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REVIEW

Investigation and analysis of demand response approaches, bottlenecks, and future potential capabilities for IoT-enabled smart grid

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Abstract

Significant attempts have been made to make the electrical grid more intelligent and responsive to better meet customers' requirements while boosting the stability and efficiency of current power systems. Smart grid technologies, which have just recently emerged, facilitated the incorporation of demand response (DR) by introducing an information and communication backbone to the current system. The Internet of Things (IoT) has emerged as a key technology for smart energy grids. Security concerns have emerged as a major obstacle to the widespread adoption of IoT-enabled devices because of the inherent Internet connectivity of these smart gadgets. Therefore, security is a crucial factor to address before the widespread implementation of IoT-based devices in power grids. In this study, the framework and architecture of smart grids that are enabled by the IoT are first examined. Then, the role of IoT for DR in smart grids and different approaches adopted worldwide to make DR schemes more effective, have been discussed in detail. Finally, the authors discuss how IoT-enabled smart grids can benefit from cutting-edge solutions and technologies that make them more secure and resistant to cyber and physical attacks.

1 | INTRODUCTION

1.1 | Emerging smart grid

With the modernization of the cities due to technological development and rapid population growth, the demand for an intelligent electrical grid system that can easily handle the diverse demand of different consumers has risen. National Institute of Standards and Technology (NIST) has devised a structure for modern electrical grids to guarantee customers a reliable, secure, and sustainable operation of electrical grids at a minimum capital cost [1]. Figure 1 shows the development steps toward the transformation of a traditional grid into a well-organized and modern grid, also known as a "Smart Grid."

In a modern Smart Grid (SG) system, different power generation resources, especially renewable energy such as wind and solar power resources along with the power storage units are integrated into one unit. These two emerging power generation technologies are smaller in size but are distributed and environment friendly [2], strengthening the grid resilience and reducing electrical stress on load centres [3, 4]. A smart grid utilizes a wide variety of sensor technologies to support a bidirectional control of electrical supply and communication protocols for constant monitoring and control of the grid. This two-way communication network made the smart grid capable of communicating

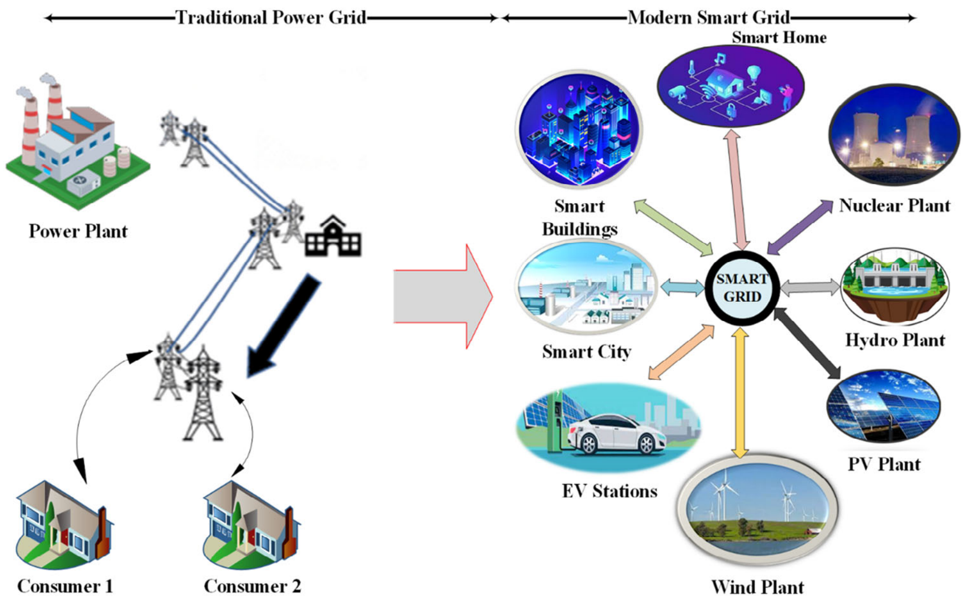

FIGURE 1 Emerging growth of traditional power grid to modern smart grid.

different measurements and control signals between their end users, which helped to manage their assets properly. Also, there is a need to further process the data collected from the grid entities within the short time span and take necessary actions. For this, a grid must be assisted with the necessary computational resources that can handle such a large volume of collected data from different sensors dispersed all around the grid premises [5, 6]. Table 1 shows the comparison between traditional grids and modern smart grids.

1.2 | Rise of IoT in smart grids

The IoT is one of the most innovative solutions in the telecommunications industry at present. The IoT is often defined as an interconnected system of different devices embedded with transducers, Smart electronics equipment, Control software, and actuators that can exchange data via a linked network (typically the Internet) [7, 8]. The decentralized processing and two-way connectivity of IoT make it a viable option for resolving the inevitable challenges of upgrading existing power grids to modern smart grids. Services in a smart grid environment include integration of different kinds of renewable energy resources (Solar, Wind, Biogas etc.), the establishment of connection for real-time data monitoring and control of electricity unit consumption and tariff calculation between customer and utility companies, a proper network to communicate statistics for analysis and to take an appropriate action based on statics analysis [9]. The smart energy grid generates a copious amount of data and information that need to be communicated, analysed, and stored data to monitor, control and manipulate in order to use for different kind of analysis for decision-making to an intelligent control. In this respect, the IoT looks to be a feasible option with considerable potential for usage in the smart energy grid system, given its multifarious advantages in various sectors.

IoT may facilitate a successful transition from the inefficient traditional power grid to a more effective smart energy system, and boost the system's accuracy and competence via its intelligent and adaptive features [10]. Power quality and reliability are two of the most significant challenges with traditional power grids, but the IoT addressed better solutions to these problems.

Conventional power grids may be converted into smart grids using renewable energy plants with the use of advanced metering infrastructure (AMI) and smart metering (SM) technologies by incorporating intelligent information-processing capabilities throughout the energy flow between the service provider and customers [11, 12]. With a suitable combination of actuators and transducers in AMI, IoT offers considerable potential for monitoring and control of energy usage. This integrated system is collecting information such as energy consumption, voltage and current readings, phase measurements, and numerous types of data for intelligent control. Better energy grid management is made possible by the IoT potential to gather, transfer, and intelligently analyse massive volumes of data. IoT technologies have the potential to significantly improve smart energy grid systems in a variety of areas, including management of power generation infrastructure, transmission and distribution operations management via supervisory control and data acquisition (SCADA) connected systems, advanced metering infrastructure, and monitoring of carbon footprint and environmental conditions. The cyber risks of the traditional centralized SCADA system may be addressed by using modern cloud and edge computing technologies for the distributed monitoring and administration of decentralized energy supplies. And since it can be easily connected to other smart entities like smart appliances, smart homes, smart buildings, and smart cities, the IoT-enabled smart grid can control and manage the electrical grid more effectively

TABLE 1 Comparison between traditional grid versus smart grid.

Features	Traditional grid	Smart grid
Power generation	Centralized	Decentralized (enabling distributed energy resources (DERs))
Flow of electricity and information	Mostly unidirectional	Two-way (bidirectional)
Topology	Limited topologies	Different network topology
Metering	Traditional	Digital (advanced metering infrastructure (AMI))
Customer participation	Limited (few customer choices)	Extensive (many customer choices)
Renewable energy sources (RESs) integration	Seldom	Accommodating
Reducing greenhouse gas	Not	Reduced by enabling electric vehicles (EVs) and RESs
Operation, maintenance, and self-healing	Lack of self-monitoring	Self-monitoring and self-healing by using automation devices
Power restoration	Mostly manual restoration	Self-restoration by using automated fault detection (sensors) and self-healing algorithms
Sensors	Few sensors	Sensors throughout
Reliability (failures and blackouts)	Prone to failure and cascading outages	Pro-active, real-time, and islanding to avoid the cascading events and blackout
Operational cost and wastage at peak hours	High at peak hours due to Inefficiencies in load management	Low at peak hour due to distributed generation
Control	Limited due to limited monitoring and manual control mechanisms	Pervasive
Improving resilience to disruption	Not	Improved by predictive analytics and maintenance
Improve grid security	N/A	Improved
Enabling new products, services, and markets	N/A	Enabled
Plug-in electric vehicles (PEVs) and new energy storage options	N/A	Enabling transition

[13]. However, this necessitates using advanced computing techniques and resource-allocation methods. IoT-enabled smart grid has certain challenges, despite improved energy system monitoring and control. IoT cyber attackers, for instance, launch a variety of assaults into smart grids in the following three categories: operational, economic, and system security. The following are a few instances of such attacks:

- Electrical power blackout at small and large scale
- Major losses to the power companies and power supplier
- Customers' privacy risks due to the release of personal data
- Deliberate falsification of energy use records
- Transactive energy networks are being disrupted

Several technologies have been created to combat the threats, including machine learning techniques, artificial intelligence (AI), blockchain, and multifactor strong authentication. Demand response is a program created to encourage end users to alter their typical consumption habits in response to changes in power pricing. Through electricity DRs, SGs can lower the demand for power investments while implementing energy-saving strategies including peak load shaving. Networking, marketing strategies, integrated technology in power systems, and DR as a measure for reducing peak demand and boosting grid reliability have all been extensively covered in the literature that is currently available. A DR programme should concentrate primarily on raising the smart grid system's information processing requirements. They contend that the DR system will generate enormous amounts of data, which could result in a fundamental internal security issue as discussed in [14]. The architecture and parts of a DR system have been the subject of numerous contributions in the literature. As an illustration, [15] built a web-based energy information system and Identified its common components. A high-level architecture for a decision support system for demand-side management was put forth by [16]. A home energy management system (HEMS) model based on optimization was employed by [17] and applied to the real-time transport protocol and time of use (ToU) pricing schemes. Numerous authors researched incentive-based DR systems as inputs and planned power use based on DRs and price signals in the literature. All electrical appliances in Huang's DR system have a controller, including interruptible, deferrable, and multi-operational controllers as illustrated in [18]. In reviewing the impact of DRs on energy efficiency, reference [19] discovered that DR programmes with proper IoT protocols typically resulted in energy savings. This research presents a communication and computation-based DR programme (CBDR) for future grid systems after conducting a thorough literature assessment of DR programmes. The study improves the DR programme even further by implementing a cooperative and customer-friendly tariff by incorporating proper communication infrastructure, monitoring consumer behaviour through the installation of smart metres and home displays; reducing peak demand through the use of DR schemes on power volume distribution; and maintaining responsive data-sharing interactions between consumers and the power grid. Both smart tariffs and smart communications will heavily promote DR among utility providers and users. In this work, IoT enabled demand response review is presented to provide customers with price and incentive changes via a quick and secure communication network along with the security risks and protection [20].

1.3 | Motivational factors and contributions

This study aims to provide valuable insights and a comprehensive understanding of IoT-enabled smart grid systems. It delves into various facets of IoT applications within the context of smart energy systems, shedding light on potential security vulnerabilities and the measures necessary to ensure their secure operation.

Key contributions of this study encompass recent breakthroughs in implementing smart grid concepts utilizing IoT, along with an exploration of the possibilities and challenges associated with integrating communication technologies into electrical infrastructure. The research also delves into the diverse demand response (DR) programs designed to incentivize customers in adapting their energy consumption habits and offers an overview of the strategies employed to optimize cost-effectiveness for both consumers and utility service provider. It provides a comprehensive analysis of DR's reliability, its impact on consumer privacy, and the essential cybersecurity considerations. The research extends to the domain of IoT technologies for disaster relief, exploring factors such as load flexibility, rapid communication, cybersecurity for consumer privacy, reliability, and energy-efficient solutions. It highlights the potential of grid-connected smart meters (SMs), enabling real-time monitoring of energy consumption, thereby facilitating precise adjustments in energy production and consumption through continuous communication between users and the grid. Additionally, this study investigates and categorizes IoT security vulnerabilities within the electricity system, offering effective solutions to address notable risks include power theft in smart meters, as well as false data injection attacks (FDIA) and denial of service (DoS) attacks on IoT-based energy management systems.

In summary, this research contributes significantly to the comprehension of IoT-enabled smart grid systems, their security aspects, demand response programs, disaster relief applications, and cybersecurity considerations.

1.4 | Paper organization

This paper is organized into the following sections. A short and brief explanation of deploying DR schemes under smart grids is presented in Section 2 followed by different DR approaches in Section 3. While Section 4 discusses the role of IoT in DR implementation, and Section 5 illustrates cyber-physical security vulnerabilities in IoT enabled smart grid system. Section 6 provides potential future research gaps and challenges in IoT-enabled smart grids. Section 7 concludes this research. Paper organization is shown in Figure 2.

2 | DEMAND RESPONSE UNDER SMART GRID PARADIGM

Demand response will play a crucial role in the system operation in Smart grid-based power system networks. DR strategies are being implemented more effectively as compared to wholesale retailers. Moreover, new generation companies have faced increase retail competition [29, 30].

More retail competition causes several issues, both market-based and network-based problems. The former issues arise when spot price volatility in the wholesale energy market poses financial risks to producers or retailers [31, 32]. The latter arises when transmission system operators (TSOs) and distribution system operators (DSOs) are responsible for ensuring a constant and stable power supply [33]. Traditionally, this latter category of issues has been handled unilaterally, with generating utilities either maintaining a security margin of generation so that it can be dispatched whenever the independent system operator (ISO) requests it or reducing generation to return the network to its normal state from a constrained state. The only unused source that could help in these situations is demand-side resource. Electric power research program institute (EPRI) devised a program called "Demand Side Management (DSM)" is a global program for many other kinds endeavours, including but not limited to load management, energy efficiency, energy savings etc. [34]. Issues like the environmental impacts of burning coal to problems include DSM initiatives like energy efficiency and energy saving schemes [36]. End-users' deviation from their typical patterns of energy use in reaction to temporary or permanent price increases, or to incentive payments meant to reduce power consumption.

The end-user customer which is responsible for final consumption may also be wholesale market participants. The DR may be broken down into many categories, as seen in Table 3, depending on electrical consumption.

2.1 | Demand response (DR) benefits

Some key reasons to include the demand side into the system's operations are listed below [37–43]:

(i) At generation level: Because DR has the potential to lower system peak demand over time, it might mitigate the need to construct new power plants, which can have significant environmental implications.
(ii) At transmission level: Transmission system operators may reap the rewards of DR by increasing the stability of the transmission network. Reducing the likelihood of forced outages caused by insufficient system reserves improves network dependability. System reserves may be restored to their pre-contingency levels with the use of DR sent by the TSO during peak demand periods.
(iii) At distribution level: To better manage distribution-level network restrictions, DSO implements DR:

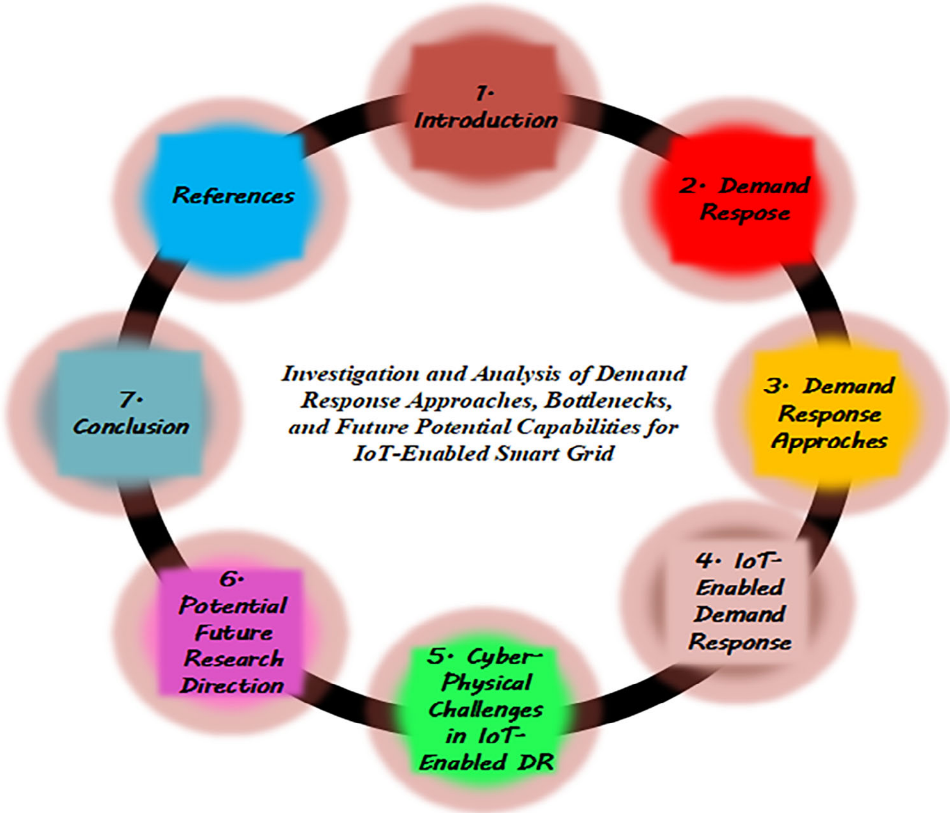

FIGURE 2 Paper organization.

(iv) Easing the issue of power transmission under voltage constraints.
(v) Reducing traffic in distribution centres.
(vi) Streamlining outage management and boost-up supply quality.

Congestion at peak times places an unnecessary strain on the network's individual parts, but DR helps alleviate that pressure. This improves both the quality and dependability of the service provided.

(i) At power market level: Power is purchased on the wholesale market and resold to customers at a set price. As a result, retailers from the wholesale market face the financial risks associated with the spot price volatility in the real-time scenarios. But utility companies may mitigate a large portion of their exposure by offering financial incentives to clients who agree to lower their use during periods of high volatility and peak spot pricing. Both the company and the customers may profit financially from DR's if there is a short time effect on the power markets.

At smart grid level: The incorporation of DR as a crucial component for the smart grid is further motivated by the widespread use of distributed generation (solar, small wind, geothermal) and storage (standalone, plug-in hybrid electric vehicles (PHEVs)). For instance, when wind speeds are very high, there is sometimes a surplus of power. On the other hand, wind farm's payback time increases significantly due to the inefficiency caused by a decrease in wind power due to low wind speed. Thus, DR may be utilized to boost demand in these circumstances.

2.2 | Infrastructure required for DR physical implementation

Smart meters have the ability for bi-directional communication between load serving entity (LSE) and the end-user. For DR manipulation, smart meters or AMI, that is, millions of smart meters networks are compatible to accept signals from the LSE, such as during certain periods for permissible levels of power requirement (e.g. to decrease local transformer loading) or according to price signals. Depending upon end user loads which may be residential, industrial, or commercial, EMS are crucial components for automatic control in order to participate effectively in a DR program. Certain regional differences can be observed if we overlook energy management systems (EMS) implementation globally. Especially in the Home Energy Management Systems (HEMS) market, the US is a front-runner in EMS adoption. In Parallel to the US, relevant pilot projects are also supported by European utilities [44]. Since EMS benefits for both the end-users and the utilities have been largely much admired and it can be identified that several most important utilities have already declared their EMS products commercially available [45], their usage in the interim future is probable to upsurge in different end-users' nature. For effective DR implementation, data transfer capability is the main requirement [46]. For DR program implementation, three data communications domains are considered: the home area network, the smart meter field, and Internet. Note that the home area network may also mention commercial, residential and industrial end-users. Smart meter domain is an AMI comprising several smart meters. The Internet is a wide-ranging publicly accessible platform of the IT industry obtained by means of different internet providers [47]. By making use of AMI, signals are received by EMS for desired actions execution by means of home area network. Internet is an interface for communication sharing between several systems about required action. WAN and NAN are other communications ways employed depending on the communication range for DR implementation [48]. Several communication approaches are appropriately being able to tackle the bandwidth criteria and latency. Generally, communication techniques can be categorized as wired and wireless techniques. Less costs are required for wireless communication because of getting out of supplementary wiring costs [50]. Further investigation about infrastructure for communication techniques for DR practical deployment can be found in [51–54].

There are many tries for DR-related smart grid operational characteristics regulation generally in world. The US NIST has established a regulatory outline to create mutual smart grid inter-operability measures by engaging investors, industry partners, academia, and the administration. For example, Open Automated Demand Response (Open ADR) is a Department of Energy (DoE) permitted standard established by the "DR Research Centre" that is a communications data model for sharing DR indications between LSE and end-users. Standard entitled "DR capabilities supporting technologies for electrical products" has been adopted commonly by both New Zealand and Australia There are also many other standard conclusions regarding DR, particularly in the US and established Europe and Australia [56].

2.3 | DR scheme

Incentives offered by the utility provider are crucial to DR programs, which aim to encourage users to reduce their energy consumption. As a result, DR programs need to raise consumer knowledge and interaction about the advantages of DR so that more customers will accept it or adjust their power use. Customers are urged to join DR programs for a variety of reasons, including financial savings, reduced risk of blackouts, and a greater sense of personal accountability. DR programs may be roughly categorized into two types: incentive-based and price-based. Some research suggests that these programs go under several titles, including "direct" and "indirect" DR, "emergency-based" and "economic-based," and "system-led" and "market-led." DR is employed to achieve the following three different aspects:

(i) Peak clipping: Peak clipping is used to decrease peak energy usage to prevent the load from surpassing the supply capacity of distribution substations or the thermal limit of transformers and feeders. Since peak clipping reduces part of the demand from users, user satisfaction and comfort would decrease.
(ii) Valley filling: Energy storage systems, such as rechargeable batteries and PHEVs, may be used for valley filling to encourage off-peak energy usage.
(iii) Load shifting: Without lowering customers' overall energy consumption throughout the day, load shifting involves adjusting the energy consumption across the time horizon, such as moving demand from on-peak to off-peak times (the combination of peak clipping and valley filling).

Essentially, demand response programs are the tariffs or other mechanisms by which a power company encourages its customers to alter their energy consumption habits [57]. The algorithms may modify the power load profiles of the customers in ways that boost the grid's stability and efficiency. It is possible to classify demand response systems into two basic categories [58].

2.3.1 | Incentive-based scheme (IBS)

Customers in this group get incentives for reducing their energy use in response to specific requests, as specified by contract. Depending on the specifics of the agreement between the client and the utility provider, the program administrator may be able to directly schedule, decrease, or discontinue service in order to achieve cost savings [59, 60]. These programs only applied to large-scale industries and commercial sectors, but recently they were expanded to include residential customers as well [61]. This method of gaining on-demand access to customers' residences is intrusive. One of the biggest problems with direct load control (DLC) and similar incentive programs is that they cannot be easily scaled to accommodate an increasing number of participants without compromising consumer privacy [62]. Participants in the incentive program get compensation for reducing their energy use in response to predetermined demand triggers such as periods of high usage or unexpected system stresses. Incentive payments for load adjustment are made available via this program to certain customers regardless of or in addition to their power rates [63]. The following is a list of some of the more important ones:

1. Direct load control (DLC): If customers agree to have their air conditioners and water heaters turned off remotely whenever the electricity company deems it necessary, they will get financial incentives [64]. The main concept is to lessen demand at busy times. DLC has been made available to homeowners and industries for decades by utilities like Baltimore Gas and Electric and municipalities like New Bern, North Carolina [65].
2. Interruptible/curtailable Load: Users will get an incentive reduction on their power rates in exchange for agreeing to reduce a percentage of their interruptible/curtailable usage during times of heightened grid reliability risk [66].

3. Demand bidding and buyback: Users may save money at times of high demand or system disruptions if they are ready to reduce their power use in exchange for a predetermined bid price [67]. Smaller users need third parties or agents to organize and represent them to bid, since the program is primarily given to big users (1 MW or more).
4. Emergency demand reduction: In the event of an emergency reliability issue when the grid has no reserves available, users are compensated for their load reductions (on short notice) [68]. By lowering their energy use, bigger customers may act as "virtual spinning reserves" for the utility company under this scheme.

2.3.2 | Price-based scheme (PBS)

In this scheme, customers are offered different electricity rates for different times of the day. Companies in the utility industry implement variable pricing via a decentralized procedure. Load balancing is promoted by encouraging consumers to control their loads by lowering or moving energy use to another time spam rather than at peak hours [69]. Electricity rates might be fixed or fluctuate based on demand (day, week, or year). A customer's actions are influenced by the ever-changing cost of power. Some examples of this scheme are: ToU, critical-peak price (CPP), and real-time pricing (RTP) fall in this category [70, 71]. Different types of DR Programs and achievable DR benefits and Costs have been summarized in Table 3 as follows.

1. Time-of-use (ToU) pricing: Depending on when the day or year or the amount of energy used, consumers may be subject to various power rates. Every interval often lasts more than one hour [72]. In Ontario, Canada, for instance, Time-of-Use (ToU) pricing is implemented using a three-tiered structure (on-peak, mid-peak, off-peak) (different in summer and winter).
2. Critical peak pricing (CPP): If the grid's stability is threatened on specific days, the regular peak price is substituted with a prespecified higher charge to decrease energy consumption [73]. This tariff's core rate structure is time-of-use (ToU) pricing.
3. Real-time pricing (RTP): This tariff, often known as dynamic pricing, sees power rates frequently fluctuate during the day (typically every 15 min or every hour) [74]. Typically, RTP is made available either an hour in advance or one day in advance. In Illinois USA, for instance, they use RTP based on the hour in conjunction with dynamic adjusment pricing (DAP). RTP is largely regarded as one of the most effective and cost-effective price-based strategies [34].
4. Inclining block rate (IBR): This tariff has two tiers of rates (lower and higher blocks), so that users pay more per kWh as their use increases [75]. Through the application of IBR, the peak-to-average ratio of the grid may be decreased by encouraging load shifting during off-peak hours [75].

Customer privacy and system scalability are not issues with price-based programs. However, it is not fair to impose the same cost for a certain length of time to all consumers regardless of their usage level (externality problem). Customers may also be confused by the practice of periodically adjusting prices. More importantly, clients need a scheduling method, either manual or automated, to manage the load. These DR plans assume that customers' electricity consumption will shift in response to fluctuating prices, incentive programs, or unforeseen events that risk the grid's reliability. Savings in consumer energy and costs, decreased need for additional generating capacity, less air pollution, lower peak-energy prices and many other power system issues can be solved by DR that are beneficial for both the utility and its customers.

3 | DEMAND RESPONSE APPROACHES

Demand response is an optimization method to optimize electricity usage and cost. The concept of demand response revolves around the dynamic interaction between a power utility and its consumers. Therefore, a critical initial step in this process entails the development of mathematical models that accurately represent and characterize the behaviours of both the utility and the end-users.

Utility function: Quadratic utility functions are commonly employed, and these functions reflect that the additional benefits gained from each additional unit diminishes at a constant rate as consumption increases.

$$\begin{cases} \omega x - \left(\dfrac{\alpha}{2}\right) x^2 \ , & 0 \le x < \omega/\alpha \\ \dfrac{\omega^2}{2\alpha}, & x \ge \omega/\alpha \end{cases} \tag{1}$$

The parameter $\omega > 0$, fluctuates among users at various times throughout the day, while the parameter $\omega > 0$, remains constant and predetermined. Here are more complex and realistic load models for various household appliances:

Category 1: These are essential appliances, like lighting and cooking, which must remain active for a specific period (T_a for each appliance). They come with well-defined usage limitations.

$$\begin{cases} x_a^t \equiv b_a^t & \forall t \in \tau_a \\ x_a^t = 0, & otherwise \end{cases} \tag{2}$$

Category 2: Shiftable appliances, such as PHEVs, where users primarily concern whether the task can be completed within a designated time (T_a for each appliance). These appliances also have constraints.

$$\begin{cases} 0 \le x_a^t \le x_a^{-t} & \forall t \in \tau_a \\ x_a^t = 0, & otherwise \end{cases} \quad \text{and} \quad \sum_{t \in \tau_a} x_a^t \ge e_a \tag{3}$$

Category 3: A unique subset of shiftable appliances, like washers or dryers, with elastic demand that must be satisfied without interruption. The tasks of these non-interruptible appliances should be completed within a continuous time frame.

$$r_a^t = \begin{cases} e_a\,, & t = 1 \\ e_a - \sum_{r=1}^{t-1} x_a^r\,, & t = 2, \ldots \ldots . T \end{cases} \tag{4}$$

Cost function: Two options are available: the piece-wise linear cost function, which corresponds to an inclining block rate structure, and the quadratic cost function. The piece-wise linear cost function involves segmented linear cost increments, often associated with tiered pricing, while the quadratic cost function presents a more continuous, curvilinear approach to cost calculation.

3.1 | Convex optimization

Convex optimization is a problem whose objective function as well as constraints function are convex. Mathematically, it can be expressed as follows

$$min_x f_0\,(x) \tag{5}$$

Under constraints function

$$f_i(x) \leq b_i \tag{6}$$

$$i = 1, \ldots\ \ldots\ \ldots m \text{ and } f_0 \ldots\ \ldots\ \ldots f_m : \mathbb{R}^n \rightarrow \mathbb{R}$$

For instance, a 40-mile commute in a plug-PHEV requires 16 kWh of charging time per day, or a dishwasher started at lunchtime should be done by supper time. In [78], the authors attempted to increase customer benefits while meeting everyone's energy needs within a finite resource. While the issue is solvable using centralized convex optimization methods such as the interior point approach, it is instead dual decomposed and solved in a distributed manner to protect the privacy of both the electricity company and its customers. By virtue of strong duality, the dual problem is identical to the original. In a similar way, the convex optimization problem is distributive solved in [77] using the Karush–Kuhn–Tucker (KKT) condition. By sharing data on electricity prices and consumption patterns, the power grid operator and its customers may collaborate to find a viable solution. It is possible to reduce the cost minimization problem from [76] to a linear form and solve it in a reasonable amount of time using computer resources. However, suppose the energy consumption of users is treated as discrete rather than continuous. In that case, the cost minimization issue becomes as complex as mixed-integer linear programming, necessitating the use of additional computer software, such as IBM ILOG CPLEX Optimization Studio or Yet Another LMI Toolbox for MATLAB (YALMIP), to find an optimal solution. In conclusion, convex optimization is often considered as one of the fundamental methods for demand response. However, if we think of more complex scenarios, the issue becomes more difficult, necessitating a wide range of different unique procedures.

3.2 | Game theory

One definition of "game theory" is "a model of interactive decision-making processes based on the study of selfish and rational individuals." A game G consists of three fundamental components: (1) players N; (2) strategies $\{X_i\} \in N$, and (3) payoff functions $\{W_i\} \in N$. Each player $i \in N$ chooses one of the best strategies $x_i \in X_i$ in order to maximize the function payoff W_i which depends upon the other players' strategies as well. A key idea in game theory is Nash equilibrium. There is no advantage for any player to deviate from this approach on their own; hence it is static and unchanging. The dynamic between the power company and its customers in demand response is a game relationship. Game theory simulates the relationship between the power company and its customers and designs incentive- or price-based programs to encourage conservation [79]. Nash or other equilibrium points are often reached in game-theoretic methods to demand response, and these points may represent the ideal solution for both the supply and demand sides. So, game theory is a useful tool for improving decision-making in demand response systems. Two market models for smart grids are analysed in [80], focusing on the demand response games: marketplaces that are (1) competitive, and (2) oligopolistic. The suggested distributed demand response techniques in both cases converge on their respective optimum equilibriums over time. Game theory is proposed in [81, 82] as a decentralized method for controlling energy usage and storage and coordinating the charging and discharging of plug-in hybrid electric vehicles. As shown in both works, the produced Nash equilibriums have the best possible performance on a worldwide scale, both in terms of reducing the cost of generating electricity for the grid and in terms of the quality of the frequency. To decrease power costs for consumers and optimize system load [83] create congestion-game-inspired distributed demand response methods [84]. A typical computer network congestion issue provides a suitable starting point for such an approach. The advantage is that there is always a Nash equilibrium in a potential game, which is what congestion games are. The energy consumption scheduling methods suggested in [33, 85] use two-way information flow to reduce costs associated with synchronized usage of a shared energy supply by numerous users. Game-theoretic methods not only ensure that the specified problem's Nash equilibrium is reached, but also protect the confidentiality of both the supply and demand sides. Along with game theory Price theory [86], auction [87, 88], and hedging [89, 90] are also a few of the other economic methods used to address demand response problems. These methods are crucial in reducing the burden of modelling the power company's and its customers' economic activities and interactions in demand response.

3.3 | Dynamic programming

With dynamic programming, the complex question is broken down into simpler ones and then solved step by step in reverse. This strategy will take less time than heuristic techniques. Because of the time dependence of energy consumption, the best strategy for demand response cannot be solved statically but must be dynamically determined. In [91], time slot-based dynamic programming is used to reduce power costs; this method is more effective than others. However, there is a downside to using dynamic programming, and that is the increased memory and processing cost it often requires. The stochastic inputs in [92–98] are taken from the uncertainty in power pricing and the stochasticity of renewable generation. The difficulty of solving non-deterministic issues arises because their value functions depend on the current state. Overall, time-varying parameters, such as renewable energy and RTP, drive the need for dynamic programming in the demand response industry. One of the most common ways to deal with these factors and boost demand response performance is via dynamic programming.

3.4 | Markov decision process

In the case of hourly-based RTP, for instance, the precise future power costs are uncertain. However statistical information about them might be derived from a vast amount of past data. It is natural to model the issue of scheduling energy usage in order to reduce daily power costs as a Markov decision process due to the inherent unpredictability of electricity prices [100]. The concept is based on the idea that future prices rely on a set of probability density functions, which are assumed to be independent of existing prices or user behaviour. Smart grids, which are being modelled as a multi-time scale Markov decision process in [101], will also be impacted by the unpredictability of wind power. This is because a stationary Markov chain may be used to represent and forecast the non-stationary and variable output of a wind turbine. The authors in [102] demonstrate that the underlying Markov chain for PHEVs is non-stationary, meaning that the transition probabilities between states change with time. The authors go further into the non-stationary Markov decision process and develop the best charging/discharging strategy for PHEVs. To sum up, the technique of dynamic programming to enhance the demand response performance is complemented by the Markov decision process, which specifically handles the time-varying parameters in demand response that display Markov features.

3.5 | Stochastic programming

Using the notion that probability distributions are either known or may be predicted, stochastic programming is used to solve optimization problems with unknown outcomes. In [103], the authors suggest a stochastic gradient algorithm for dealing with the uncertainty of renewable energy and also explore the effects of the stability of renewable energy on the performance of the system. The stochastic gradient method relies on the statistical information that can be derived from a huge amount of past data in order to predict the amount of renewable energy output in the future. In [104], the authors offer a wait-and-see strategy in the field of stochastic programming for the case of stochastic wind power. Wait-and-see is an option since the authors were able to obtain a closed-form solution to the stochastic programming issue. Considering that it is impossible to accurately forecast future energy demand from consumers, the authors of [105] propose the use of stochastic programming to characterize demand uncertainty as a probability density function. There is an element of stochasticity that comes because of the inaccuracy in estimating residential energy consumption patterns [106]. In summary, variable parameters in demand response can be addressed by stochastic programming if their probability density function is known. Stochastic programming is a subset of dynamic programming that uses statistical information about random factors to produce optimal demand response choices.

3.6 | Metaheuristic optimization techniques particle swarm optimization (PSO)

Optimization techniques are nature or bio-inspired technique that models the behaviour of different natural phenomenon to generate a population of candidates for an optimization issue. Each particle (potential answer) is propelled in a random direction, with its path impacted by its own and other particles' prior experiences, until it reaches the optimal solution. The dynamics of particle motion are controlled by inertia, individual performance, and team effort. These optimization techniques have the benefit of solving difficult restricted optimization problems quickly and correctly with little expense in terms of memory and dimensions. The Metaheuristic methods are used by the authors of [107] to address the cooperative scheduling issue for ubiquitous DERs since it is simple to implement and takes just a reasonable amount of time to compute. In addition, co-evolution expands PSO's capacity to address complicated and high-dimensional issues, such as the problem of designing microgrid systems that meet stringent reliability requirements [108, 109].

The search space dimension may be drastically reduced when a binary or integer optimization is used to solve the problem, since discrete variables are used instead of continuous ones. When a PHEV is parked, for instance, it employs binary algorithm to choose between charging, discharging, and doing nothing at every given time slot [110]. Each particle's location encodes, using only two bits of binary data, one of three potential states for the car it is associated with. The authors of [111] also employ binary optimization technique to plan interruptible loads while minimising the overall cost. When one of the interruptible loads is scheduled to be reduced in output within a certain time period is represented by a binary variable. Binary search algorithms are used to intelligently arrange the ON/OFF state of energy generation units in [112–114], whereas integer optimization technique is used to determine the

TABLE 2 The architecture of fog-based SCADA system.

System architecture	Fog-based SCADA parts			
	Terminal devices	**Fog computing devices**	**Cloud systems**	**SCADA systems**
Components	Instruments, motors, and home electronics	Wi-Fi access points, antivirus programs, cloud nodes, and routers	Gateways, cloud data centres, and cloud storage	Instrumentation/controllers and HMIs
Connection type	Wireless	LANs/WANs	LANs/WANs/VPNs/APIs	Wired and wireless
Tasks	Data collection	Perform necessary processing and analysis on data gathered	Compile and analyse the data obtained for statistical purposes	Real-time data collection for monitoring and management

TABLE 3 DR classification, benefits, and costs.

DR programs classification	DR programs benefits	DR programs costs
Incentive based programs (IBP)	**Participant**	**Participants**
➢ Classical • Direct control • Interruptible/curtailable programs ➢ Market based • Demand bidding • Emergency DR • Capacity market • Ancillary services market	➢ Incentive Payments ➢ Bill savings ➢ Market-wide • Price reduction • Capacity increase • Avoided infrastructure costs	➢ Initial • Enable technology • Response plan ➢ Running • Inconvenience • Rescheduling • Onsite generation
Price Based Programs (PBP)	**Reliability**	**Program Owner**
➢ Time of use (ToU) ➢ Critical peak pricing (CPP) ➢ Extreme day pricing (EDP) ➢ Extreme day CPP (ED-CPP) ➢ Real time pricing (RTP)	➢ Reduced outages ➢ Customer participations ➢ Diversified resources **Market performance** ➢ Reduces power market ➢ Options to customers ➢ Reduces price volatility	➢ Initial • Metering and communication • Billing system • Customer education ➢ Running • Marketing • Administration • Incentive payments • Evaluation

best way to park several grid-capable automobiles. Suboptimal solutions may be reached in a Reasonable amount of processing time if the problem's dimensions and complexity are scaled down.

4 | IoT-ENABLED DEMAND RESPONSE

IoT technologies have potential applications in many areas of energy systems. Fog computing, a cutting-edge IoT solution, provides a wide range of opportunities for enhancing and controlling SCADA-connected transmission networks. As a result of advancements in IoT technology, most modern smart home gadgets now operate entirely automatically. Several IoT-based smart grid applications and several solutions are discussed in this section. SCADA plays an essential role in the management and supervision of the electrical power industry from production to transmission and distribution [19–21]. Recently, as IoT technologies like fog computing have become more widely available, SCADA system operations have become more optimized. The for-based energy grid SCADA system architecture is outlined in Table 2. Local Area Networks (LANs), Wide Area Networks (WANs), Virtual Private Networks (VPNs), and application programming interfaces (APIs) are the abbreviations of connection types of communication systems.

An AMI's purpose is to keep utilities updated on their customers' electricity usage in real-time [22]. Within the next five years, the AMI system is expected to deliver real-time tariffs that will enable users to make energy-efficient choices. IoT-based AMI has great potential for improving and controlling customers' energy usage due to reliable smart meter networks [23]. To facilitate efficient energy management, AMI may be linked to a wide range of devices, including but not limited to lamps, fans, dishwashers, switches, power outlets, and geysers. Figure 3 shows the different integration levels of IoT devices in distribution networks where general packet radio service (GPRS) is communicating with base transceiver station (BTS) and further communication is performed [24].

IoT enabled smart meters are being deployed for optimal energy management in homes, commercial buildings, smart cities and grids by recording and transferring the real-time data of energy consumption to the utility service providers to get intelligent monitoring and control [25, 26]. IoT-enabled smart meters have benefits and drawbacks as outlined in Figure 4 [27, 28, 35].

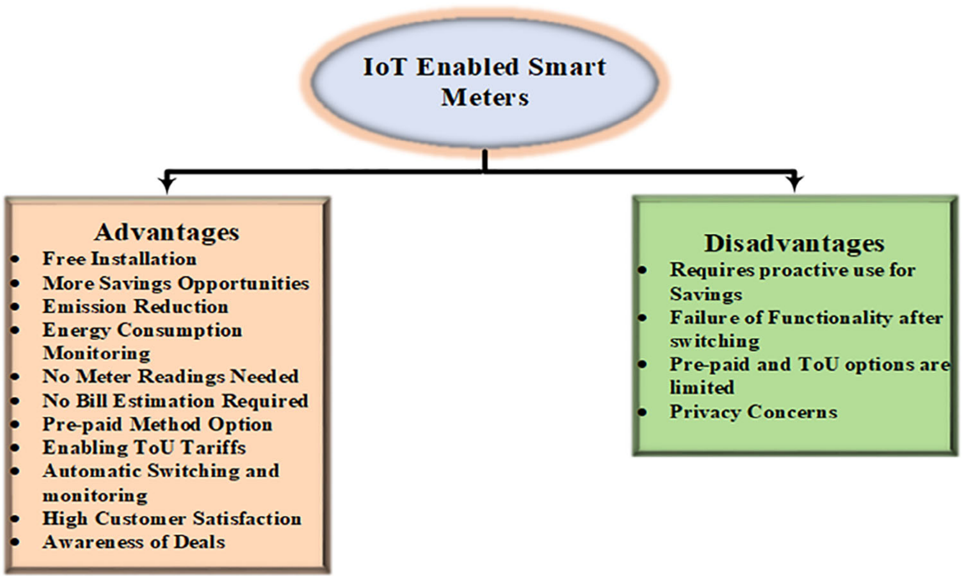

FIGURE 3 Integration of IoT scheme in distribution system.

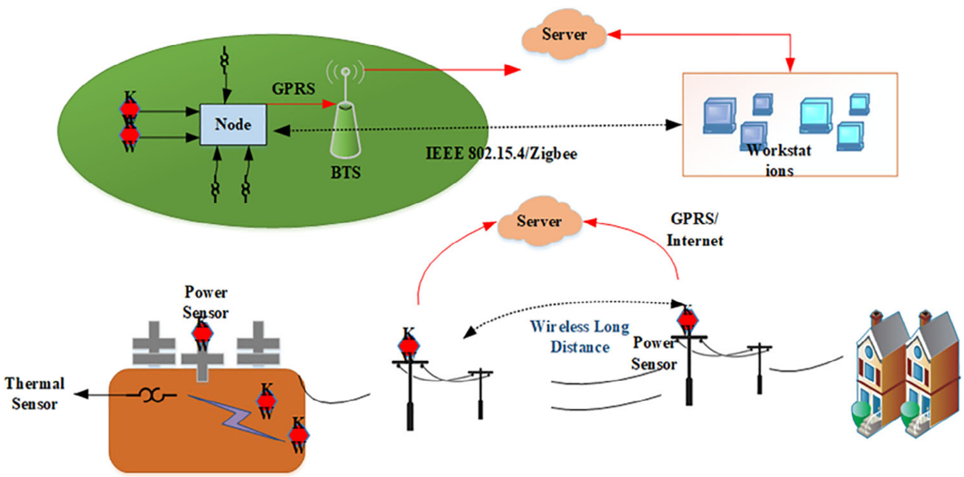

FIGURE 4 Advantages and disadvantages of smart meters.

4.1 | IoT-enabled DR in smart grids

The fundamental nature of domestic DR applications has yet to be defined, and it follows a different form of standardization than that initially employed in the energy sector. The International Electrotechnical Commission (IEC) is the most prevalent motivating factor in the electricity N/W sector. In order to save money on electricity, consumers may use appliances like front-load washers that have the ability to postpone the start of the washing cycle until off-peak hours. When the sun is shining brightly and photovoltic (PV) is generating a lot of electricity, or when the wind is blowing strongly and a lot of wind energy is being created, the optimal time to run a clothes-monitoring machine is not during peak demand. Similarly, customers may agree on a suggested planned runtime for appliances like air conditioners, tumble dryers, and dishwashers, or use portable heating and cooling equipment to cut out on expensive peak-use periods. Given the impending necessity to implement variable tariff accounting throughout low voltage distribution networks (LVDN), this proposal displays a forward-looking attitude. Accordingly, the Low Volt-Grid operator must have already installed Smart Meters (LVGrid). It is suggested that the N/W used for smart metering communications be kept distinct from the N/W used for Home-DR communications for the reasons described above, including for the sake of privacy management and from an implementation standpoint. Another perk of this method is that it satisfies the mandated freedom to choose desired local electricity-SP. Providing home-DR services is seen as a way for electricity-SPs to set themselves apart from rivals. Local electricity-N/W-SP provides the electricity-SP control centre with data about LVGrid's capabilities, control mechanisms, and rates. The local electricity-N/W-SP then uses this data to reconcile the smart metre pricing with the customer's home electricity use. Electricity service providers (ESPs) broadcast their rates to the company-supplied gateway router (DR-Adapter/Router). The control and cost data are received and stored by the DR Adapter/Router. In response to a user's request, the following linked devices inquire about the possibilities that are now accessible, either by direct consumer interaction (known as "programming") or, in the instance of the washing machine, through the controller's internal demand planning. Strong data encryption and privacy are recommended, and the electricity-SP should manage and ensure these features [115].

The goal of the project was to improve energy management for both consumers and the utility by using IoT technologies. The project relied on free and publicly available protocols including smart energy profile 2 (SEP2), ZigBee IP, and IETF. Beginning in October 2012, this project continued for a total of three years, ending in 2015 with a 4.5 million EUR investment. An efficient, economical, and flexible method for condition monitoring and residential energy management is illustrated in [45]. Basic functions include the monitoring and control of household appliances remotely. The fundamental features of the designed model are the unobtrusive management of residential load, which provides an intelligent solution for controlling energy usage through IoT. This feature helps people adjust their work schedules to save energy. Approximately 97% reliability in sensing information transfer was seen as a consequence of using the suggested approach.

In order to deal with the issue of several vendors, a heterogeneous meter network based on already-established open standards is developed [116]. Since then, the traffic burden has decreased by more than 90%. This approach can be utilized in the DR system, for tracking, analysing, and controlling energy use. A virtual smart metering that works on real time data management is presented in [117]. Numerous device characteristics were measured and evaluated using a multi-agent system and the DPWS protocol's Web services as shown in Figure 5.

One device, using this method, may share its meter readings with thousands of subscribed virtual smart meters. In addition, this method enabled automatic detection of the added metering hardware. To deal with the virtual smart meter's heavy traffic, a synchronization approach was developed for the physical smart meter. Effective metering measurement for DR applications is made easier using this method. To control energy use at home, a set of Web of Things application is designed in [118]. The user can just log in to see real-time energy data and adjust the load profile accordingly. Embedded instruments were suggested to monitor domestic appliances and report to a website if there was a deviation from the usual energy use [119]. According to the supplier's advertised rates, the user's appliances may be operated remotely at the peak hours of the day. Users adjust their energy use based on price signals in order to optimize their own advantages. Server is always kept updated with the changing utility pricing and the preferred customer set pricing for the appliance. Using these updated values, the server adjusts appliance operation to reduce energy use and costs.

An economical residential load management system is created in [120]. This system collects data from home appliances and updates with relevant messages containing data for different parameters perceived by those gadgets. A combination of wireless and wired connections facilitates in-house communication in this setup. When an abnormal case is detected on the gateway, the customer is alerted via a new post on their Twitter account, which is based on an integration of the customer's appliance schedule and the normal operation case (healthy state) of each device. Additionally, the consumer may remotely regulate the use of the appliances.

Using a controller-based infrared remote-control module, a DR system for frequently aggregating window/split ACs to lower the peak demand and save energy costs is developed [121]. Findings indicated that the suggested system with demand management might reduce overdemand penalties and carbon dioxide emissions on a yearly basis. As can be seen in Table 4, one of the primary benefits of DR is the evolution of communication and monitoring technologies that underpin DR methods, such as the use of smart metering infrastructure and IoT.

Additionally, IoT applications in DR were given greater consideration than the more conventional use of load management and control. Though a lot of literature is available on industrial IoT-based DR schemes, current research is mainly focused on residential load management. IoT-based comprehensive DR schemes are given less attention for the customers' use.

4.2 | IoT-enabled DR for smart cities

The smart city concept, which aims to increase the quality of life while reducing expenses, has recently been made possible in several application areas [50, 122]. The EIS system is tested, and an integrated information system is suggested to monitor and control the environmental conditions [44]. These IoT applications are realized by using a system configuration structure like that shown in Figure 6. Smart home management (SHM) is a newly emerging application category that integrates existing risk assessment methods. There are five main processes involved in this sorting: detection, localization, classification, evaluation, and prediction. The Building Automation and Control Networks (BACnet) is a web-based automation solution that is an alternative solution of ZigBee and wireless sensor network (WSN) and is designed specifically for use in urban IoT applications. In [122] explanation, BACnet may offer some more IP technology choices as compared to ZigBee technology. Virtual link layers (VLLs) are used by BACnet, for example, to combine the different protocols that make up the network and the transport layer.

As previously indicated, the smart city idea faces a number of significant challenges. The authors [46] proposed a model for the smart city idea based on a layered structure; this model, which they termed a "smart city infrastructure" (SCI), is built on four distinct layers. Additional service structures, infrastructure for managing resources, and connections to other

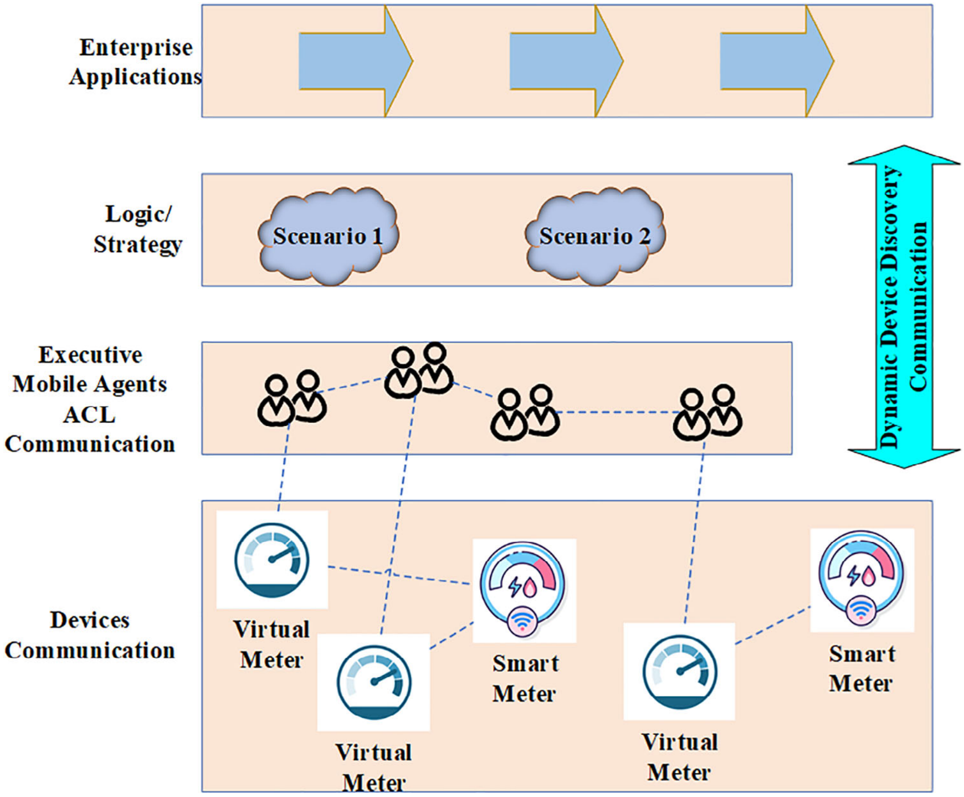

FIGURE 5 The service-based multi-utility metering.

TABLE 4 Leading Low Power WAN (LPWAN) technologies.

Technology	Standard	Data rate	Frequency band	Bidire-ctional	Interference immunity	Security	Power efficiency	Transmitter power	Battery lifetime
LTE-M	LTE (R12)	0.2–1 Mbps	Licensed cellular	Yes	Medium	32-bit	Medium	23 dBm	7–8 years
NB-IoT	LTE (R13)	Up to 100 kbps	Licensed cellular	Yes	Low	–	Very high	23 dBm	1–2 years
LoRa	LoRaWAN	0.3–38.4 kbps	Sub-GHz	Yes	Very high	32-bit	Very high	20 dBm	8–10 years
Sigfox UNB	N/A	100 bps	Sub-GHz	No	Low	16-bit	Very high	15 dBm	7–8 years

Abbreviations: LoRa, Long range; LTE-M, LTE for machines; NB-IoT, narrowband internet of things; Sigfox UNB, Sigfox ultra narrow band.

communication networks make up the final layer. A well-structured cyber-physical system (CPS) system can greatly enhance the convenience and security of smart cities; it can also improve the comfort of smart homes. In [48], the authors investigate energy-based smart city applications by analysing of energy-related applications of smart cities with respect to numerous characteristics, including energy production, storage, infrastructure, facilities, and transportation (mobility) [125]. In [49], a smart city energy management and testing framework is presented whereby innovative control strategies are analysed by considering the case of heterogeneous source data.

However, when smart city ideas are applied in the real world, it becomes clear that many urban IoT applications are being created all over the world. To improve the quality of life in the city, authorities in Amsterdam, the Netherlands, have introduced a suite of IoT applications in the areas of lighting, mobility, and public applications. Philips and Cisco have presented new ideas and developments for smart city applications that are based on network-enabled LED lighting [50]. The City 24/7 smart screen project is an information platform being built in New York City, USA, as part of the smart city initiative. In order to disseminate the aforementioned technologies, this venture makes use of smart displays that can communicate with one another over Wi-Fi networks. Also, in Nice, France, another smart city application is being implemented which covers the four primary services: Transportation, lighting, garbage collection, and environmental monitoring [50].

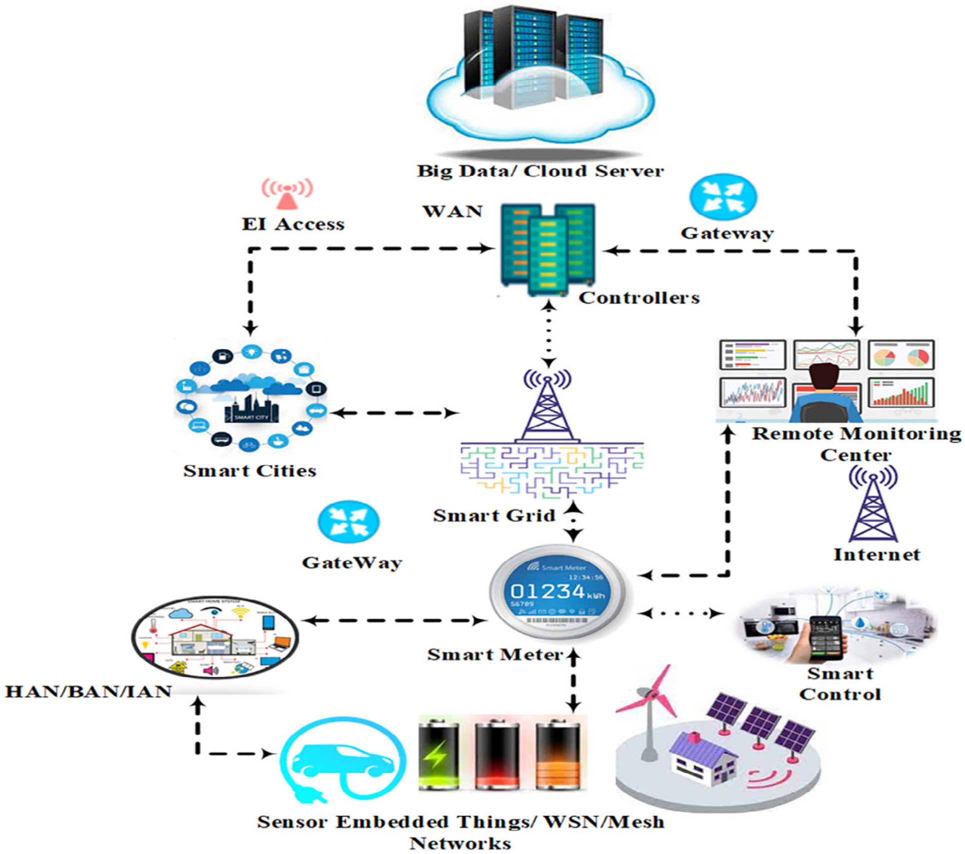

FIGURE 6 IoT application with energy internet (EI) concept.

4.3 | IoT-enabled DR for smart homes

The term "smart home management system" (SHMS) refers to a network of interconnected intelligent home appliances and other devices that communicate via some internet protocol to the central system [51]. While different terminologies are used in different applications, the underlying operations are the same. Smart home management system (SHMS) systems acquire observing data from sensors and smart objects, then operate equipment by communicating instructions. Moreover, the SHMS updates the system if any significant change happens. Two main control structures are being utilized for every SHMS system management: mobile apps and the IoT middleware architecture [51–53, 55, 126].

The US government has maintained an essential attention on the DR management due to the high energy consumption of residential customers. Home load management systems (HLMSs) were created as a direct result of this tenacity. Therefore, those who participate in DR programs may get the benefits of doing so while simultaneously lowering their waste output. In addition, incorporating SHMS modules into users' SMs may result in the development of autonomous agents of the independent framework [56]. With the use of SHMS and HLMS customers are guaranteed increased efficiency. In addition, clients who enrol in utility companies' specialized programs to save energy expenses may gain a number of advantages. SHMSs and HLMSs, on the other hand, allow governments and service providers to profit from DR initiatives [57, 123, 124, 127].

Home energy management systems (HEMS) are a subset of SHMS that focus on energy management in residential buildings. To provide two-way wireless communication, neighbourhood area networks (NANs) depend primarily on SMs [127–129]. Figure 7 shows how gateways transmit data collected from various networks to command-and-control different units. Like other IoT applications, SHMSs may be organized in a layer-based structure. Sensors, actuators, smart objects, and gateways make heavy use of the physical (PHY) and media access control (MAC) layer combination, which is often presented as the device layer [130]. In [131] security and other authentication techniques are discussed for smart home management privacy concerns. In [132–137], it is suggested that a non-IP SHMS architecture based on the constrained application protocol (CoAP) be used for secure IoT network communication. Secure Internet of Things (IoT) protocols, such as Constrained Application Protocol (CoAP), Hypertext Transfer Protocol Secure (HTTPS), Message Queue Telemetry Transport (MQTT), and Extensible Message and Presence Protocol (XMPP), may be used by all the devices and apps in a smart home.

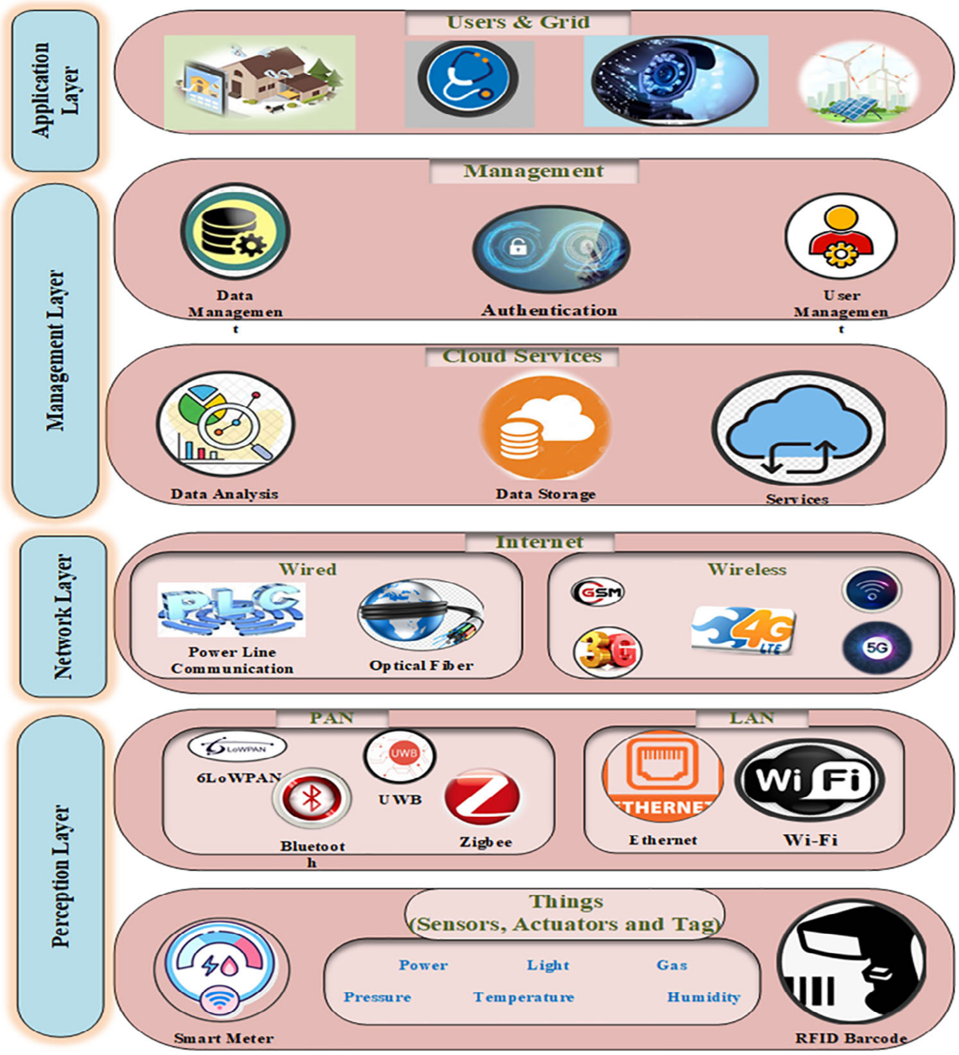

FIGURE 7 Different layers and applications of IoT in smart grid environment.

4.4 | Recent practical advances in IoT-enabled DR in smart grids

This study primarily surveys current developments in DR practice in Europe, the United States, and China. There has been significant growth in interest in permitting DR throughout much of Europe, and in certain places, tangible progress has been made. New smart meters, such as those produced by the "Enel Info+," "FLEXICIENCY," and "Smart Demo Grid" programs, feature a dedicated communication channel with Home Area Networks [138]. Some refrigerators, wastewater treatment facilities, and electric space heaters have been field-tested in Denmark, proving that they can be rapidly adjusted to provide frequency regulation services to power grids [139].

Low- and medium-voltage power line communication networks have been built in Romania, and roughly 1300 homes and small economic operators have had advanced smart metering management systems installed using fibre optics and GPRS [140–142, 145]. A system has been tested in the field in Norway and Switzerland, called the "Scalable Energy Management Infrastructure for Aggregation of Households," [41] was designed to allow aggregators to efficiently manage large-scale household appliances. Over the next decade, the government of the United Kingdom also intends to provide every home with a "smart metre" that will enable two-way communication between utility and customers [29]. This paves the way for DR signals to be sent between power suppliers and system operators in milliseconds [29], and also between electricity suppliers and customers. Also, the DR aggregator EnerNOC has a Network Operating Centre for managing Heating, ventilation, and air conditioning (HVAC), lighting, and pumping systems in large commercial and industrial buildings [143]. ComEd's assessment study [144] suggests that the potential advantages of installing wireless, radio frequency communication networks and IT systems for advanced metering may outweigh the expenses associated with doing so. State Grid Corporation of China (SGCC) has launched many initiatives over the last decade to construct instantaneous, two-way communication networks for DR. [29]. To achieve precision control at the millisecond level [146], an optical fibre communication network covering roughly 10,000 MW loads by 2020 has been deployed. The use of this approach has been recently encouraged in six more Chinese provinces [29]. Air conditioning management systems in public buildings have been reprogrammed to allow for more nuanced temperature control. In 2016, the overall controlled capacity had reached 335 MW, with improvements made to around 1337 public buildings, 500 commercial buildings, and 400 industrial buildings. Additionally, beginning in 2017, customers' air conditioning systems were upgraded, and by 2020, the controlled capacity reached 2000 MW. To sum up, advancements in information communication technologies (ICT) have prompted more and more grid firms worldwide to prioritise the development of instant communication systems to facilitate grid-consumer engagement. As a result, customers have greater access to data on their electricity use and more chances to profit from DR. Concurrently, power system social welfare may improve.

4.5 | Cyber security and consumer privacy of IoT-enabled DR

Cybersecurity and consumer privacy have emerged as major societal concerns due to the proliferation of information and communication technologies (ICTs) and IoTs [29]. More emphasis has been placed on cyber security in current DR initiatives and their associated communication networks. For instance, in the United States OpenADR, while in China "Control System Reformation of Air Conditioning Systems in Public Buildings" are playing a key role. Keeping its own Public Key Infrastructure (PKI) [147] OpenADR in the United States allows meeting the security standards of the industry and the Cyber Security Guidelines issued by the National Institute of Standards and Technology. In order to restrict communication to only clients and servers, the PKI employs digital certificates stored on both ends. In order to authenticate their connections, OpenADR Servers and OpenADR Clients must each acquire a valid OpenADR-specific digital certificate. Elliptic curve cryptography (ECC) and the Rivest–Shamir–Adleman (RSA) encryption technique are also used in OpenADR [147, 148]. The security of the transport layer may be effectively ensured in this way.

Figure 8 depicts the Chinese Government's cyber security protection structure for the "Control System Reformation of Air Conditioning Systems in Public Buildings" project. Keep in mind that the functioning of power systems necessitates the use of both private networks and extranets for communication. By using the extranet in this fashion, the power system and DR control communications systems may be completely separated from one another. In addition, as can be seen in Figure 8, the project's security encryption chip technology has been used in the air conditioning industry's monitoring and control terminals.

4.6 | Reliability analysis of power systems considering IoT-enabled DR

Regulating electricity from DR is more prone to uncertainty than that from conventional generating units because of variables, including customers' social-behavioural patterns [149], varying kinds of loads [150], and random failures of ICTs [168, 169]. The dependability of a power system must be carefully examined in light of the uncertainties introduced by DR in order to guarantee its safe and stable operation. In [151], a technical model of flexible loads is combined with a social-behavioural survey approach to assess the regulating power associated with an incentive-based DR. The findings reveal that the effectiveness of DR as a regulatory tool varies with factors such as load kinds, location, ambient temperatures, and subsidy levels. In light of this, utilities should carefully weigh the costs of peak demand reduction through DR against the price of building additional producing units. To account for the dynamic reaction of the loads during reserve deployment, a multi-state reliability model of operational reserve supplied by thermostatically regulated loads is presented in [150, 152]. Based on the findings, DR may have an effect on the short-term reliability of the power system, and that DR regulation capacity is distinct from traditional regulation by producing units.

In addition, time-sequential simulation techniques and reliability-network-equivalent approaches are presented in [153] for assessing the dependability of power systems with variable loads. The findings show that the resilience of the electricity system may be affected by factors such as the reduction and redistribution of uncertainty resulting from consumer behaviour, random errors in the signal transmission process, and the diversity of loads. This result serves as a reminder that DR's regulating capabilities may lower system reliability, contrary to the common belief that DR always improves power system reliability. It is shown in [153] that DR programs may mitigate the effects of wind power fluctuation on a power system's reliability, but that DR uncertainties can have a major influence on the effectiveness of such programs. Overall, DR is beneficial in that it helps improve the reliability of power systems [171]. The assumption here is that customers' social-behavioural aspects and load kinds are completely addressed during regulation and that random failures of ICTs occur within a narrow range.

5 | CYBER-PHYSICAL SECURITY VULNERABILITIES AND CHALLENGES IN IoT-ENABLED SMART GRIDS

The increased use of IoT-based technologies has led to smarter and more interactive energy grid systems, which in turn boost reliability, efficiency, and flexibility. Vulnerabilities in cyber defence, on the other hand, are more widespread [172]. For this reason, we will discuss the risks associated with using the Internet of Things in smart energy systems and how to lessen such risks in next section.

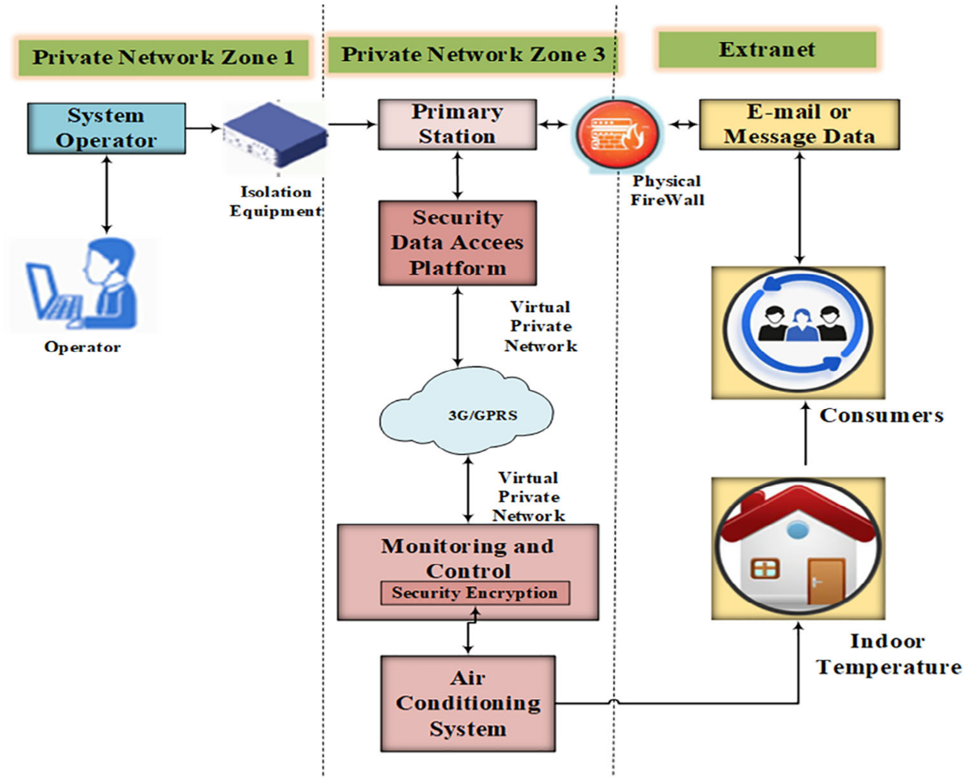

FIGURE 8 Cyber security protection structure.

The larger the network, the more potential entry points there are. If security is compromised at even a single node, the whole network is at risk. When it comes to network security, professionals agree that avoiding third-party components is the best course of action. It's possible for Trojans to infect these devices and then propagate to others on the network. Training is necessary for the usage of any technology. Personnel who have not been adequately prepared are more vulnerable to phishing attacks. Not all protocols for transferring data are equally safe. Several protocols rely on unencrypted data transfer. Because of this, they are vulnerable to data-extraction attacks using a "man in the middle" technique. The basic goal of maintenance is to ensure that everything continues to function normally. It also has the potential to be used in cyberattacks. In order to perform testing and maintenance on a security system, its operators routinely turn it off. Table 5 gives the main goals of the hackers to attack the smart grid security.

TABLE 5 Goals of security to hack under cybercrime.

Security goals	Attack category	Description
Availability	Flooding attack	Hindering people from using services
	Denial of service	Discontinue responding to user requests
	Jamming channel	Congestion of the system
	Buffer overflow	The buffer's memory overwritten
Integrity	False data injection (FDI)	Data manipulation
	Social engineering	Attacks on people rather than computers or networks
	Session hijacking	Putting a temporal limit on a user's access to resources
	Data manipulation	Data tampering
	Replay attack	Continuously transmit data
Confidentiality	MITM	Data extraction from sent packets
	Packet sniffing	Packet analysis

5.1 | Historical cybersecurity attacks on IoT-enabled smart grids

In this section, we will review a number of notable incidents of cyberattacks throughout the world [173] to help us better understand the threats presented by cyberattacks on the essential infrastructure of electrical grids.

Twelve people were seriously hurt when hackers attacked a tram system in Lodz, Poland. Injuries from a cyber-kinetic assault have never been seen before. An employee of Texas Power Company (TPC) hacked the company's network in order to deactivate the power forecasting systems. They used active logins to get access that were given to them and were not deactivated. Stuxnet was developed to sabotage Iran's nuclear program, but it has since shown that it can do serious physical harm to critical infrastructures as well [174]. It does this by attacking the computer controllers and SCADA systems that monitor and operate industrial machinery. New York's Bowman

Avenue Dam had its floodgates hacked into, allowing water to pour out of the city. As we learned from our investigations, all it would have taken is a little adjustment to the parameters governing water flow or to the dosage of chemicals used in water treatment for the effects of having been catastrophic. The consequences of this turning out to be true would have been catastrophic.

As the number of cyberattacks in the energy industry rises, the security and dependability of smart grids are put at greater risk. Attacks on the electrical system in Ukraine that were really successful in 2015 are evidence of this danger. Distributed denial of service attacks occurred when attackers got access to distribution grid operator consoles and remotely closed breakers, cutting power to local areas. As a result of the assault, 30 substations lost power, impacting about 230,000 people. It is possible that attackers in similar instances would either infiltrate communications channels or alter data, or they would flood the highly linked network with data traffic, reducing the capacity of operators to monitor and run the grid [174]. A cyberattack on the internet service provider Dyn slowed or stopped access to several well-known websites in the USA. The cybercriminals conducted extensive denial-of-service attacks. The Mirai botnet, which searches the internet for unprotected IoT devices using the factory default login and password, was taken over by the distributed denial of service (DDoS) assault. After taking over a plethora of vulnerable IoT gadgets, they bombarded Dyn's servers with service requests. The site crashed due to an influx of fraudulent users.

Two apartment buildings in Lappeenranta, Finland, experienced a complete loss of heating and hot water due to a targeted distributed denial of service assault in the dead of winter. In July 2017, a power network that supplies energy to the UK and Ireland was attacked. The goal of the hack was to compromise power management systems and so disable part of the grid. Several forged emails were sent to high-ranking officials in the electricity industry, allowing them to pull it off [175]. Thankfully, the explosive did not go off because of a bug in the attackers' computer code.

5.2 | Adverse impacts of cyberattacks on smart grids

Here, we will go through a few scenarios when hacks cause heavy losses (from both financial and stability perspectives) of IoT-enabled smart grids. Cyberattacks on smart energy infrastructure might have serious financial and physical ramifications. Although this investigation has concentrated on cyber technical/physical assaults on smart grids, it is also crucial to pay more attention to cyberattacks in terms of related economic threats. Cyberattacks against smart grids, especially those that include a large percentage of renewable energy supplies, have caused significant economic hardship. The electricity market is a hybrid of instantaneous and futures trading [154, 155]. Finding the most economical approach to optimization and load forecasting issues is of primary importance in the day-ahead market. Optimization algorithms would be unable to precisely calculate the location marginal prices (LMPs) of the grid if the day-ahead market were subject to false data injection (FDIA) hacks, which would have a negative effect on load forecasting [156, 157]. However, the transmitted power from each producing unit is evaluated by the real-time market to ensure that the load requirement of each bus is met [158, 159]. To produce the congestion pattern and analyse real-time LMPs, it is also important to compute the power that flows across transmission lines. As a result, FDIA assaults may compromise accurate state estimates in real-time energy markets [160–164].

For IoT-enabled smart grids, the FDI assaults have had serious material and technical repercussions. When facing FDIA assaults, smart grids often have to cope with both steady-state stability and transitory consequences [184]. IoT technology enables the wireless transmission of the vast amounts of data and information that have been collected, greatly reducing the need for labour-intensive processes [166]. Power outages are not the only thing that worries people in the energy industry nowadays; theft is a huge problem as well. Energy companies and their customers have both lost a lot of money due to theft. Tampering with a meter to make it falsely reflect the use and thus raise or lower bills is the most common form of energy theft. Typically, energy theft involves tampering with the energy meter in order to steal power without getting billed for it [167]. The following objectives may be pursued using cyberattacks on automation equipment in both critical and non-critical facilities [168, 169]:

1. To get into a system and obtain access to other resources; this might be accomplished by hacking a smart light bulb, for example.
2. To interfere with service in a roundabout way; for instance, by remotely adjusting the temperature of a building's air conditioning.
3. To gather and share information, the use of a program that can hack smart devices to make them seem off so that you may record and leak conversations around them.
4. Misuse of the system, such as causing epileptic seizures in people by flashing lights at a certain frequency.
5. To launch a coordinated assault on vital infrastructure, including hospitals, using a wide variety of smart devices. The goal is to disable smart home automation systems quickly and efficiently by attacking a large number of Internet of Things-enabled smart home automation devices.

Energy grid efficiency and reliability are enhanced by the transactive energy system's use of an integrated idea of financial and operating strategies to dynamically regulate demand and supply balance throughout the grid. A great deal of information must be transferred across the system's many market mechanisms. The following is a technique that cyberattacks may use to compromise the reliable functioning of transactive energy systems [165, 170, 171]:

1. A system-wide blackout or data theft may be caused by malware being injected into the system.

2. Hackers have several motivations for damaging or compromising smart meters.
3. To tamper with the relay and circuit breaker control signals in order to disrupt the transactive system.

5.3 | Detection and mitigation of IoT-enabled cyberattacks

Stakeholders of smart grids are likely to include customers (consumers and prosumers), electric utilities, power system operators, and ancillary service providers. Smart grid data management, particularly smart meters, becomes difficult when several parties are involved. The goal of integrating security and privacy across domains is to increase protection for all parties involved. Several frameworks exist to assist this process. The security framework divides security into three subcategories: communication security, secure computing, and system control security. There are several facets to communication security [171], including cryptography, route security, and network privacy. Achieving end-to-end encryption and multiple hop routing that can guarantee the security of transmitted data is a major objective in the management of communication security [172]. The literature is full of methods that have been offered to deal with the history, aspects, issues, and solutions of cybersecurity for smart energy grids. Recent research has indicated that integrating AI approaches is one of the most effective solutions to the increasing complexity of the grid brought on by the widespread deployment of smart IoT devices. Several studies have shown that the smart grid is susceptible to human mistakes, which in turn may be brought on by social engineering assaults [173, 174]. For this reason, we have separated the most promising new approaches to protecting IoT-enabled smart grids into two categories: non-human-centric approaches and human-centric approaches.

5.3.1 | Non-human-centric methods

There are three main types of non-human-centric approaches: (1) machine learning-based approaches, (2) cloud computing-based approaches, and (3) blockchain-based approaches. Listed below is a synopsis of each approach. Thousands of sensors are used in the smart grid architecture which monitor all the devices connected in the network and produce copious amounts of data in the form of log files and time-series information. The information collected by sensors is stored on a cloud server and must be prepared for transmission before being transmitted. Servers can also be used on local network but keeping information on a local server required the highest degree of protection. However, sophisticated optimization methods [174, 175] limit their utility for use in pattern recognition features or predictions. In recent years, machine learning techniques have been shown to be useful in identifying cyberattacks. Unlike rule-based methods, machine learning can detect intrusions by analysing historical data. Together, JRipper and Adaboost were developed in [176] and [177, 178] to foresee power system interruptions. The model divided the data on attacks, natural disasters, and the absence of any occurrence into three distinct categories. Unsupervised ensemble-based learning (EBL) model showed the highest performance (accuracy of 73%). The findings they received with their algorithm proved its efficacy by showing that it could provide accurate predictions, outperforming the other approaches that were compared to it.

To learn more about how cloud-computing security measures might be applied to smart energy systems, a thorough literature research was also done. An attribute-based online/offline searchable encryption technique was presented in [179] to reduce the overhead associated with encrypted material. First, we bifurcated our encryption and trapdoor methods into two distinct stages. The second phase included an offline execution of an attribute control policy and encryption. The next stage included protecting the proposed method against two types of attacks: (1) selected plaintext attacks, and (2) selected keyword attacks. When everything was said and done, the proposed strategy was tested in a real-world scenario, a cloud-based smart grid [180, 181].

The acceleration of a wide variety of security features in smart energy systems [182] is increasingly reliant on the complex core solution of integrating blockchain with IoT-enabled smart grids. As a result of the availability of public key algorithms, the present centralized ledger system may be converted into a distributed ledger by using blockchain-based methodologies. Using a distributed processing framework, blockchain techniques provide end-to-end encryption technology to ensure secure and reliable communication [183]. Safe and approved access to smart city resources is described in [208], which describes a blockchain-based security approach for doing so. The suggested approach relied on two models- (1) a blockchain model and (2) object security architecture (OSCAR) for the IoT-to provide an authentication and authorization procedure for restricted settings. OSCAR utilized a public ledger to build multicast classes for approved consumers, while the blockchain-based approach set forth a flexible and untrustworthy authorization scheme. In addition, a meteor-based application was developed to serve as a streamlined interface for various forms of smart city infrastructure. Users could manage and control smart municipal infrastructure, including traffic lights, utility meters, and surveillance cameras with this app. As a solution to the problems of data loss, unauthorized access, and stolen identities plaguing IoT-enabled smart grids, a novel distributed authentication and authorization system based on blockchain-based approaches was presented in [184–186]

5.3.2 | Human-centric methods

Combining two separate authentication steps, makes the password-cracking technique exponentially more difficult. Since the authentication procedure now requires more than one form of identification, it will be more difficult for unauthorized individuals to access the data. Some examples of multifactor authentication methods include using short message service (SMS) tokens, email tokens, hardware tokens, software tokens, and even a phone [187]. Technology improvements have made assaults on smart devices more challenging, so hackers are shifting their focus to human targets. As a result of advancements in machine learning, attackers can now accurately predict and simulate a wide range of human actions and reactions. In light of this, it is clear that educating staff is essential to preventing the hackers' destructive goals from being realized. The risk of data security or privacy breaches is reduced when robust passwords are used to access sensitive information. Weak passwords increase the likelihood of password guessing attacks. Access may be gained to a system by password guessing, which is a technique used to access the desired device. Furthermore, the attacker uses up bandwidth and resources while launching many assaults, which makes it harder for genuine users to get access [188]. One of the major problems with users is that they cannot be educated in the same manner as professionals, making them one of the weakest links in terms of cybersecurity. Therefore, there must be safeguards in place to prevent cyberattacks on smart equipment like smart meters and smart inverters. One of the most efficient ways to safeguard devices from hackers is to make the internal operating systems unbreakable [189]. Users should be suspicious of any program that needs their permission to function. A customer's smartphone may contain sensitive information, and certain third-party applications may ask for more data than is necessary. Statistics show that almost all users (98.5%) either never provide the rights apps ask for or only do so on occasion. Reports indicate that 93.6% of users immediately or within one minute accept the terms and conditions of the apps [190].

TABLE 6 Current research topic for IoT enabled smart grid—AMI and DSM.

Application type	Power grid stage	Required improvements: Communication	Security	Big data
Real time monitoring	Generation	√	√	√
Line fault monitoring	Transmission	√	√	–
Smart transformer control	Distribution	√	√	–
Home energy management system	Consumption	√	√	√
Power plant control	Generation	√	√	–
Line measurements	Transmission	√	√	–
Power quality analysis	Transmission	√	√	√
AMI and DSM	Distribution	√	√	√
Micro-grid management	Consumption	√	√	√
Distributed generation	Generation	√	√	–
Substation monitoring	Transmission	√	√	√
Substation automation	Distribution	√	√	–
Electric vehicle control	Consumption	√	√	–
Appliance control	Consumption	√	√	–

6 | POTENTIAL FUTURE RESEARCH DIRECTIONS

As our research showed, the evolution of IoT systems is ongoing and is directly related to the state of the art in information and communication technology. Several SG infrastructures are also undergoing transformation into the Internet of Things technologies. Studies reveal that owing to the complex nature of IoT networks, their evolution is difficult to predict with precision. The biggest benefit of IoT systems is that they enable billions of interconnected devices to communicate to each other and exchange data across wide-area networks (WANs) and low-power wide-area networks (LPWANs). Massive improvements in data clouds, CPS systems, WSN, information and communications technology ICT systems, and wireless mesh network WMN are also anticipated to be necessary for the growth of IoT systems. As central data hubs, WSNs are often recognised as the backbone of the IoT and SG systems. WSNs will become pervasive technology due to the unique characteristics of wireless devices. It is anticipated that many applications will be enhanced to enable IoT systems in a variety of domains. Concerns about the quality of service (QoS) and support capacities of WSNs are seen as the most important areas to be studied soon. Table 6 provides a summary of the current research gaps.

- Due to the intricate nature of the SG systems' underlying communication infrastructure, it is sometimes referred to as a "system of systems." We see that SG studies, comprising modelling, analysis, and application concerns, may be able to meet the obstacles resulting from the combination of the power grid and communication technologies. A combination of wired and wireless communication protocols is crucial for the efficient and reliable operation, administration, and monitoring of SG systems. As a result, new research addressing the connection between ICT and cyber physical system (CPS) may be considered to progress all phases of SG infrastructures. Load management, remote monitoring, developing electric vehicles, integrating microgrids and distributed energy resources, demand side management and DR are all important challenging issues encountered at various points in the SG infrastructure.
- Data processing phases must be integrated with the CPS's physical components through wired and wireless communication channels. Consideration also must be given to big data's security needs. Figure 9 depicts the generation, distribution, and security stages of the cyber-physical system integration achieved by an IoT-based SG infrastructure. Data processing, metering data management, decision support, and big data processing methods are only some of the physical system application kinds that may be used with big data.
- Due to the interconnection of many devices, IoT-based systems produce vast data stacks, which need sophisticated processing and storage solutions. Data filtering, signal processing, and other analytic techniques should be used for the collected data stacks to create useful insights.

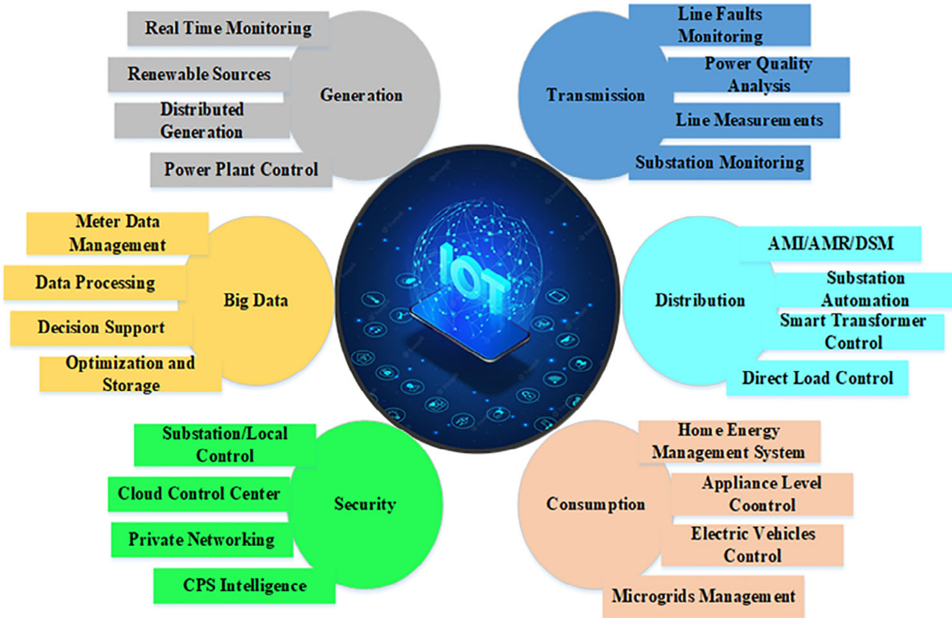

FIGURE 9 Potential future research areas in context of IoT-based smart grids and applications.

- Middleware applications and software are expected to be one of the most studied fields soon [191, 192] because of the importance they hold in enhancing these techniques.
- IoT-based SG applications also face challenges with machine learning and deep learning strategies for large data analytics, as explored in [193]. To deal with enormous data quantities, heterogeneity, high volumes, and massive structures, deep learning approaches may be included in the development of middleware-enhanced data analysis techniques.
- Private networks, cloud-based control hubs, substations, local control applications, and CPS intelligence are all the focus of security studies. The issues of cyber security and privacy are addressed by bolstering the usage of authorisation, encryption, authentication, identity, and public key infrastructure (PKI) methods. If we want IoT-based SG infrastructure to be reliable, the devices utilised in the management environment must meet the system-wide security standards.
- Accordingly, investigations into authentication and identity are predicted to be one of the primaries focuses of security and privacy research in the near future. Many types of communication technologies, protocols, and frameworks are used to make possible IoT applications in SG systems. As a result, it is expected that security and privacy concerns would be given considerable consideration with a view toward improving communication confidentiality.
- In addition, future works will pay a lot of attention to encoding and encryption techniques made for IoT devices.

Based on the findings of these investigations, it seems that public key infrastructure (PKI) might be a useful tool for bolstering the security of IoT devices. On the other hand, end-to-end security in IEEE 802.15.4 networks, as well as security for the physical, media access control, and network layers, have emerged as promising topics for further study in response to security and privacy concerns.

- Other presumed open research opportunities in IoT include new communication technologies for long-distance communication that use less electricity. The LPWANs provide a thorough strategy to back a fresh idea that satisfies these criteria. As conventional means of communication prove inadequate for low-power, long-distance communication, a lot of attention has been dedicated to LPWAN-based communication systems [192, 194–197].
- Our research also showed that SG-like applications are critically needed in smart surroundings, including smart cities, smart homes, smart meters, and smart EMSs. As a result, given that all these applications (SG and other smart environments) have huge heterogeneous network architectures, it is crucial to provide safe frameworks that are compatible with all aspects of the system.
- it is anticipated that the SG applications will provide a wealth of future IoT network research opportunities. We also think that our research can help advance future IoT applications with regard to connection, interoperability, and security by analysing problems and improvements in these areas.
- The implementation of DR in a smart grid paradigm faces several obstacles. Regulators will always need substantial evidence before sanctioning expenditures even if DSM and DR adoption can make the grid more flexible, self-healing, and contains social advantages. It is also possible that the utility sector will not be able to afford a financial rollout to pay for new technology without government incentive schemes.
- There is a pressing need to upgrade outdated infrastructure, such as electromechanical power meters, with newer, more advanced "smart" options. Since the early retirement

of equipment may not be financially viable for the end users, this may provide a challenge for the utilities and regulators. Rapid progress is necessary to actualize DR in many nations due to a lack of legislation, standards, and ICT infrastructure. In addition, the distribution companies insufficient familiarity with ICT technology makes it challenging for them to operate smart grid components. Smart grid designs need strong partnerships with industry-leading information and communication technology firms.
- Educating the consumer on the advantages and implementation concerns of DR is a major task. Additionally, financial institutions, regulators, and politicians should be the targets of such initiatives. To achieve widespread customer adoption of the technology, thorough market research and product development studies are required. There is currently no consensus on how AMI should be built and run in terms of standards and protocols. There is a chance that any investment made in such a setting may become obsolete. To mitigate investment risk, it is necessary to do a cost-benefit analysis considering these factors and incorporating an estimate of the cost of the equipment the client would install to automate response.

7 | CONCLUSION

The IoT is the next step towards a worldwide and widespread connection to any device or electronic component that can communicate and do computations, independent of the device's access technology, available resources, or location. The IoT will improve existing smart energy networks by enabling real-time management and tracking of the smart grid's individual nodes. To motivate consumers to adjust their energy usage patterns and join demand response programmes, smart pricing, which employs smart metres and two-way communications, is essential. Demand response is a promising new technology that can help improve system operation, expansion, and market efficiency by encouraging end-user interaction and responsiveness in order to better match demand to supply or respond quickly to system contingencies. Renewable energy, DERs, PHEVs, and energy storage in demand response provide the flexibility to further improve system efficiency; nevertheless, the complexity introduced by these technologies requires unique approaches. Here, we propose some demand response strategies for dealing with the complex problems in this area. There is growing recognition that DR has the potential to play a pivotal role in smart grid deployments, and that DR programmes can encourage end-user participation in the energy supply chain. Strongly implemented connectivity infrastructures based on the IoT ensure bidirectional energy and signal flow. The increased chance of a cyberattack and the potential for catastrophic effects is exacerbated by the large number of interconnected devices, making it harder to ensure the security of grid-connected equipment. As a result, the attack surface of smart grids will grow as the number of IoT-enabled devices integrated into them increases.

AUTHOR CONTRIBUTIONS

Muhammad Adnan Khan: Conceptualization; formal analysis; writing—original draft. **Tahir Khan**: Conceptualization; formal analysis; resources; software; writing—original draft. **Muhammad Waseem**: Conceptualization; formal analysis; funding acquisition; project administration; supervision; writing—original draft; writing—review and editing. **Ahmed Mohammed Saleh**: Formal analysis; investigation; methodology; writing—review and editing. **Nouman Qamar**: Conceptualization; formal analysis; software; validation; visualization. **Hafiz Abdul Muqeet**: Conceptualization; funding acquisition; project administration; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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