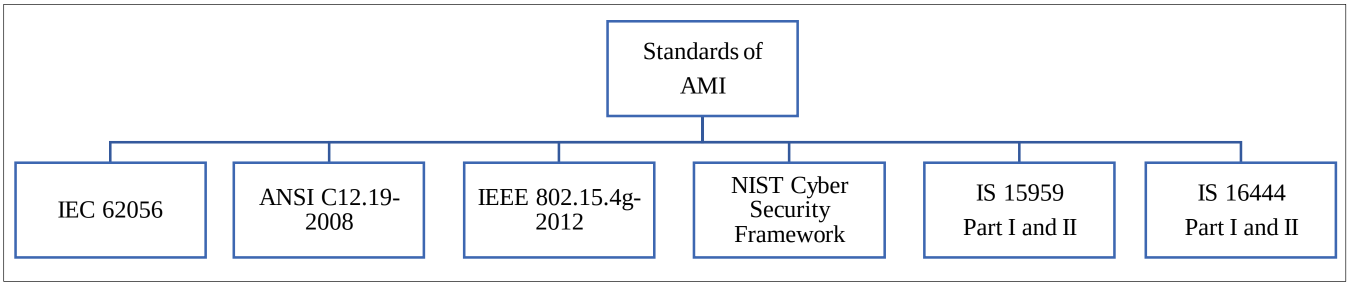


Fig. 2 Standards for AMI

1.6.1. International Standards

1) International Electrotechnical Commission (IEC 62056): Its first edition was published in the year 2002. It is a set of standards specifying electricity metering data exchange interface requirements. It provides a standardized way for utility companies to exchange metering data with other systems and devices.
2) Approved American National Standard (ANSI C12.19-2008): This standard specifies communication protocols and data exchange formats for utility metering devices. It defines the structure and content of messages exchanged between meters and other devices.
3) Institute of Electrical and Electronics Engineers (IEEE 802.15.4g-2012): This standard specifies the physical and Media Access Control (MAC) layer specifications for wireless communications in smart grid applications. It provides a communication protocol for low-data-rate wireless networks.
4) National Institute of Standards and Technology (NIST) Cyber Security Framework: It is a set of guidelines provided by the United States National Institute of Standards and Technology for securing AMI systems from cyber threats. The first edition of the guidelines was published in 2014. It includes standards for risk management, cyber security controls, and incident response.

1.6.2. National Standards

1) IS 15959: It consists of IS 15959 Part 1 (2011) and Part 2 (2016). The first part of the standard is intended for use as a companion to IEC 62056. The second part of the standard is intended for use along with IS 15959 (Part 1) on data exchange for electricity meter readings, tariff, and load control. It applies to alternating current Static direct connected watt-hour smart meter Class 1 and 2 designed per IS 16444. It also specifies the protocol and communication testing requirements.
2) IS 16444: It consists of two parts, IS 16444 Part 1 (2015) and Part 2 (2017). These standards cover the general requirements and tests for alternating current static direct connected watt-hour smart meter, Class 1 & 2. Smart meters shall be subject to metrology tests, load switch capability tests, data exchange protocol, and smart meter communicability tests as per the given in the guidelines.

All these standards help ensure that AMI systems are secure, reliable, and interoperable, which is crucial for the efficient management of energy resources and the transition to a more sustainable energy future.

According to the Central Electricity Authority's regulations, all utilities must test smart meters to ensure their stability, dependability, interoperability, and billing accuracy based on the national standards, i.e., Bureau of Indian Standards (BIS) standards.

1.7. Benefits of AMI

AMI offers utilities and consumers real-time energy consumption data, facilitating more efficient power grid management and resource allocation. This leads to reduced waste, heightened energy efficiency, and enhanced service reliability.

Additionally, AMI aids in preventing energy theft and supports initiatives such as time-of-use pricing, demand response programs, and energy-saving recommendations, resulting in economic benefits for utilities, customers, and society as a whole. AMI's potential extends to mitigating energy crises by equipping utilities with the necessary tools and information to manage energy supplies effectively.

1.8. Bibliometric Analysis

It provides an overview of existing literature on advanced metering infrastructure. It was carried out using the web of science database on the number of research articles published annually and distributed by country. The analysis has been conducted for the last decade, i.e., from 2012 to 2022.

This period was chosen since, before 2012, just a few study publications, ranging between two to five, were found. Whereas from the year 2012 onwards, there was a drastic change in publication in the AMI domain.

As per the data available on the Web of Science (WoS) collection, KCI Korean Journal, and SciELO citation index Database, 954 papers were published in the given period. For the year 2023, more than 70 publications have already been made, and the count is still increasing.

Table 3. Benefits of AMI from an Indian perspective

Serial Number	Section	Description
1.7.1	Enhancing Grid Visibility	AMI provides real-time energy consumption data, empowering Indian utilities to monitor and manage the grid more effectively. It identifies areas with increasing energy demands, allowing proactive responses to prevent interruptions, crucial for India's rapidly growing energy needs.
1.7.2	Promoting Energy Efficiency	AMI offers Indian consumers insights into their energy usage patterns, motivating them to reduce waste and conserve energy, supporting India's drive for sustainable and efficient energy use.
1.7.3	Streamlining Energy Management	AMI equips Indian utilities with accurate and timely energy consumption data, optimizing power grid management and resource allocation. This results in waste reduction and efficient use of available energy resources, which is essential for a country with diverse energy sources like India.
1.7.4	Facilitating Demand Response	AMI aids Indian utilities in managing energy demand during peak hours by providing real-time data on consumption, reducing reliance on expensive energy sources, and ensuring stable power supply, vital for India's densely populated urban areas.
1.7.5	Enhancing Energy Theft Detection	AMI systems identify unusual energy usage patterns, enabling swift detection and prevention of energy theft and safeguarding energy supplies in a nation where energy theft can be a significant issue.
1.7.6	Delivering Economic Benefits	AMI provides economic benefits for Indian utilities, customers, and society as a whole. It eliminates manual meter readings, reduces operational costs, ensures accurate billing, and enhances service reliability, contributing to India's goal of affordable and accessible energy. AMI also supports time-of-use pricing, demand response, and energy-saving recommendations, helping Indian consumers manage their energy expenses effectively.
1.7.7	Improving Environmental Sustainability	AMI's data-driven approach can lead to more efficient energy use in India, reducing carbon emissions and supporting India's commitment to environmental sustainability and clean energy.
1.7.8	Enhancing Customer Engagement	AMI enables Indian utilities to engage with customers more effectively by providing them with detailed information about their energy consumption, promoting informed decision-making, encouraging energy conservation practices, and potentially offering rewards for energy-saving efforts.
1.7.9	Increasing Grid Resilience	By actively monitoring and managing the grid, AMI contributes to increased resilience against outages, natural disasters, and cyberattacks in India, ensuring a reliable energy supply for a country with a growing economy and infrastructure demands.
1.7.10	Supporting Renewable Integration	AMI facilitates the integration of renewable energy sources, such as solar and wind power, into India's energy grid by providing real-time data and insights, helping balance the grid and reduce dependence on fossil fuels.

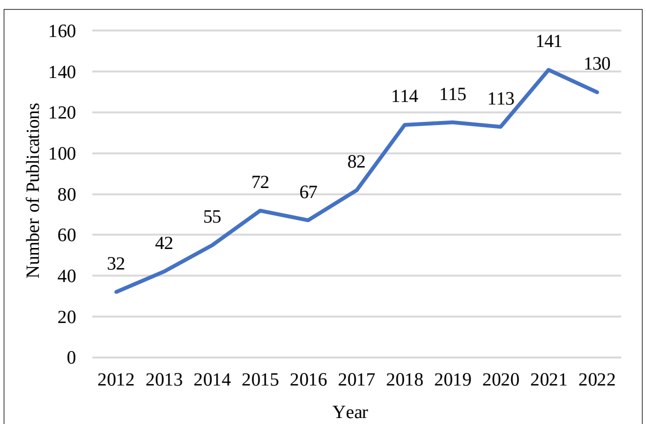


Fig. 3 Time-trend analysis

Figure 3 indicates that the research topic of Advanced Metering Infrastructure (AMI) has gained increasing relevance over the years, as evidenced by the yearly increase in the number of high-quality journal publications. The year 2021 stands out as the peak year for AMI research, with a total of 141 research articles published.

This upward trend in publications underscores the growing interest and active research in the field of AMI. It suggests that researchers worldwide are recognizing the importance of AMI in the context of smart grids and sustainable energy systems. The increasing number of publications also indicates that there are still many aspects of AMI that are being explored and understood. New methodologies, technologies, and applications related to AMI are likely to be developed and tested. As we move forward into 2023, we can expect this trend to continue, given the current pace of publications. The ongoing research and development in AMI will undoubtedly contribute to advancements in smart grid technology and sustainable energy management.

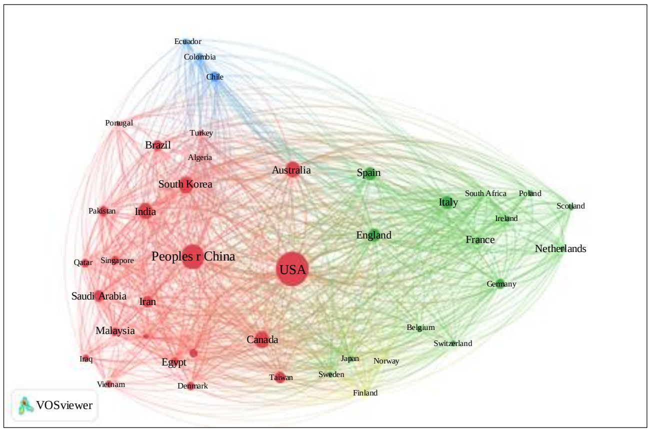


Fig. 4 Major countries involved in the AMI as a research area

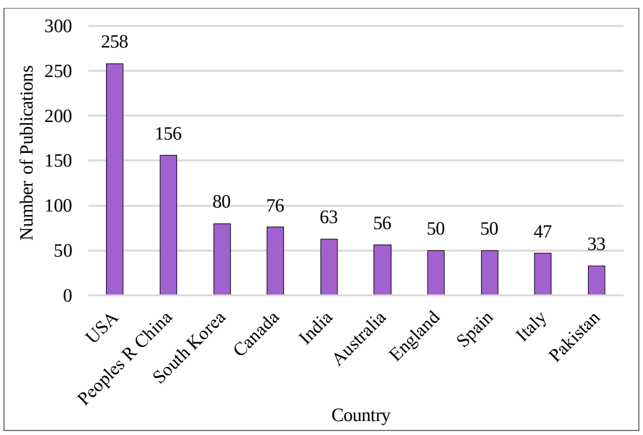


Fig. 5 Country-wise distribution of research articles

Figures 4 and 5 provide a comprehensive overview of the global contributions to Advanced Metering Infrastructure (AMI) research. The United States of America stands at the forefront with a substantial contribution of 258 research articles, reflecting its pioneering role in this field. Notably, India has also made significant progress in AMI research, securing the sixth position globally with a contribution of 63 research articles within the specified time period.

This demonstrates India's active engagement and substantial contributions to the global discourse on AMI. These findings underscore the widespread interest in AMI research across the globe. They highlight the collaborative efforts of various countries to propel our understanding and application of AMI in smart grid technologies forward. In addition to the United States and India, other countries have also made notable contributions.

The People's Republic of China, with 156 articles, and South Korea, with 80 articles, hold the second and third positions, respectively. Canada follows closely with 76 articles. Australia, England, Spain, and Italy are also in the top ten, with 56, 50, 50, and 47 articles respectively.

Pakistan makes its entry into the top ten with a contribution of 33 articles. This diverse geographical representation in AMI research not only reflects the universal relevance of this topic but also fosters a rich exchange of ideas and approaches from different cultural and technological perspectives.

As we move forward, this collaborative and global approach will be instrumental in addressing the complex challenges of smart grid implementation and advancing sustainable energy management practices worldwide.

1.9. Relevant Research Articles

Numerous studies have delved into the multifaceted realm of AMI and its role within the context of smart grids. For instance, one such investigation examined the intricate interplay of AMI components in a broader smart grid framework [11]. Additionally, the challenges associated with the adoption and integration of advanced metering infrastructure in the specific context of Colombia were meticulously explored in another scholarly endeavor [12].

Furthermore, a comprehensive study scrutinized the formidable obstacles that hinder the widespread deployment of advanced metering infrastructure throughout the Asia Pacific Economic Cooperation (APEC) region [13]. In the realm of AMI, the intricacies extend beyond mere infrastructure, encompassing the design of smart meter schemes, communication protocols, and security considerations. Previous research efforts have diligently scrutinized these aspects while also acknowledging certain hurdles encountered during the implementation process, accompanied by proposed remedies [14].

Furthermore, a survey has ventured into the realm of international experiences concerning the deployment of advanced metering infrastructure, offering valuable insights into diverse global contexts [15]. However, this research paper distinguishes itself from these antecedent studies by providing a unique and exhaustive analysis of the challenges inherent in implementing AMI within the intricate landscape of India.

In doing so, the study delves into a nuanced examination of these challenges and, notably, proposes a comprehensive set of mitigation strategies to navigate and alleviate these challenges effectively. This approach facilitates a more profound understanding of the complex interplay between AMI and the Indian energy landscape, offering valuable insights for both academia and industry practitioners alike.

2. An Exposure to Power Distribution Network Initiatives in India

The country has surplus generation capacity and exporting power to neighbouring countries. Similarly, the Indian transmission grid is robust and has five regional grids connected synchronously to fulfill the one-nation grid objective. However, the distribution sector faces various challenges and issues. Despite being on the concurrent list of the Constitution of India, power is supported by the central government through several programs, initiatives, and schemes (Refer to Table 4).

The Government of India has planned to deploy 250 million smart meters. The goal will be challenging, but it is attainable. In developed countries, such as the USA, which has installed 111 Million [16], Japan is to install 80m smart meters by 2025 [17], and China they have reached 242 Million [18]. No other country in the world has attempted a program as ambitious. India has also established goals for renewable energy of 175 GW by 2022 and 450 GW by 2030 [19].

Therefore, infrastructure-based improved metering technology is essential for integrating renewable energy sources. In addition, India has executed eleven smart grid pilot projects and four major smart grid projects [30-31]. As part of its smart grid journey, the government has established the National Smart Grid Mission (NSGM) to carry out different smart grid-related tasks. Among the eleven pilot projects, the Puducherry pilot project was India's first smart grid pilot project with AMI functionalities [27, 32].

All of the Smart grid pilot projects are sponsored under the Integrated Power Development schemes. As per the NSGM report published in Jan 2023 [24], the pilot projects are completed except TSECL, the Tripura pilot project, which is going to complete the project using its own resources. Regarding the major smart grid project, they are in the process.

2.1. National Level Programs

In India, Central and State governments are working together to develop the infrastructure of AMI by implementing National-level programs such as the National Smart Grid Mission (NGSM) and Smart Meter National Programme (SMNP) and also improving its international relations with countries like France to deal with a supply chain of Smart meters. The following are the national programs under process in India for developing Smart Grid infrastructure:

2.1.1. Smart Meter National Programme (2009)

The government of India is taking steps towards implementing smart grids to provide affordable energy to consumers, with the first phase being the implementation of AMI through the Smart Meter National Programme (SMNP). Energy Efficiency Services Limited (EESL) is playing a vital role in achieving universal access to power throughout the country. The Smart Meter National Program aims to replace the existing 250 million conventional meters in India with smart meters. Initially launched in Uttar Pradesh and Haryana, where AT&C losses were 28.42% and 34.36%, the program is expected to significantly improve energy efficiency and reduce losses in the power sector [25].

2.1.2. National Smart Grid Mission (2015)

The NSGM has been actively working since January 2016 to accelerate the adoption of smart grid technology in India. NSGM has the necessary resources, authority, and functional and financial independence to develop and supervise smart grid policies and initiatives nationwide [26]. The schemes implemented in the power distribution sector are indeed aimed at enhancing the existing infrastructure in both rural and urban areas.

The primary focus is on utilizing smart and advanced technology to increase the efficiency, reliability, and sustainability of the power distribution system. One of the key aspects of these schemes is the deployment of smart grids. These are electricity networks that use digital technology to monitor and manage the flow of electricity. Smart grids can detect and react to changes in electricity usage, thereby improving the reliability of power supply and reducing power outages.

Moreover, these schemes also emphasize the integration of renewable energy sources into the distribution grid. This not only helps diversify the energy mix but also contributes to environmental sustainability. The implementation of these schemes involves various stakeholders, including government agencies, private companies, and consumers. Government agencies are responsible for policy formulation and regulation, private companies bring in investment and technical expertise, and consumers play a crucial role, as their cooperation is essential for the successful implementation of these schemes.

2.2. Participation of Private Organizations in the Power Distribution System

In India, electricity distribution is mainly managed by government-owned companies known as discoms. These discoms are in charge of supplying electricity to people living in their specific areas. However, in recent years, there has been a shift in the structure of the power distribution sector. This shift is characterized by an increasing trend towards privatization, with private discoms making their entry into certain states.

This move towards privatization is part of a broader structural reform aimed at improving efficiency, reducing losses, and enhancing the quality of service in the power distribution sector. The entry of private players is expected to bring in much-needed capital, technological innovation, and managerial efficiency. It is also anticipated to foster competition, which could lead to better service quality and improved customer satisfaction. Among the major private discoms that have emerged in India are Tata Power Delhi Distribution Limited (TPDDL), BSES Rajdhani Power Limited (BRPL), BSES Yamuna Power Limited (BYPL), and Torrent Power Limited (TPL).

These companies have made significant strides in their respective areas, bringing about substantial improvements in operational efficiency and customer service. For instance, TPDDL has been recognized for its efforts to reduce AT&C losses. Similarly, BRPL and BYPL, both part of the Reliance Infrastructure, have been instrumental in transforming the power distribution landscape in Delhi. Torrent Power, on the other hand, has made its mark through its operations in Gujarat, Maharashtra, and Uttar Pradesh.

2.3. An Insight into AMI Business in India

The AMI market in India is expected to see significant growth in the next decade despite the slow adoption of smart grid technologies, particularly smart metering, over the past several years. Berg Insight estimates that through 2025, the Indian market will develop at a compound annual growth rate of 76.2%, accounting for up to 15-20% of smart meter exports in Asia. According to Levi Ostling, a smart metering analyst at Berg Insight, stated that ambitious initiatives to deploy roughly 250 million smart meters within a short timeframe have not been successful.

Instead, the number of installed smart meters has only doubled over the last two years, reaching a modest 3 million units by the end of 2020 [27]. Concerning the companies in the AMI business, in India, 26 companies are working as vendors to supply smart meters. Among these widely used smart meter companies are developed by Larsen & Turbo, Genus Power, and Intellismart. In India, many initiatives have taken over in the last decade and are still in count. The national-level programs such as NSGM and SMNP are doing tremendous work in the AMI field. Introducing competition through the involvement of private entities has also shown drastic improvement in the reduction of AT & C losses [5].

3. Current Status of AMI Implementation through Various Schemes and Programs in India

The implementation status of advanced metering infrastructure in India has been divided into subcategories to help readers understand the deployment status in depth. These include deployment through agencies, schemes, and states in India. This approach allows for a more nuanced understanding of the progress and challenges in AMI implementation across different regions and sectors in India.

By examining the deployment status through various agencies, we can gain insights into the roles and contributions of different stakeholders in AMI implementation. Looking at the deployment through different schemes provides a view of the strategic initiatives and programs that are driving AMI implementation.

It helps to understand the policy and regulatory landscape that is shaping the AMI ecosystem in India. Examining the state-wise deployment status offers a geographical perspective on AMI implementation. It highlights the regional disparities and local challenges in AMI deployment and can guide targeted interventions for specific states.

Table 4. Major ongoing schemes related to the distribution power sector in India

Sr. No.	Power Distribution System Schemes	Year of Launch	Objectives
1	Integrated Power Development Schemes (IPDS)	3rd December 2014	To enhance the networks responsible for distributing and transmitting electricity in urban regions.
2	Deen Dayal Upadhyayaaya Gram Jyoti Yojna (DDUGJY)	25th July 2015	Augmentation of sub-transmission & distribution infrastructure in rural areas
3	Pradhan Mantri Sahaj Bijli har Ghar Yojna (SAUBHAGYA)	25th September 2017	To link all unconnected families without power in rural regions and unconnected households without electricity in urban areas still in economic need.
4	Ujawal Distribution Assurance Yojna (UDAY)	5th November 2015	To achieve energy efficiency and conservation, reduce the expenses associated with power generation, ensure financial and operational stability for state-owned utilities, and promote the development of alternative energy sources such as renewable energy.
5	Revamped Distribution Power Scheme	20th July 2021	To provide financial support to distribution companies (State own) for modernizing and upgrading their infrastructure, with an emphasis on raising the supply's reliability and power quality for end users

(Source: https://powermin.gov.in/ [28])

Table 5. Deployment status of AMI agencies wise

Agency Wise	Sanctioned	Installed Smart Meter	Installed Smart Meter (Prepaid)	In Stock
EESL	78,13,246	30,86,852	11,87,384	3,39,813
PFCCL	1,51,740	1,48,595	0	1,994
RECPDCL	7,14,921	1,51,727	0	10,136
Utility	25,95,832	17,19,595	68,447	1,32,356
Total	1,12,75,739	51,06,769	12,55,831	4,84,299

(Source: https://www.nsgm.gov.in/en/state-wise-map [29])

Table 6. Deployment status of AMI scheme wise

Scheme Wise	Sanctioned	Installed Smart Meter	Installed Smart Meter (Prepaid)	In Stock
DDUGJY	39,200	38,400	0	534
IPDS	12,60,818	8,10,250	0	10,610
NSGM	1,79,433	1,45,221	0	28,196
PMDP	6,85,488	1,27,514	0	10,136
SG Pilot Project	1,56,533	1,56,533	0	0
Utility Owned	89,54,267	38,28,851	12,55,831	4,34,823
Total	1,12,75,739	51,06,769	12,55,831	4,84,299

(Source: https://www.nsgm.gov.in/en/state-wise-map [29])

3.1. Deployment Status of AMI Agency Wise

In India, the landscape of smart meter installations is dominated by a few key players. The Energy Efficiency Services Limited (EESL) leads the pack with the highest number of smart meter installations, accounting for approximately 61% of the completed work. This significant contribution by EESL underscores its pivotal role in advancing India's smart grid infrastructure.

Following EESL, the state-owned distribution businesses of individual states have made substantial progress, completing about 34% of the work. Their collective efforts have played a crucial role in expanding the reach of smart meter technology across various states in India. In addition to these major contributors, other organizations have also made notable strides in this area.

Power Finance Corporation Consultation Limited, for instance, has carried out work for the state of Himachal Pradesh, contributing to around 3% of the total installations. Lastly, REC Power Development and Consultancy Limited has also made its mark by completing the remaining 2% of the work. These collective efforts by different agencies highlight the collaborative approach adopted in India to accelerate the deployment of smart meters.

3.2. Deployment Status of AMI Scheme Wise

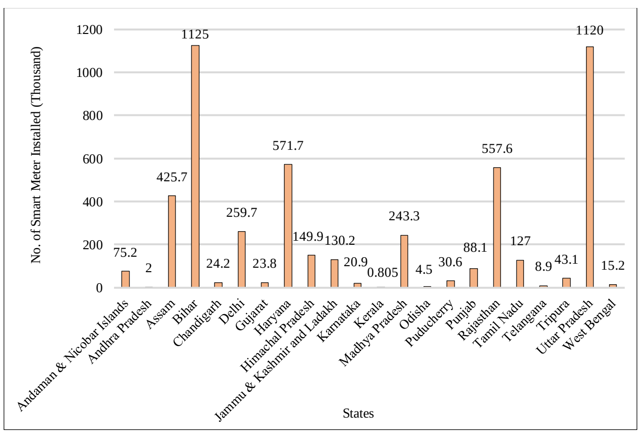
In the realm of smart meter installations in India, state-owned distribution companies hold the record, accounting for a substantial 74.97% of installations. This demonstrates their significant role in advancing India's smart grid infrastructure. The Integrated Power Development Scheme (IPDS), which aims to improve distribution and sub-transmission in urban regions, is the second major contributor, with 15.86% of the deployed smart meters. The IPDS's focus on urban areas is crucial for ensuring reliable and efficient power supply in these densely populated regions. Additionally, the National Smart Grid Mission, a government initiative aimed at modernizing the nation's power grid, has deployed 2.84% of the smart meters.

This initiative is instrumental in promoting the use of smart grid technologies across the country. The remaining installations have been completed by various other programs. The Prime Minister's Development Package (PMDP) has contributed 2.49%, while the Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY), a rural electrification scheme, has added 0.75%. Lastly, other smart grid pilots not under IPDS have contributed 3.06%. These joint endeavors underscore the diverse strategies being employed in India to expedite the rollout of smart meters.

As we continue to progress, these collective contributions will play a pivotal role in molding a more efficient and sustainable energy future for India.

3.3. Deployment Status of AMI State Wise

The deployment of smart meters in India is an ongoing process, and it is a significant step towards modernizing the country's power grid infrastructure. The deployment status of smart meters varies significantly from state to state, depending on several factors, such as the local electricity distribution system, the availability of funding, and the political will of the state government. States like Uttar Pradesh, Bihar, and Haryana bag the top three positions in the highest number of smart meter installations. However, several other states, such as Maharashtra, Arunachal Pradesh, Nagaland, Manipur, Uttarakhand, Goa, Chhattisgarh, Jharkhand, Sikkim, Meghalaya, and Mizoram, have not yet begun to implement AMI.



(Source: https://www.nsgm.gov.in/en/meter-dash [30])

Fig. 6 Deployment status of AM state-wise

AMI initiatives in India are gaining momentum, with several smart grid projects already underway. As mentioned earlier, the government has set a target to install 250 million smart meters across the country by 2025. Several state-owned distribution companies have already begun rolling out smart meters, and private players are also entering the market [31]. Overall, the ongoing status of AMI initiatives in India is promising and has the potential to transform the power distribution sector in India. However, the implementation of AMI has faced challenges such as financial concerns, consumer resistance, cybersecurity, etc.

Furthermore, Regulatory hurdles have also slowed down the rollout of AMI. Despite these challenges, the government and industry stakeholders are committed to driving the adoption of AMI technology in India. Efforts are going underway to address these challenges and create an ecosystem that supports the growth of AMI.

4. Implementation Challenges and their Respective Mitigation Strategies for AMI in India

4.1. Background

Researchers have examined various aspects to comprehend the difficulties in the implementation of advanced metering infrastructure. These aspects include technological factors such as per capita electricity consumption, electricity production capacity, transmission and distribution losses, and economic factors such as Gross Domestic Product (GDP) and the percentage of GDP invested in the energy transition. The study focuses on the top five nations, including the USA, Japan, China, Germany, and India, which are among the leading countries worldwide in smart grid technology investment [27]. The aim is to investigate and compare the differences in deployment challenges of these countries.

Except for India, the remaining AMI market leaders mentioned in Table 7 are developed countries. A developed country is a state that has a high standard of living, a well-developed economy, and adequate technological infrastructure. The developed nations are in a much better position than India in terms of economic factors like gross domestic product. The capital invested for the quick transition of energy accounts for an additional significant economic determinant.

Table 7. Background of top five investors in smart grid technology

Name of the Country	Per Capita Electricity Consumption of the year 2021 kWh [32]	Gross Domestic Product (Current US$) of the Year 2021 (Millions) [33]	Electricity Production Capacity of the Year 2021 (TWh) [34]	Energy Transition Investment of the Year 2021 (US$) [35]	Transmission and Distribution Losses (%) [36]
USA	13,076	22,996,100.00	4381	114 B 0.496 % of GDP	6
India	1,218	3,173,397.59	1669	14 B 0.44% of GDP	19
Japan	8,183	4,937,421.88	1030	26 B 0.527% of GDP	4
China	5,985	17,734,062.65	8537	266 B 1.5% & GDP	5
Germany	7,008	4,223,116.21	584	47 B 1.113% of GDP	4

It amounts to 0.909% of the GDP on average of the above-mentioned developed nations, which is about twice as much as India has invested. Electricity consumption is a technical component that indicates a person's standard of living in a given country. It is 8563 kWh per capita on average in the above-mentioned developed countries, about seven times more than in India.

India ranks third in terms of the performance of its power industry and its capacity to produce electricity. Transmission and distribution loss is the final and most crucial element. The entire power sector losses are responsible for 90% of losses occurring in the distribution. India has an overall T and D loss of 20.66%, more than double the global average. It demonstrates that although India is performing well on the generation and transmission side, its distribution power industry must take a big step to improve it. This is all about the background information that must be addressed before confronting the difficulties of the AMI implementation.

4.2. An Insight into the Implementation Challenges of AMI

In the world, the dominant challenges for deploying advanced metering infrastructure are issues related to finance, the active participation of consumers, and the need for universal standards. As we have seen in Table 6, the developed countries in the AMI market have no concerns about financial issues as they are much more capable of investing capital more than twice compared to India for the energy transition.

For active customer participation, an individual in developed countries is most likely to do so as they have a high-quality base living standard. These nations are fully outfitted with advanced technology and have trained employees. As a result, transmission and distribution losses range from 4% to 6% on average, demonstrating the distribution companies' success in each country. Hence, these problems are irrelevant in Developed countries.

As mentioned earlier, the inclusion of India in the analysis signifies a notable shift in the magnitude and nature of the challenges posed by advanced metering infrastructure. As such, it is evident that a country's economic and technical strengths play a pivotal role in determining the issues it faces during its deployment of AMI. At the same time, many of the challenges experienced by India can also be relevant to other developing countries.

4.3. Challenges and Mitigation Strategies for Deployment of AMI in India

There are several challenges to implementing Advanced Metering Infrastructure (AMI) in India (Refer to Table 8), which can significantly impact the power system's efficiency, effectiveness, and sustainability. While these challenges may overlap, they can be categorized according to the respective participants involved in AMI implementation. The challenges are divided into five main categories: the government, utilities or DISCOMs, consumers, prosumers, and manufacturers and suppliers. By identifying these challenges and categorizing them accordingly, an upcoming researcher can better understand and address the issues that arise during the implementation of AMI in India.

4.3.1. Challenges for the Government

1) Financial Concern: As per the data made available on the PRAAPTI portal and PIB Website, the overdue amounts for state-owned distribution businesses as of 18th May 2022 were Rs. 1,00,018 Cr. and the LPSC dues were Rs. 6,839 Cr. (excluding disputed amounts and LPSC). To overcome these, the government has proposed a scheme known as Ujjawal Distribution Assurance Yojna (UDAY).
   This scheme allows payment of dues in installments by the utilities, but the situations still need to be overcome. Another thing is that the initial cost of an individual smart meter ranges from around 5 to 10 thousand. Considering the 130 crores plus population, India may require 30 million plus smart meters for individual use. So, installing smart meters by replacing the existing ones may require billions of rupees, which is a significant hurdle to governments as the state-owned distribution companies are already suffering from a financial crisis. Hence, with limited access to capital, the government may find the relatively high initial costs of smart meter deployment financially infeasible.
   Mitigation Strategies: The government must majorly concentrate on the distribution side and take other significant steps, as has been done under the Ujjwal Distribution Assurance Yojna (UDAY) scheme. Furthermore, the government can implement financial and operational reforms, provide financial assistance, promote energy efficiency, and increase renewable energy generation.
2) Regulatory Framework: The government plays a crucial role in setting up a regulatory framework that enables the successful implementation of AMI. However, these frameworks are often found uncertain and non-uniform in states.
   Mitigation Strategies: The government should establish a clear and comprehensive regulatory framework that outlines the roles and responsibilities of various stakeholders, including utilities, regulators, and consumers. This framework should address data privacy, consumer protection, and cybersecurity issues. The government should also establish a regulatory oversight mechanism to ensure utilities comply with the regulatory framework and consumer protection measures. This could include periodic audits, inspections, and reporting.
3) Developing Standards for AMI Technology: The technology used in AMI is rapidly evolving, with new hardware, software, and communication protocols being developed and deployed all the time. This makes it challenging for standards-managing bodies to keep up

with the latest developments and ensure up-to-date standards.

Mitigation Strategies: Collaborate with international standards bodies, such as the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE), to ensure that Indian AMI standards, such as the Bureau of Indian Standards (BIS) are aligned with global best practices.

4) Finalizing the Smart Metering Program's Objectives and Vision: Most utilities begin the program only after receiving subsidies or schemes since these are time-limited schemes. Utilities believe that the efficiency of meter readings will improve and that correct billing will be generated. As a result, these two factors will contribute to higher revenues and lower commercial losses. As a result, goals are reduced to three or four objectives, with an inadequate vision of future requirements. As a result, the smart metering solution is deployed without regard for future requirements [37].

   Mitigation Strategies: The government can develop a clear policy, collaborate with key stakeholders, develop a detailed implementation plan, establish a dedicated team, incentivize distribution companies, and regularly review and evaluate the program's progress.

4.3.2. Challenges for Utilities or DISCOMs

1) Technical Infrastructure: In India, the technical infrastructure is inadequate due to many reasons, which can be political, economic, and environmental, especially in high-altitude areas.

   Mitigation Strategies: The technical infrastructure challenges of AMI in India require a collaborative effort between utilities, technology providers, and policymakers by investing in technical infrastructure development, leveraging cloud-based solutions, building interoperability, etc.

2) Replacement of a Massive Number of Existing Conventional Energy Meters: In India, smart meters have only come into the big picture in the last decade. According to the Saubhagya dashboard, India has almost 100% of household electrification. The majority of installed energy meters in India are conventional ones. They account in terms of millions. Hence, replacing this considerable number of traditional energy meters with smart meters is becoming a significant hurdle.

   Mitigation Strategies: Distribution companies can conduct a comprehensive assessment, develop a detailed implementation plan, partner with technology vendors and service providers, create a comprehensive training and awareness program for customers, have a dedicated team to oversee the rollout, and conduct regular audits and evaluations to measure the effectiveness of the rollout.

3) Handling Consumers Resisting Attitude from Installing Smart Meters: Instances have been reported in certain regions of Bihar, India, wherein smart meters are installed without proper meter testing. As a result, numerous customers have been subjected to excessive charges. Such incidents have led to widespread reluctance and resistance among individuals towards adopting smart meters in their households.

   Mitigation Strategies: Distribution companies can communicate the benefits of smart meters by conducting customer awareness programmes, addressing privacy and security concerns, offering incentives or subsidies, providing transparent information about the installation process, allowing consumers to opt-out, being responsive to feedback, and providing training to support for the use of smart meters.

4) Integration with Legacy Systems: Many DISCOMs may have legacy systems that are not designed to work with AMI technology. Integrating AMI with legacy systems could be a significant challenge, leading to delays and increased costs. Legacy systems refer to the existing systems or technologies that DISCOMs used to manage their electricity distribution network before the deployment of AMI.

   Mitigation Strategies: To address this challenge, DISCOMs must thoroughly assess their existing systems and infrastructure to identify gaps or compatibility issues with the new AMI technology. They also need to invest in appropriate upgrades or replacements of their legacy systems to ensure that the new AMI technology can seamlessly integrate with the existing systems.

4.3.3. Challenges for the Manufacturer & Suppliers

1) Designing Low-Cost and Highly Reliable Technologies: In the Indian market, customers tend to be highly price-sensitive and often hesitate to pay a premium for advanced metering technology. Consequently, it is imperative to develop cost-effective solutions characterized by high reliability and accuracy.

   Mitigation Strategies: Manufacturers and suppliers can explore innovative business models such as leasing or rental options to reduce the upfront cost for utilities. They can also leverage economies of scale by manufacturing products in large quantities to reduce the cost of production.

2) Dealing with Uncertainty in the Regulatory Framework: The regulatory framework for AMI implementation in India is still evolving, which can create uncertainty for manufacturers and suppliers. The regulatory environment needs to be stable and predictable to attract investment and encourage manufacturers to develop new products and technologies.

   Mitigation Strategies: Manufacturers and suppliers can work with the government to develop a stable and predictable regulatory framework, encouraging investment in AMI implementation in India. They can also provide inputs to regulatory bodies to ensure the regulatory environment is conducive to innovation.

3) Technical Expertise: AMI implementation requires technical expertise in various areas, such as communication networks, software, and hardware. Manufacturers and suppliers need to ensure that they have a skilled workforce to support AMI implementation.
Mitigation Strategies: They can conduct training workshops for their employees to upskill them or partner with local universities to offer specialized courses in AMI technology. They can also invest in research and development to develop cutting-edge solutions that meet the unique challenges of the Indian market.

4) Issues with Supply Chain: The supply chain for smart meters in India may face material shortages, transportation delays, and quality control issues. This can affect the availability and reliability of smart meters, resulting in delays in their deployment.
Mitigation Strategies: Develop resilient supply chains by partnering with reliable suppliers, establishing backup plans for critical components, establishing the service center, and implementing quality control measures throughout production.

Table 8. Challenges of AMI in India

Challenges for Consumer	Technical Challenges	Challenges for Utilities or DISCOMs	Challenges for Government	Challenges for Prosumers	Challenges to the Manufactures & Suppliers
Customer Participation	Network Coverage and Connectivity	Technical Infrastructure	Finance Concern	Dealing with Net Metering	Designing low-cost and Highly Reliable AMI Technologies
Additional Payment for Two-way Communication	Interoperability of Technology	Replacement of Massive Conventional Meters	Regulatory Framework	High Installation Cost	Dealing with Uncertainty in a Regulatory Framework
Extra Financial Burden on them for the Installation of a Smart Meter	Validation and Testing	Handling the Resisting Attitude of Consumers from Getting Installing Smart Meters	Finalization of Objective and Vision	Interconnection with the Grid in the Presence of AMI	Technical Expertise
Handling and Learning New Technology	Data Management	Integration with Legacy Systems	Developing Standards for AMI Technology	Reliability of Grid	Issues with Supply Chain

4.3.4. Challenges for Consumers

1) Customer Participation: An AMI project's success depends on the customer engagement level. Customers will participate in AMI and demand response initiatives only if they comprehend the importance and benefits associated with them. In India, more than 70% of the population settles in rural and semi-rural areas, and most of them cannot afford electricity. So, when it concerns finance for AMI deployment, it will directly or indirectly burden Indians. Therefore, until and unless they become aware of AMI technology benefits, the customers may not be part of the deployment efficiently.
Mitigation Strategies: In order to promote consumer engagement with AMI in India, distribution companies can undertake several measures, such as organizing awareness programs at the village level, as well as utilizing social media platforms like Facebook and Twitter to disseminate information about the benefits of AMI on a national level.
2) Extra Financial Burden on them for the Installation of a Smart Meter: Utilities want customers to pay for installing a new smart meter, which can be an additional financial burden for people.
3) Additional Payment for Two-Way Communication: Customers have to pay for two-way communication after installing smart meters. For example, if a customer uses cellular technologies, the user has to recharge to perform the same.
Mitigation Strategies for 2) and 3): Conducting a cost-benefit analysis can help determine the most cost-effective solution to the implementation of AMI with two-way communication. This analysis can also help to identify the costs associated with implementing the infrastructure, including the cost of smart meters, information and communication technologies, and data management systems [38].
4) Handling and Learning New Technology: Learning new technologies and handling them can also be challenging to the consumer in India as most people are not familiar with technologies such as home energy management systems.
Mitigation Strategies: Discoms can provide easy-to-understand information, give access to usage data, allow for flexible consumer choice, develop a comprehensive training program, and have a dedicated customer support team.

4.3.5. Challenges for Prosumers

1) Dealing with Net Metering: Prosumers producing surplus energy might encounter difficulties in receiving compensation for their excess electricity under net metering regulations. Net metering permits prosumers to sell unused renewable energy back to the grid. However, net metering policies in India are not uniform across all the states.
   Mitigation Strategies: The government can provide a clear framework for net metering policies that ensure that prosumers receive fair credit for the energy they produce. Utilities can also provide transparent billing systems that clearly show the credits earned by the prosumers.
2) High Installation Cost: Prosumers may face high upfront costs to install and integrate energy production systems with AMI systems compared to the normal consumer.
   Mitigation Strategies: The government can provide incentives such as subsidies or tax credits to encourage prosumers to adopt energy production systems. Utilities can also offer financing options to reduce the upfront cost for prosumers.
3) Interconnection with the Grid in the Presence of AMI: In an interconnection of AMI with the grid, prosumers can potentially sell excess electricity back to the grid. However, this creates a challenge for utilities to accurately measure and account for the energy being generated and consumed by prosumers. In traditional metering systems, energy flows only in one direction - from the utility to the consumer. However, with the introduction of prosumers, energy can flow in both directions, creating a bi-directional flow of electricity. This requires the implementation of two-way metering systems that can measure both the energy consumed by the prosumers from the grid and the energy generated by the prosumers, which is sent back to the grid. Integration of prosumers into the grid through AMI can also lead to voltage fluctuations and power quality issues. Prosumers with variable energy output, such as solar panels, can cause voltage fluctuations that can affect other consumers on the grid. Additionally, the quality of the power being generated by prosumers may not always meet the required standards, leading to power quality issues on the grid.
   Mitigation strategy: Utilities must ensure that their AMI systems are equipped with bi-directional metering capabilities and that the data collected from prosumers are accurately measured and accountable. Utilities must also ensure that their systems can manage voltage fluctuations and power quality issues caused by the prosumers side.
4) Reliability of Grid: The grid is often unreliable, which can create challenges for prosumers who rely on it to sell excess energy back to the grid. This can also make it difficult for prosumers to maintain a stable energy supply to their homes and businesses.
   Mitigation Strategies: The grid can be made reliable, especially for prosumers, by implementing advanced voltage control and protection measures to manage voltage fluctuations caused by prosumers with variable energy output in the field. In addition, the authorities can also deploy power quality monitoring and control systems to ensure that the power generated by prosumers meets the required standards. Furthermore, developing effective communication channels between utilities and prosumers to facilitate the exchange of information and ensure that both parties are aware of any issues or concerns related to the grid can be a better solution.

4.3.6. Technical Challenges

1) Network Coverage and Connectivity: Smart metering communication networks may need help with network coverage and connectivity in remote or rural areas, making it difficult to collect and transmit data from smart meters.
   Mitigation Strategies: To reduce such technical challenges, the concerned authorities must work on building an adequate infrastructure. They should also create a dedicated team to oversee the rollout and troubleshoot any technical challenges that may arise.
2) Interoperability for Communication Technologies [37]: Though we know it is challenging, utilities, solution providers, and regulators need to make efforts to achieve this. The most important reason for achieving this is that technologies behave differently due to varied geographical areas, and no single technology will work anywhere.
   Mitigation Strategies: Utilities must have the option to implement hybrid technology, and smart meters must accommodate at least two technologies. These will avoid single-vendor dependence in the future because these are long-term contracts. If this gets achieved at a certain level, we may see quicker AMI rollouts and improvement in the performances of the utilities.
   Choosing Proper Communication Channels: Distribution companies face a real challenge in selecting the right communication channel for advanced metering infrastructure, as the availability of communication technologies in the market is huge. The communication technologies include Power Line Communication (PLC), RF Mesh Cellular technology, etc.
   Protocols: Different protocols, including open and proprietary protocols, can be used in Advanced Metering Infrastructure (AMI) systems. Each type of protocol has its own challenges:
   Open Protocols: The open protocols, such as Modbus and ZigBee, are publicly available and can be used by any manufacturer. One of the main challenges of open protocols is ensuring interoperability between different devices and systems, as different manufacturers may implement the protocol slightly differently.
   Proprietary Protocols: These protocols are owned and controlled by a single manufacturer or organization. The main challenge with proprietary protocols is that they may need to be compatible with devices and systems from

other manufacturers, making it challenging to ensure seamless communication between devices.

Mitigation Strategies for communication issues: This involves evaluating the compatibility of different communication protocols with the current metering infrastructure in use, taking into account regulatory or compliance requirements, and assessing the security of the protocols. Additionally, the level of technical support and maintenance required, as well as the reliability of the protocols, should be evaluated. It is important to consider the scalability and flexibility of the protocols, as well as consumer preferences, while making a decision. Distribution companies must also keep in mind the unique challenges that may arise in Indian circumstances, such as rural connectivity, power supply, and network infrastructure. By considering these factors, distribution companies can choose the most suitable communication channels and protocols for their AMI implementation.

3) Meter Data Management System:
    i) Data Quality: One of the challenges in MDMS is ensuring the continued high quality of smart meter data. While smart meters themselves generate accurate and consistent data, maintaining this quality throughout the data management process, including validation and cleansing, can be challenging.
    ii) Data Integration: MDMS faces the challenge of seamlessly integrating smart meter data with other diverse data sources, such as weather data and grid information. This integration is essential to provide a holistic view of energy usage. The complexity lies in harmonizing these different data streams and formats within the MDMS, enabling utility companies to derive meaningful insights and make informed decisions.
    iii) Data Storage: The sheer volume of data generated by smart meters at high-frequency intervals poses a significant storage challenge for MDMS. Managing this continuous stream of data efficiently and cost-effectively requires robust storage solutions. Additionally, MDMS must address the challenge of long-term data retention and archiving, ensuring that historical data remains accessible for regulatory compliance, analytics, and auditing purposes.

    Mitigation Strategies for challenges in handing the huge data using MDMS: To effectively deal with the Meter Data Management of AMI in India, the following vital steps should be taken: Clearly define the project goals and objectives, select appropriate technology for data collection, Design a robust data management system, implement a reliable communication infrastructure, train personnel, ensure compliance with regulations continuously monitor and improve the system. It is essential to understand the Indian electricity distribution system and regulations thoroughly to implement suitable technology and data management practices.

4) Validation and Testing during the Integration of Information and Operational Technology [37]: Utilities typically rely on the expertise of solution providers when testing the functionality and performance of AMI systems. However, solution providers may need more knowledge or understanding of utilities' specific challenges and constraints in the field.

    As a result, once the AMI systems are deployed at a large scale, issues that were not identified during testing or addressed adequately are bound to arise. These issues could range from technical glitches or malfunctions to problems with data management or cybersecurity. Therefore, utilities need to be actively involved in the testing and validation process, working closely with solution providers to ensure that the AMI systems meet their specific needs.

    Mitigation Strategies: Utilities must depute domain experts from all functions for the project to facilitate solution providers in delivering correct solutions. At the same time, utility management should have periodic reviews on the actual status and guide the team wherever necessary. Even if it takes longer, the validation stage should be done thoroughly and with proper planning.

4.3.7. Other Challenges

The implementation of AMI in hilly areas such as North Eastern states, Ladakh, Jammu and Kashmir, in India is a significant and unique task. The factors which make it a big hurdle are concerns about its geographical location and environment. Some of the crucial challenges are given below:

1) Topography: The steep slopes, rocky terrain, and dense forests can make laying down cables and installing AMI equipment challenging.
2) Connectivity: It is difficult to establish a reliable communication network between the AMI devices and utility servers due to the lack of connectivity.
3) Power Supply: Frequent power outages may occur that can lead to a loss of data and affect the functioning of AMI devices.
4) Weather Conditions: Extreme weather conditions, such as heavy rainfall, snowfall, and landslides, can damage the AMI infrastructure, leading to frequent breakdowns and interruptions in the power supply.
5) Maintenance: Due to the harsh weather conditions, the maintenance cost increases, and it also reduces the lifespan of the equipment.

Addressing these challenges will require a concerted effort from utility companies, governments, and stakeholders. A comprehensive plan that takes into account the unique challenges of hilly areas and provides solutions to address them will be necessary to implement AMI successfully in these regions.

5. Research Scope in AMI with an Indian Viewpoint

AMI is an evolving technology that uses smart meters, communication networks, and data management systems to enable the measurement, collection, and analysis of energy consumption data. Current research trends in AMI include the development of more accurate and reliable smart meters, using advanced data analytics to improve energy efficiency and demand response management, and the integration of AMI with other technologies, such as renewable energy systems and electric vehicles.

Additionally, there is a growing focus on using AMI to support the development of smart cities by integrating energy data with other types of data, such as weather and traffic information. Another trend is the study of security and privacy issues in implementing AMI. Research trends in detail:

5.1. Designing and Development of Indigenous Affordable Smart Meter

In order to design a cost-effective and reliable indigenous smart meter for both consumers and utility companies in India, several key considerations must be addressed. One of these is the need to keep upfront installation costs as low as possible while ensuring ongoing maintenance is affordable. The meter should have improved communication and networking capabilities, which can be achieved by using wireless technologies such as ZigBee, Z-Wave, and cellular networks. Real-time data collection is essential for accurate and reliable metering. Cybersecurity features like encryption, secure communications protocols, and network segmentation are necessary to protect against malicious attacks.

Multi-language support is also important to ensure that the meters are accessible to different groups of the population. Remote management is another critical feature that enables utilities to manage and troubleshoot meters remotely, reducing the need for field technicians. Load control by third parties is an area of interest in the design of smart meters, as it allows for more efficient management of the grid. Additionally, features to support grid integration, such as demand response, distributed energy resources, and energy storage, should be incorporated. Interoperability with other smart devices, such as home automation and distribution automation systems, is essential to improve the efficiency of the grid. Energy efficiency is another important consideration, with researchers working on developing low-power semiconductors and PCBs that consume minimal energy while still providing accurate readings.

5.2. Developing Low-Cost and Highly Reliable Communication Technologies for AMI

Researchers/Manufacturers may use the below technologies and integrate them to develop an improved communication network:

1) Wireless Technologies: Use of wireless technologies such as Zig Bee, Long Range (LoRa) technologies, and cellular networks, as well as the implementation of secure and reliable communication protocols to ensure the privacy as well as integrity of data transmitted over the network.
2) Power Line Communication (PLC): Another trend is using PLC for AMI, which utilizes the existing electrical power grid infrastructure to transmit data.
3) Neighborhood Area Network (NAN): In India, research has been focused on developing wireless communication technologies for the NAN, which can connect smart meters to the utility company's servers. For instance, the use of Narrowband Internet of Things (NB-IoT) and Long-Range Wide Area Networks (Lora WAN) for the NAN is gaining popularity due to their low power consumption and long-range connectivity.
4) Home Area Network: Research in India is focused on developing secure and reliable communication technologies for the HAN. One trend is to use ZigBee or Wi-Fi technologies to connect the smart meter with the in-home display unit, which can provide real-time energy usage data to consumers.
5) Local Area Network: In India, research is focused on developing LAN-based communication technologies for AMI that can handle large data volumes generated by smart meters. For example, Ethernet or Power Line Communication (PLC) technology for LAN is gaining popularity due to its high bandwidth and low cost.
6) Cellular Technologies: The development of cellular technologies like 4G/5G for AMI in India is focused on reducing costs and improving the reliability of communication networks. This involves exploring ways to optimize the use of existing infrastructure and developing new technologies that are specifically designed for AMI.

Additionally, research is being done on using blockchain technology to create secure and decentralized communication networks for AMI.

5.3. MDMS & Smart Meter Data Analytics (SMDA)

AMI data is sent at pre-scheduled intervals using smart meters, generating enormous amounts of data, i.e., big data. Managing voluminous smart meter data is key for predicting all futuristic implementations regarding asset optimization, power procurement, or energy transitions.

Multiple applications exchanging information add to the complexity. Due to the lack of expertise in this area, utilities will have difficulty predicting failures and optimizing their assets [37]. The non-capabilities of handling data could cause many issues for the utilities. This overall impact of non-conversion of the data into meaningful form has a total effect on the power procurement costs of AMI data asset optimization and delay in the energy transition to cleaner fuels in the future.

Therefore, many of the researchers are using Artificial Intelligence (AI) or Machine Learning (ML) algorithms, smart meter data analytics, or big data to convert this voluminous or big data into meaningful trends. The only hurdle in dealing with SMDA for the researcher is that no datasets are made available by the government for public use or research. It may be because of regulations, but it can also be a precaution against cyber-attacks. Some data sets are available online, like UMass Trace Repository, CER Smart Metering Project, etc., but there is no assurance about their reliability as these are secondary datasets.

1) Machine Learning or Deep Learning: Machine learning techniques such as clustering, classification, and regression have been widely used for smart meter data management. It can be done using programming language or software such as Python, R, or Matlab. These techniques can help detect anomalies, predict or forecast energy consumption patterns, and optimize energy usage.
2) Big Data Analytics: Smart meters generate a huge amount of data. Hence, big data analytics platforms such as Apache Hadoop, Spark, Storm, and Drill have been used to manage and process the data. These techniques can help to analyze the data in real time, identify patterns, and make predictions.

All these trends can provide insights into the current health of the network and system-like failures expected to occur shortly. It can also be used for future system planning, power procurement predictions, and impact analysis due to integrating multiple new technologies into the system. ([39] to approach SMDA with an Indian perspective)

5.4. Cyber Security

As the adoption of AMI is expanding in India daily, there is a pressing need to ensure its cybersecurity. The research trends in the cybersecurity of AMI in Indian circumstances involve a holistic approach to protect against cyberattacks. This includes conducting risk assessments and developing secure communication protocols with encryption techniques. Furthermore, implementing access controls, creating incident response plans, complying with cybersecurity regulations, promoting cybersecurity awareness, and training personnel can also be done to avoid cyber threats. One of the main challenges in the Indian environment is developing frameworks that can be adapted to the country's unique energy landscape while ensuring that AMI systems remain secure.

This requires a comprehensive approach that accounts for the increasing adoption of AMI, integrating renewable energy sources, and developing consumer engagement mechanisms. Overall, the cybersecurity of AMI in India requires a strong commitment from policymakers, utility providers, and researchers to ensure that it remains secure against evolving cyber threats and attacks. By adopting the latest research trends in cybersecurity and promoting cybersecurity awareness and training, India can develop a robust and secure AMI system that enables sustainable energy management while protecting consumer privacy and security.

6. Conclusion

In this paper, an insight into the AMI of the Indian smart grid has been discussed in detail. Implementation of AMI in India is a significant task that requires a combination of technical, financial, and regulatory efforts. The technical challenges include the integration of smart meters with the existing infrastructure and ensuring their compatibility with different types of technologies. The financial challenges consist of the high initial investment required for the deployment of AMI and the need to ensure a viable business model for the utilities.

Another crucial challenge for the successful implementation of Advanced Metering Infrastructure is customer support and acceptance, which is vital to realizing AMI's full potential in India. Hence, to ensure the successful deployment of AMI in India, it is crucial for regulators to establish clear guidelines and standards. In addition, the regulatory body must address consumer privacy and security concerns that may arise during the implementation of AMI.

Despite the challenges associated with deploying AMI, it holds immense potential for improving accountability and reliability of electric power distribution systems by enabling better monitoring of electricity supply and its consumption. AMI can lead to improved energy efficiency, reduced AT&C losses, and better customer service, making it a highly desirable technology for the power sector in India.

The government, utilities, and stakeholders must work together to overcome these challenges and ensure the successful implementation of AMI in India. Implementing AMI and tackling its challenges is essential for India's vision towards sustainable growth and development in the twenty-first century.

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