Internet of Things-aided Smart Grid: Technologies, Architectures, Applications, Prototypes, and Future Research Directions

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Abstract—Traditional power grids are being transformed into Smart Grids (SGs) to solve the problems of uni-directional information flow, energy wastage, growing energy demand, reliability and security. SGs offer bi-directional energy flow between service providers and consumers, involving power generation, transmission, distribution and utilization systems. SGs employ various devices for the monitoring, analysis and control of the grid, deployed at power plants, distribution centers and in consumers’ premises in a very large number. Hence, an SG requires connectivity, automation and the tracking of such devices. This is achieved with the help of Internet of Things (IoT). IoT helps SG systems to support various network functions throughout the generation, transmission, distribution and consumption of energy by incorporating IoT devices (such as sensors, actuators and smart meters), as well as by providing the connectivity, automation and tracking for such devices. In this paper, we provide the first comprehensive survey on IoT-aided SG systems, which includes the existing architectures, applications and prototypes of IoT-aided SG systems. This survey also highlights the open issues, challenges and future research directions for IoT-aided SG systems.

Index Terms—Internet of things (IoT), Smart grid (SG), Home Area Network (HAN), Neighborhood Area Network (NAN), Wide Area Network (WAN)

I. INTRODUCTION

A. Motivation

A traditional power grid consists of a large number of loosely interconnected synchronous Alternate Current (AC) grids. It performs three main functions: generation, transmission and distribution of electrical energy [1], in which electric power flows only in one direction, i.e., from a service provider to the consumers. Firstly in power generation, a number of large power plants generate electrical energy, mostly from burning carbon and uranium based fuels. Secondly in power transmission, the electricity is transmitted from power plants to remote load centers through high voltage transmission lines. Thirdly in power distribution, the electrical distribution systems distribute electrical energy to the end consumers at reduced voltage. Each grid is centrally controlled and monitored to ensure that the power plants generate electrical energy in accordance with the needs of the consumers within the constraints of power systems. Nearly, all the generation, transmission and distribution of electrical energy is owned by the utility companies who provide electrical energy to consumers and bill them accordingly to recover their costs and earn profit.

The traditional power grid worked very well from its invention in 1870 until 1970 [1]. Even though the consumers’ demand for energy grew exponentially, it was still rather predictable. However, there has been a dramatic change in the nature of electrical energy consumption since 1970, as the load of electronic devices has become the fastest growing element of the total electricity demand and new sources of high electricity consumption have been developed, such as electric vehicles (EVs). The power grids endure a significant wastage of energy due to a number of factors, such as consumers’ inefficient appliances and lack of smart technology, inefficient routing and dispensation of electrical energy, unreliable communication and monitoring, and most importantly, lack of a mechanism to store the generated electrical energy [2–4]. Furthermore, power grids face some other challenges as well, including growing energy demand, reliability, security, emerging renewable energy sources and aging infrastructure problems to name a few.

In order to solve these challenges, the Smart Grid (SG) paradigm has appeared as a promising solution with a variety of information and communication technologies. Such technologies can improve the effectiveness, efficiency, reliability, security, sustainability, stability and scalability of the traditional power grid [5]. SG solves the problem of electrical energy wastage by generating electrical energy which closely matches the demand [2–4]. SG helps to make important decisions according to the demand of energy, such as real-time pricing, self healing, power consumption scheduling and optimized electrical energy usage. Such decisions can significantly improve the power quality as well as the efficiency of the grid by maintaining a balance between power generation and its usage [6].

SG differs from traditional power grids in many aspects. For instance, SG offers a bi-directional communication flow between service providers and consumers, while a traditional power grid only offers only uni-directional communication from the service provider to the consumer. SG provides supervisory control and data acquisition (SCADA), advanced
SG deploys various types of devices for monitoring, analyzing and controlling the grid. Such monitoring devices are deployed at power plants, transmission lines, transmission towers, distribution centers and consumers premises, and their numbers amount to the hundreds of millions or even billions [1]. One of the main concerns for SG is the connectivity, automation and tracking of such large number of devices, which requires distributed monitoring, analysis and control through high speed, ubiquitous and two-way digital communications. It requires distributed automation of SG for such devices or "things". This is already being realized in the real world through the Internet of Things (IoT) technology.

Initially, the Internet served as a connectivity of people-to-people and people-to-things. However by 2008, the number of things connected to the Internet surpassed the number of people in the world, thus the impact of IoT technology keeps rising. IoT is a network of physical objects or things connected to the Internet. Such objects are equipped with embedded technology to interact with their internal and external environments. These objects sense, analyze, control and decide individually or in collaboration with other objects through high speed and two-way digital communications in a distributed, autonomous and ubiquitous manner. This is exactly what is required for the SG. Hence, IoT technology can help SGs by supporting various network functions throughout the power generation, storage, transmission, distribution and consumption by incorporating IoT devices (such as sensors, actuators and smart meters), as well as by providing connectivity, automation and tracking for such devices [10].

SG is considered as one of the largest applications of the IoT [11]. Today, the number of things that use electricity is higher than the number of things connected to the Internet, and essentially everything which uses electricity could be made more useful by connecting it to the Internet. Hence in the future, the IoT would be larger than the SG today, and the modern and intelligent grid (i.e., SG) will not be possible without the IoT technology. By making the IoT technology as a global standard for the communications and the basis for SG, new doors will be opened for maximizing the prospects for future innovations.

### B. Contributions of this Survey Article

To the best of our knowledge, there is no survey that covers IoT-aided SG systems. In this survey, we comprehensively cover architectures, applications and prototypes, as well as the open issues, challenges and future research directions for IoT-aided SG systems. The contributions of this survey are summarized as follows:

- A discussion on the current prototypes for IoT-aided SG systems;
- A discussion on big data management in IoT-aided SG systems;
- An overview of IoT and non-IoT communication technologies for SG systems; and
- A presentation of the open issues, challenges and future research directions of IoT-aided SG systems.

Table I presents the list of acronyms used in this paper.

| Acronyms | Definitions |
|----------|-------------|
| ADR | Adaptive Data Rate |
| AMI | Advanced Metering Infrastructure |
| ATM | Asynchronous Transfer Mode |
| CGI | Common Gateway Interface |
| DER | Distributed Energy Resource |
| DSN | Digital Subscriber Lines |
| EPON | Ethernet Passive Optical Network |
| FAN | Field Area Network |
| GPS | Global Positioning System |
| GSM | Global System for Mobile |
| GUI | Graphical User Interface |
| HAN | Home Area Network |
| IaaS | Infrastructure as a Service |
| IoT | Internet of Things |
| IPv6 | Internet Protocol version 6 |
| ISM | Industrial, Scientific and Medical |
| LTE | Long Term Evolution |
| MAC | Medium Access Control |
| M2M | Machine-to-Machine |
| MBWA | Mobile Broadband Wireless Access |
| NAN | Neighborhood Area Network |
| NAT | Network Address Translation |
| NIST | National Institute for Standards and Technology |
| NMEA | National Marine Electronics Association |
| LWMM | Lightweight Machine-to-Machine |
| OPGW | Optical Power Ground Wire |
| OPLC | Optical Power Line Communications |
| PaaS | Platform as a Service |
| PLC | Power Line Communications |
| PKI | Public Key Infrastructure |
| PSTN | Public Switched Telephone Network |
| RF | Radio Frequency |
| RFID | Radio Frequency Identification |
| SDN | Software as a Service |
| SCADA | Supervisory Control and Data Acquisition |
| SG | Smart Grid |
| SIM | Subscriber Identity Module |
| WPAN | Wireless Personal Area Network |
| UPnP | Universal Plug and Play |
| Wi-Fi | Wireless Fidelity |
| WiMAX | Worldwide interoperability for Microwave Access |
| WMAN | Wireless Metropolitan Area Network |
| WiLTE | Voice over Long Term Evolution |
| VM | Virtual Machine |
| UAV | Unmanned Aerial Vehicles |
| UWB | Ultra-Wideband |
| WAN | Wide Area Network |
| WLAN | Wireless Local Area Networks |
| WWW | World Wide Web |

### C. Comparison with Existing Survey Articles

While there have been a large number of separate surveys on the IoT and the SG, to the best of our knowledge, there is no existing survey that covers the intersection of IoT and SG systems. This survey differs from previous individual surveys on IoT and SG systems because it combines IoT and SG systems together and it specifically covers IoT-aided SG systems.
There is a number of surveys on the IoT that have focused on the overview, principles, vision, applications, challenges and architectures of the IoT [12]–[15]. Many surveys have also focused on security [16]–[18] and cloud computing for the IoT [19]. Moreover, social IoT has become a very hot topic of IoT [20], [21]. Other groups of surveys on the IoT have focused on software defined networking (SDN) [22], data mining [23], LTE uplink scheduling [24] and context aware computing [25]. The standardization of the IoT is also surveyed in [26], [27]. Another survey [28] has focused on experimentation with the IoT.

Surveys focused on the SG have presented the general overviews of the SG concept [4], including challenges and standardization activities [29], [30], as well as applications and architectures [5], [31]–[33]. Moreover, information management schemes for SG have been surveyed in [34]. Security issues, which are important factors to be considered in the SG, are surveyed in [35], [36], and privacy-aware metering is reviewed in [37]. Other areas which have been surveyed in the domain of SG include energy efficiency [38], power demand forecasting [39], load balancing [40], optimization and pricing methods [41], and renewable energy [42]. Additionally, some surveys focus on solving the problem of spectrum scarcity in SG through Cognitive Radio (CR) technology [4], [7], [10], [43]. A survey on cloud-assisted IoT-based SCADA systems security has very recently been published in [44].

D. Article Organization

The organization of the paper is presented in Figure 1 and is as follows: In Section II, we provide an overview of IoT technology and SG systems, as well as the integration of IoT technology into SG systems. In Section III, we present the current applications of IoT-aided SG systems, followed by a detailed analysis of the existing architectures of IoT-aided SG systems in Section IV. In Section V, we present prototypes and experimentations for IoT-aided SG systems. We discuss big data management in IoT-aided SG systems in Section VI. Section VII presents an overview of IoT and non-IoT communication technologies for SG systems. In Section VIII, we highlight the open issues, challenges and future research directions for IoT-aided SG systems. Finally, we conclude in Section IX.

II. INTERNET OF THINGS AND SMART GRID: AN OVERVIEW AND INTEGRATION

A. Internet of Things

The IoT is defined as a network that can connect any object with the Internet based on a protocol for exchanging information and communication among various smart devices in order to achieve monitoring, tracking, management and location identification objectives [45]. The IoT focuses on the realization of three main concepts, namely things-oriented, Internet-oriented and semantic-oriented. The things oriented concept involves smart devices, such as RFID tags, sensors, actuators, cameras, laser scanners, the Global Positioning System (GPS) and NFC. The Internet oriented concept enables communication among smart devices through various communication technologies, such as ZigBee, WiFi, Bluetooth and cellular communications. and connects them to the Internet. The semantic oriented concept realizes a variety of applications with the help of smart devices.

Over the past few years, the IoT technology has gained significant attention in various applications, and has allowed for the interconnection of the Internet to various network-embedded devices used in daily life [46]. It has automated the operation of various systems, such as health care, transportation, military, home appliances, security, surveillance, agriculture and power grids. In some areas, IoT devices are equipped with transceivers, micro controllers and protocols, enabling their communication with other devices as well as with external entities to allow the realization of completely automated systems [47].

B. Smart Grid

The SG has been promoted as a promising solution for minimizing the wastage of electrical energy and as a means to solve the problems of traditional power grids, making possible advances in efficiency, effectiveness, reliability, security, stability, and increasing demand of electrical energy [48]. The main SG attributes are that it offers self-healing, improved electricity quality, distributed generation and demand response, mutual operation and user participation, and effective asset management.

As presented in Figure 2, the SG completely revolutionizes the energy generation, transmission, distribution and consumption in four sub-systems. It is comprised of three types of networks, a Home Area Network (HAN), a Neighborhood Area Network (NAN) and a Wide Area Network (WAN). HAN is the first layer; it manages the consumers’ on-demand power requirements and consists of smart devices, home appliances (including washing machines, televisions, air conditioners, refrigerators and ovens), electrical vehicles, as well as renewable energy sources (such as solar panels). HAN is deployed within residential units, in industrial plants and in commercial buildings and connects electrical appliances with smart meters. NAN, also known as Field Area Network (FAN), is the second layer of an SG and consists of smart meters belonging to multiple HANs. NAN supports communication between distribution substations and field electrical devices for power distribution systems. It collects the service and metering information from multiple HANs and transmits it to the data collectors which connect NANs to a WAN. WAN is the third layer of an SG and it serves as a backbone for communication between network gateways or aggregation points. It facilitates the communication among power transmission systems, bulk generation systems, renewable energy sources and control centers [2].

C. Integration of the IoT into a SG

The SG has already achieved wide adoption in information sensing, transmission and processing, and now IoT technology plays a significant role in grid construction. IoT technology provides interactive real-time network connection to the users
and devices through various communication technologies, power equipment through various IoT smart devices, and the cooperation required to realize real-time, two-way and high-speed data sharing across various applications, enhancing the overall efficiency of a SG [49]. The application of the IoT in SGs can be classified into three types. Firstly, IoT is applied for deploying various IoT smart devices for the monitoring of equipment states. Secondly, IoT is applied for information collection from equipment with the help of its connected IoT smart devices through various communication technologies (see Section VII). Thirdly, IoT is applied for controlling the SG through application interfaces.

IoT sensing devices are generally comprised of wireless sensors, RFID, M2M (machine-to-machine) devices, cameras, infrared sensors, laser scanners, GPSs and various data collection devices. The information sensing in an SG can be highly supported and improved by IoT technology. The IoT technology also plays an essential role in the infrastructure deployment of data sensing and transmission for the SG, assisting in network construction, operation, safety management, maintenance, security monitoring, information collection, measurement, user interaction etc. Moreover, the
IoT also enables the integration of information flow, power flow and distribution flow in a SG [50], [51]. Additionally, existing SG architectures mainly focus on the needs of power distributors to manage the complete power grid [52]. The consumers are accessed with a network of smart meters by means of General Packet Radio Service (GPRS) or other mobile networks. The new reality where consumers may already have other smart home infrastructures (such as WiFi) has not yet been incorporated in the network communications of existing SG architectures [53], [54]. While some architectures do consider existing smart home infrastructures, they are not designed for scalability in large deployments [55], [56]. The protocols specific to IoT and SG systems therefore cannot be directly applied to IoT-aided SG systems, as they only consider the individual characteristics of either the IoT or the SG systems, which is not sufficient for an integrated IoT-aided SG system.

A SG is comprised of four main subsystems, power generation, power transmission, power distribution and power utilization. IoT can be applied to all these subsystems and appears as a promising solution for enhancing them, making the IoT a key element for SG. In the area of power generation, the IoT can be used for the monitoring and controlling of energy consumption, units, equipment, gas emissions and pollutants discharge, power use/production prediction, energy storage and power connection, as well as for managing distributed power plans, pumped storage, wind power, biomass power and photo-voltaic power plants [57]–[59]. In the area of power transmission, the IoT can be used for the monitoring and control of transmission lines and substations, as well as for transmission tower protection [57], [58]. In the area of power distribution, IoT can be used for distributed automation, as well as in the management of operations and equipment. In the area of power utilization, the IoT can be used for smart homes, automatic meter reading, electric vehicle charging and discharging, for collecting information about home appliances’ energy consumption, power load controlling, energy efficiency monitoring and management, power demand management and multi network consumption [57], [58]. Figure 3 presents the existing (see Section III) and potential applications of IoT-aided SG systems.

In the rest of this section, we describe the suitability of IoT technology and preferred communication technologies for various functions of the three SG layers, i.e., for HAN, NAN and WAN.

1) Home Area Networks (HANs): HANs may have either a star topology or a mesh topology. The preferred communication technologies for HANs are powerline communications (wired technology), ZigBee, Bluetooth and WiFi (wireless technologies). A HAN is comprised of a variety of IoT smart devices, such as a home gateway, smart meters, sensor and actuator nodes, smart home appliances and electric vehicles. A home gateway connects to smart meters and periodically collects power consumption data of the home appliances.

HANs perform two-fold functions, commissioning and control. The commissioning function identifies new devices and manages the devices. The control function enables communication among smart devices by establishing the links and performs reliable operation for the various SG layers. A HAN uses two-way communications for demand response management services [60]–[62]. In the forward communication direction, the smart meters’ load and real-time power consumption information of the home equipment, connected to IoT smart devices, are collected by home gateways and transmitted from the consumer side (the HAN) to the NAN to be forwarded to a utility center. In the backward communication direction, the home gateway acts as a central node and receives dynamic electricity pricing information from the NAN, which is then provided to smart meters or IoT smart devices for triggering the required action for home appliances.

2) Neighbor Area Networks (NANs): The communication technologies for NANs need to cover a radius of a thousand meters. The communication channels between smart meters and data aggregation points therefore must be interference free [63]. A gateway in the NAN collects consumers’ energy consumption data from smart meters in HANs and transmits the collected data to the utility companies through either private or public WANs. Basically, the topology of a NAN is comprised of two types of gateways, NAN gateways and HAN gateways. A NAN gateway connects various HAN
Fig. 3. Existing and potential applications of IoT-aided SG systems classified into WAN, NAN and HAN. These are further classified into subsystems, i.e., power generation, transmission, distribution and utilization. The blue (shaded) boxes represent existing applications while the white (empty) boxes represent potential applications. The existing applications are discussed in Section III.

gateways and serves as an access point to provide a single hop connection to HAN gateways in a hybrid access manner. The HAN gateways transmit their energy consumption data to NAN gateways through either wired (e.g., PLC, DSL) or wireless (e.g., cellular, mobile broadband wireless access or digital microwave technology) communication technologies.

3) Wide Area Networks (WANs): The WAN is the backbone for communication between network gateways, NANs, distributed grid devices, utility control centers and substations. It is comprised of two interconnected networks, core networks and backhaul networks. The core network provides communication to utility control centers with low latency and high data rate through fiber optics or cellular communications. The backhaul networks provide broadband connections and monitoring devices to NANs through wired (e.g., optical networks, DSL), wireless (e.g., cellular network, mobile broadband wireless access) or hybrid fiber-wireless networks.

D. Standardization Activities for IoT-aided SG systems

For the practical realization of technologies, standardization activities play an important role. Though efforts have taken place on both IoT and SG systems from the perspective of standardization at the individual level, there is still a need to put joint efforts towards standardization of IoT-aided SG systems. Below, we summarize standardization activities in IoT and SG systems.

1) Standardization Activities in IoT: In IoT, several standardization activities are going on. A very detailed discussion on standardization activities from the perspective of IoT and different standardization bodies can be found in [26], [64]. The oneM2M [65], [66] is standard for M2M and IoT, which is widely adopted. OMA LWM2M (Lightweight M2M) [67] is another standard for IoT which is gaining popularity due to its greater simplicity. Additionally, the Internet Engineering Task Force (IETF) has developed a set of protocols and standards for connecting the IoT devices to the Internet [27]. For instance, the Routing Protocol for Low Power and Lossy Networks (RPL) and the Constrained Application Protocol (CoAP) are examples of two protocols developed by IETF to connect lower power devices to the Internet. Machine-to-Machine (M2M) communication is an enabling technology for IoT. M2M-based communication networks and their protocol stack is discussed in [68], wherein authors briefly discuss protocol layers and standardization efforts to connect M2M devices to the Internet. A security protocol is key requirement for the successful operation of IoT. In this regard, IETE’s DICE working group (WG) has put some effort to define and adapt the Datagram Transport Layer Security (DTLS) protocol [69].

2) Standardization Activities in SG: In SG, there are several worldwide standardization efforts. IEEE, ANSI, NIST, and IETF are the key organizations which are involved in the standardization process of SG systems. In Europe, various Expert Groups have been established which look at the standardization efforts. Besides this, the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC), and the European Telecommunications Standards Institute have been working jointly to solve issues raised in the deployment of SG [29], [70], [71]. IEEE-SA has been closely working on SG systems and in this regard, the IEEE P2030 standard has been proposed, which deals with the interoperability issues of different power systems. Another effort by IEEE is the approval of IEEE’s 1547 standard which deals with the interconnection of distributed energy resources. To deal with the challenges
of NAN communications, the IEEE 802.15.4g standard was introduced. This standard deals with the physical layer issues associated with NAN communications [72]. The IEEE P1901 working group is developing standards for multimedia communication in cognitive radio-based SG systems [73].

In summary, there are still many issues which need to be addressed by the standardization community to deal with interoperability issues of IoT-aided SG systems.

III. EXISTING APPLICATIONS OF IoT-AIDED SG SYSTEMS

There are many existing applications of IoT-aided SG systems, and many more have been proposed, as represented in Figure 3. Table II presents the work done on the applications of IoT-aided SG systems. In this section, we discuss existing applications of IoT-aided SG systems in the literature [50], [74]–[85].

A. HAN Applications

1) Smart Home: IoT technology plays a major role in the SG for the realization of smart homes and appliances [76], [86], [87], such as smart TVs, home security systems, smart refrigerators, washing machines, fire detection, lighting control and temperature monitoring. The smart home includes sensor and actuator nodes for environmental monitoring that transmit the surveillance data to the home’s control unit [77]. The control unit enables users to monitor and control the appliances remotely from anywhere and at any time. The smart home is thus a key element of the SG to realize real-time interaction between users and the grid, improve the quality of services and enhance the capacity of integrated grid services, as well as to fulfill users’ energy demands in a most efficient possible way. Optimizing daily power consumption makes broad use of smart home services. For instance, users can turn on heaters or air conditioners before coming home in order to enjoy their desired environment without waiting. Additionally, users can switch on their power-intensive electrical appliances, such as their washing machine, in the middle of the night when the electricity price is lower. The control unit also uses surveillance data to detect suspicious activities and inform users to take appropriate actions. All these functions can only be realized, thanks to the IoT technology. Viswanath et al. [88] have designed a system and developed a testbed for smart home with a house having one living and three bedrooms that can accommodate six to nine persons. This system controls the energy based on dynamic pricing and performs as an energy management system. Hence, it avoids home appliances usage during the peak hours. The authors developed an Android application for allowing remote access to consumers as well. Additionally, Shah et al. [89] proposed a model for security enhancement in smart home by implementing Reed Solomon Codes for error detection and correction.

The IoT is applied to various aspects of the SG in smart homes, for instance, in a smart home’s sensor LAN protocol to control smart appliances, multi-meter reading, information gathering of power consumption (including electricity, water and gas), load monitoring and control and user interaction with smart appliances. IoT technology also provides its services to NANs, linking a group of smart homes in a neighborhood through a NAN to form a smart community [78]. Smart homes in the smart community can thus share the results of outdoor surveillance cameras to detect any accident or suspicious activity and inform the appropriate emergency centers and police stations autonomously. The concept of the smart community could be extended to form a smart city. Similarly, a comprehensive surveillance system could be developed in a smart city to monitor various activities within an entire city or even a country. Some IoT requirements and considerations for smart buildings are discussed in [90] for building management systems and energy optimization.

2) Information Management System for Electric Vehicles: Electric Vehicles (EVs) provide an eco-friendly transportation option by reducing carbon dioxide emissions [50], [91]. This is an interesting opportunity for IoT aided SG systems. The charging system for EV is composed of a power supply system, charging equipment and a monitoring system. The power supply system is responsible for the output and management of electricity. The charging equipment charges and discharges the EVs, and includes both AC and DC chargers. AC chargers provide slow charging and are generally implemented in home. Rapid EV charging requires DC chargers, generally implemented at public charging stations. Both types of chargers also include a billing function. The monitoring system is responsible for real-time monitoring of the charging system and its security. IoT technology plays a leading role in this monitoring system, providing an information management system that integrates different components of the charging system [50]. For instance, the IoT technology enables the power supply and real-time monitoring systems to send their information to the information management system, which in turns passes information to the control station, so that necessary actions can be taken. EVs are equipped with GPS, which let the IoT to help drivers to manage their batteries more efficiently by locating the nearest, most suitable charging station with the shortest waiting time, as well as providing traffic and parking information [50].

3) Automatic Meter Reading: Traditionally, power consumption information was collected manually on site at specific time intervals. This practice inevitably led to inadequacies in terms of accuracy and timeliness. IoT enables Automatic Metering Infrastructure (AMI) [92] or remote meter reading systems based on WSN, PLC and Optical PLC (OPLC) by using public or private communication networks. An AMI system is one of the most important functions of the SG, collecting the real-time electricity consumption data with high reliability, processing this information and hence providing real-time monitoring, statistics and power consumption analysis. The importance of this system lies in the timeliness, efficiency and accuracy in the power consumption data. By using this system, IoT technology could help users to save money by adjusting their electricity usage behavior based on the analysis of their power consumption [75].

4) Integration of Distributed Energy Resources (DERs): Renewable energy generators, such as solar cells, photovoltaic cells and wind turbines, are progressively integrated into
today’s power grid. They have recently attracted considerable attention in SG studies due to climate changes and environmental pressures. Renewable energy has a positive impact on the global environment by generating electricity without carbon emissions [79]. Reducing or holding back the annual increase in greenhouse gas emissions contributes to limiting the Earth’s increasing temperature. In the past few years, governments and organizations have installed a substantial number of solar cells and wind turbines to satisfy part of their power requirements [77]. Power generation patterns of renewable energy sources (solar and wind), which are distributed over the grid, are intermittent in nature and dependent on location and climate, so they pose significant challenges for the predictability and reliability of the power supply. Such problems are addressed using the seamless interoperability and connectivity provided by the IoT technology. Furthermore, the IoT technology uses sensors to collect real-time weather information which helps in forecasting energy availability in the near future. A Kalman Filter-based state estimation and discrete-time linear quadratic regulation method for controlling the state deviations is proposed in [80], utilizing IoT aided SG systems. It uses IoT technology and WSNs to sense, estimate and control the states of DERs. Furthermore, a web of things-based SG architecture is proposed in [85] for the remote monitoring and controlling of renewable energy sources.

5) Power Demand Management: Power demand management, also known as demand-side energy management, is defined as the change in the energy consumption profiles of consumers according to the time-varying electricity prices from utility companies [81], [82]. It is used to minimize the consumer’s electricity bill, and to reduce the operational cost of the power grid and energy losses, as well as to shift the demand load from peak times [83]. IoT devices collect the energy consumption requirements of various home appliances and transmit them to the home control units. Subsequently, the SG control unit schedules the energy consumption of home appliances based on the users’ defined preferences so that each consumer’s electricity bill is minimized. Demand-side energy management can be performed at different levels of the SG. For instance, it can be performed at a home-level to maintain consumers’ privacy. It can also be performed at higher levels to not only benefit the consumers but also the utility companies by generating a more effective scheduling plan [84].

B. NAN Applications

1) Smart Distribution: Smart distribution is based on advanced automated IoT technology and is one of the important component of SG [93]. It is the component that is directly connected to users in smart grid. Smart distribution grid consists of communication system, power distribution remote unit, master unit and station unit [93]. With the help of IoT technology, the smart distribution grid can immediately identify the faults in case of any disorder and can overcome the fault instantly. IoT technology helps smart distribution grid by providing various types of sensors for collecting data about temperature, humidity, noise etc. which ensures monitoring and secure operation of distribution grid [94]. The first demonstration of smart distribution by using IoT technology in distribution network of smart grid was performed in Henan Hebi IoT demonstration project in Hebi, China [94]. It uses temperature, noise and tower tilt sensors, as well as ZigBee, GPRS, 3G and power fiber. It realizes online monitoring, online inspection and life cycle management. This project was performed using 10 kV underground and overhead laying mixed line which covers 45 utility distribution transformers, 68 units of surge arresters, circuit breakers on 20 pillars, a ring counter, and four cable branch box. Readers are referred to [94] for detailed description and results of this project.

2) Smart Patrol: The patrolling of power generation, transmission and distribution used to be mainly a manual task, performed regularly at specific time intervals. However, due to climate conditions and both human and environmental factors, the quality and quantity of patrolling is not always as desired. Furthermore, it is usually not easy for power workers to patrol unattended substation equipment. The IoT technology offers a promising solution to this problem by introducing Smart patrol [50]. Smart patrol is comprised of WSN and RFID tags which are connected to the power substation with the help of IoT technology, and are used to locate the power equipment in order to improve the quality of patrolling, as well as to enhance the stability, efficiency and reliability of a power system and its supply. Smart patrol can be used for a number of applications, such as patrol staff positioning, equipment status reports, environment monitoring, state maintenance and standard operations guidance [50].

C. WAN Applications

1) Transmission Tower Protection: An integral part of power transmission, the transmission tower protection is a WAN application of IoT-aided SG systems, developed to enhance the safety of transmission towers from physical damage by plundering of components, natural disasters, unsafe construction and growing trees under the foundations [74]. Burglary and intentional damage by people are the major

| Applications | References | SG Area | SG Sub-Area |
|--------------|------------|---------|-------------|
| Transmission Tower Protection | [74] | WAN | Power Transmission |
| Monitoring of Power Transmission Lines | [75] | WAN | Power Transmission |
| Smart Patrol | [50] | NAN | Power Distribution |
| Smart Home | [50], [78] | HAN | Power Consumption |
| Information Management Systems for EVs | [50] | HAN | Power Consumption |
| Automatic Meter Reading | [75] | HAN | Power Consumption |
| Distributed Energy Resources | [77], [79], [80] | HAN | Power Consumption |
| Power Demand Management | [81]–[84] | HAN | Power Consumption |
causes of transmission tower damage. Natural disasters, such as typhoons, strong thunderstorms and global warming affects also can cause transmission towers to collapse. Additionally, key infrastructure projects, such as highways and high speed railways, are often constructed near the transmission towers and must sometimes cross high voltage transmission lines. Often the construction companies are not fully aware of the risks involved in operating near high voltage transmission towers. They use a number of large construction machines which not only pose serious dangers to their crew, but can also damage transmission lines and towers. Such construction contractors sometimes do not inform the relevant power transmission departments which makes it impossible for power transmission employees to inspect and monitor all the power transmission facilities, which could lead to risks to transmission towers.

Currently, the main method of transmission towers protection is manual patrol by the staff. However, regular manual patrol of high voltage transmission lines and towers by staff is very difficult due to manpower realities, divisions of responsibility and the level of knowledge of the staff. Furthermore, some transmission towers are difficult to approach due to their physical positioning. Hence, the patrolling quality cannot be guaranteed. The patrolling period varies from 1-10 weeks, which means insufficient monitoring and higher security risks. While it is true that some equipment, such as cameras and infrared alarms, are installed on transmission towers to monitor burglary and other potential damage, the accuracy and stability of this equipment is not yet satisfactory [74].

With the help of WSNs, IoT technology can provide remote monitoring in addressing these security threats. The IoT-aided transmission tower protection system contains various sensors which generate early warnings of threats to high voltage transmission towers, enabling quick responses. The sensors include vibration sensors, anti-theft bolts, a leaning sensor and a video camera. These sensors and the sink node form a WSN [74]. The sensors detect any threat, and send the relevant signals to the sink node. The sink node receives these signals from the sensors, processes them into data and transmits the data to the monitoring center through the Internet or any other public/private communication network.

The sensors’ deployment is presented in Figure 4 and is as follows. The anti-theft bolts are deployed on the lower part of the tower. One vibration sensor is deployed underground in the base of the transmission tower and the other is deployed on the tower, about 3-5 meters above the ground. The leaning sensor is deployed close to the vibration sensor on the tower. The camera is installed on the tower about 6-8 meters high, directed towards the transmission line. Finally, the sink node is deployed in the middle of the transmission tower.

The vibration sensors monitor the vibration signals of the ground and tower. When they detect signals that indicate excavation construction close to the transmission tower, they transmit those signals to the sink node. The vibration sensor on the tower, the leaning sensor and the anti-theft bolts can detect the signals of a burglary or vandalism in progress, and subsequently transmit those signals immediately to the sink node. In both cases, the sink node combines and processes the signals, and triggers the video cameras to send real-time images to the sink if the threat is identified. For huge construction machinery and trees that get too close to the transmission lines, the video cameras directed towards the transmission lines identify the threat and transmit real-time images to the sink. In all of the threat cases, the sink generates an alarm and forwards the images to the monitoring center through the Internet. The monitoring center handles the real-time data of a series of transmission towers. The alarm signal and images from the sink inform the monitoring center staff about any threat to a transmission tower and the staff then takes appropriate actions to handle such threats.

2) Online Monitoring of Power Transmission Lines: The online monitoring of power transmission lines is one of the most important applications of the IoT in the SG, specifically for disaster prevention and mitigation. In recent years, natural disasters have highlighted the challenges of security, reliability and stability inherent to high voltage power transmission lines. Traditionally, high voltage transmission line monitoring has been performed manually. Sensors measuring conductor galloping, wind vibration, conductor temperature, micro-meteorology and icing can now be used to achieve real-time online monitoring of power transmission lines [75]. This new online power transmission line monitoring system is comprised of two parts. In the first part, the sensors are installed on the power transmission lines between transmission towers to monitor the states of power transmission lines. The second part has sensors installed on the transmission towers in order to monitor their states and their environmental parameters. IoT enables the communication between the power transmission line sensors and the transmission tower sensors.

D. Summary and Insights

We have comprehensively surveyed the existing applications of IoT-aided SG systems. While there could be many applications of IoT-aided SG systems, as presented in Figure 3, to date there is very little work on these applications. Some applications of IoT-aided SG systems are already deployed, but many more are yet to materialize, when the full capabilities of instantaneous knowledge and massive data processing are exploited. Applications today tackle several areas of interest, such as:

- Surveillance of premises or of power equipment installations (towers and power transmission lines);
- Adjusting home consumption by dynamic scheduling, which takes advantage of fluctuating pricing;
- Meter reading and consumption monitoring, residential and commercial;
- Electric Vehicle charging and parking;
- Power demand and supply management, including integrated renewable energy sources; and
- Maintenance of power supply systems, by detecting line faults and failures.

This survey reveals that there is little literature on the application of IoT-aided SG systems in the area of power generation, transmission and utilization. The potential of renewable energy may depend, for example, on IoT-based prediction of weather conditions that can regulate energy flow
IV. Architectures for IoT-aided SG Systems

A number of architectures are available for IoT-aided SG systems. We survey such architectures in this section, and their classification is represented in Figure 10.

A. Three-layered Architecture

A three-layered architecture for IoT-aided SG systems, based on the characteristics of the IoT, has been widely used in the literature and it has been proposed in [45], [46], [50], [75], [95]–[97]. As presented in Figure 5, this architecture is comprised of three layers, a perception layer, a network layer, and an application layer.

1) Perception Layer: This layer enables the main objectives of sensing and collecting information in IoT-aided SG systems using a variety of devices. It is comprised of various kinds of IoT sensing devices, such as RFID tags, cameras, WSN, GPS and M2M devices, in order to collect data in a SG. It is categorized into two sub-layers, a perception control sub-layer and a communication extension sub-layer. The perception control sub-layer realizes the perception of the physical world by processing IoT devices, information acquisition, monitoring and control, while the communication extension sub-layer has a communication module which connects IoT devices with the network layer.

2) Network Layer: The network layer is comprised of the converged network formed by various telecommunication networks and the Internet [96]. Its function is to map the information collected by the IoT devices in the perception layer to the telecommunication protocols [95]. Subsequently, it transmits the mapped data to the application layer through the relevant telecommunication network. The core network, i.e., the Internet is responsible for the routing, information transmission, and control. The access network will be based on other telecommunication networks. The IoT management and information centers also belong to the network layer. The network layer can rely on public as well as on industry-specific communication networks.

3) Application Layer: The application layer is the integration of IoT technology and industry expertise for the realization of a broad set of IoT-aided SG applications [96]. Its function is to process the information received from the network layer, and based on this information, it monitors and troubleshoots the IoT devices and SG environment in real-time. It provides various applications of IoT-aided SG systems which are presented in Figure 3. It is comprised of application infrastructure/middleware and various types of servers related to content, web services and directory services. The application infrastructure/middleware provides computing, processing and resources for IoT technology. The key elements provided by the application layer are information sharing and security. The application layer is set to grow, especially for SGs that can provide much richer data sets. In turns, these applications dictate what data is required, at what time intervals, from the sensors.

B. Four-layered Architecture

A four-layered architecture for IoT-aided SG systems based on the characteristics of SG information and communication systems was proposed in [58]. As presented in Figure 6, this architecture is comprised of a terminal layer, a field network
layer, a remote communication layer and a master station system layer. According to the three-layered IoT hierarchical model, the terminal and field network layers in this architecture correspond to the IoT perception layer, the remote communication layer corresponds to the IoT network layer, and the master station system layer corresponds to the IoT application layer.

The terminal layer is comprised of IoT devices deployed in various SG functions, such as power generation, transmission, distribution and utilization. The IoT devices include remote terminal units, information collection devices, smart meters, smart devices and intelligent electronic devices. This layer collects information from IoT devices and transmits the collected data to a field network layer. The field network layer can be wired or wireless. Depending on the type of IoT devices, the appropriate communication network is used. As an example, ZigBee is used by sensor nodes in order to transmit the collected data to a remote communication network layer.

The remote communication network layer can also be wired or wireless. It is comprised of various communication networks which provide connectivity to the Internet, such as 2G, 3G, and LTE as wireless networks, and optical networks as a wired network. This layer serves as a middleware between IoT devices and the master station system layer. The master station system layer is the control and information system of a SG. It controls and manages all the SG functions. It can also be considered as an interface to the IoT-aided SG applications.

### C. Energy Efficient Architecture

Improving a building’s energy efficiency is an important aspect of the SG, an aspect that is required for global sustainability. Thus, smart energy is an important research area of the IoT. In the United States, buildings are responsible for around 71% of the total electrical energy consumption [98], a major motivation for designing green buildings to be energy efficient. However, thus far, such green buildings have not been as energy efficient as expected [99]. This may be due to the ill-fitting of rigid and static schedules to the lifestyle of consumers, or to the unpredictability of business requirements. Now, with the help of IoT technology, the ability to change energy settings can be entrusted to the users, using their smartphones or PCs. This allows users to suit their own schedules at will, and respond to events instantaneously by adjusting the policies as and when necessary. In 2015, an energy efficient location-based automated energy control IoT framework was proposed, using smartphones and cloud computing technologies [99]. That proposed framework changes the currently static energy management and centralized control modes to dynamic and distributed energy control at the consumer-side SG, which is composed of usually various buildings.

This framework is represented in Figure 7 and is comprised of four main components, (i) multi-source energy saving policies, (ii) monitoring and control via mobile devices, (iii) location-based automatic control, and (iv) a cloud computing platform for data storage and computation. An organization’s premise consists of various parts, such as a campus, buildings, departments, labs and rooms/offices, each with different energy requirements and policies that are important to take...
into account while managing energy consumption. Even in a single home, each family member has his/her own energy consumption preference which needs to be considered. Hence, this framework has a tree-like structure control plane as presented in Figure 7, comprised of several layers of energy saving policies at different levels (e.g., building, department, lab and room).

Smartphones are equipped with multiple networking interfaces, such as Wireless Fidelity (WiFi), 3G, Long Term Evolution (LTE), bluetooth and WiMAX, as well as GPS, which helps to obtain precise location positioning. Thanks to the global Internet access, smartphones are the ideal choice for monitoring and controlling energy control systems remotely from any place at any time. After an initial authentication and authorization, consumers can dynamically modify their energy saving policies through their smartphones by interacting with the policy servers of their home and their office buildings. The consumer can be connected to the Internet through smartphones, tablets, or laptops with WiFi or with 3G networks.

Furthermore, the location information of smartphones is used in designing automatic control policies which can switch energy consuming devices ON or OFF in homes and office buildings by detecting the location and direction of user movements. These dynamic adjustment policies also enable the coordination between buildings’ policies. For example, as presented in Figure 7, when a user has moved out of a predefined distance range from the home premises and is moving into a predefined distance range of an office building, a message will be sent to the policy server to trigger the policy control process, e.g., start the heating. The now deserted home will transit into an energy saving mode while the office building will start the processes based on the user’s preferences, such as cooling/heating to the user’s desired temperature.

Finally, this framework uses the cloud computing platform for data storage and modeling computation and analysis. The cloud provides the basic data storage and retrieval services for each building’s energy consumption data. Most of the computation-intensive modeling and analysis jobs are performed in the cloud. Moreover, the cloud provides security, reliability and configurability for the network communication between the cloud and the user. The cloud has an application layer which contains a user friendly web interface for managing the buildings’ energy systems, so that a remote user can easily configure and manage the system.

D. Web-enabled SG Architecture

An architecture for IoT-aided SG systems is proposed in [85] based on the web of things (Figure 8). The web of things is comprised of a number of web services provided on top of the IoT devices in which the web browser acts as an interface to these web services. There are two types of energy sources, non-renewable and renewable energy sources. Non-renewable energy sources include thermal power plants (combusting coal or oil) that release carbon emissions to the environment, as well as nuclear power plants. The renewable energy sources are environmentally friendly and are comprised of hydropower, wind farms, solar, biogas plants and biofuel sources, as well as geothermal and tidal/wave sources.

The energy sources in this architecture are connected to individual digital energy meters. These digital energy meters are responsible for collecting household energy consumption data. The meter readings from energy meters of non-renewable and renewable sources are collected by separate IoT gateways which communicate regularly with these meters. The collected data from IoT gateways are updated to the server periodically, and the server provides web services on top of these IoT devices. These web services include the locations of houses connected through the SG, and the meter information. Moreover, for each home, the scheduling of power sources and the controlling of the energy sources by switching the source controllers remotely through IoT devices are provided as web services. Through the Internet, by connecting to any device, a user can access these services. The energy sources for each household are switched through source changers which are controlled through IoT devices; these IoT devices switch the energy sources upon receiving instruction from the user via the server.

E. Last-meter SG Architecture

The last-meter SG is a part of the SG that is closer to the home, i.e., the part with which the consumers interact. An architecture for the last meter SG embedded in the IoT is proposed in [100], [101] and is presented in Figure 9. This architecture is comprised of three main components, sensor and actuator networks, an IoT server and user interfaces.
1) Sensor and Actuator Networks for Various SG applications: The sensor and actuator networks enable the realization of various SG applications and contain two main components: sensor and actuator nodes, and IP gateways.

a) Sensor and actuator nodes: The sensor and actuator nodes can be part of wired or wireless networks. This architecture can accommodate heterogeneous sensor networks, as the data management unit in the IoT server translates information into the format required by the SG database. The bi-directional node communication enables an IoT server to configure, program and interrogate the sensor and actuator nodes. This architecture supports the possibility of adding or removing network components in real time, even if specific node characteristics depend upon the network implementation. Hence, any node can join the network without changing the network implementation and the newly added node is automatically identified and accessible from the network administration interface for registration and configuration.

Each sensor and actuator node has to be uniquely identified in order to ensure global accessibility. However, the node addresses in sensor and actuator networks are generally only unique within a single network and may change over time. Therefore, the IoT server assigns a unique ID to each node of the network and maintains the mapping of each ID and its corresponding network address, provided by the local network coordinator. Subsequently, when a node sends a message to the IoT server, the gateway node translates its network address into a unique ID, and vice versa.

b) IP gateway: The IP gateway connects sensor and actuator nodes to the IoT server via an IP link if there is no IP capability. For uplink communication, the gateway collects data from sensor/actuator nodes, performs encapsulation/reformatting (if required) and forwards the data to the message dispatcher in the IoT server over a secure TCP/IP link. For downlink communication, it forwards the commands received from the IoT server to the intended receiver nodes. In general, the gateway performs a conversion of data into a universal format. However in this architecture, such conversion is performed by the IoT server, and therefore the gateway sends the messages over a TCP/IP link in the native format. This procedure has two main advantages. Firstly, the gateway will have low computational complexity and hardware requirements. It only has to ensure an IP connection, encapsulate the messages into TCP/IP packets and ensure the security level required by specific applications. Secondly, new functionalities and applications can be developed and added without modifying the gateway.

2) IoT Server: The IoT server has four main components: the first one is a message dispatcher, the second one is a data management unit and database storage, the third one is a configurator unit and database, while the fourth one is a secure access manager and user database.

a) Message dispatcher: To perform bi-directional communication between each gateway and the rest of the system,
the message dispatcher will be used. The message dispatcher will listen to new connections from IP nodes that want to join the system for uplink communication. It decrypts incoming packets for every connection and forwards them to the data management unit for storage and interpretation. For downlink communication, it encrypts the messages from the configurator unit into a TCP message and then forwards them to the destination gateway.

b) Data management unit and database storage: The data management unit is a collection of software modules. In this unit, each software module is able to manage the messages of a specific sensor/actuator network. These modules receive messages in their native format and then extract their payload. Two storing mechanisms are performed based on the payload. Firstly, the messages are stored in a unique format in the SG database if the payload contains either measurement data from a sensor node or a notification from an actuator node. Secondly, the message is stored in the original format into the configurator database if the payload contains specific network messages (such as configuration, management information, a node address or a communication channel).

The SG database decouples the data collection from the data processing and visualization so that the users do not have to interrogate the nodes directly. The decoupling allows the nodes to stay in sleep mode most of the time and to only wake up periodically to receive commands and configuration messages, as well as to send measurement and status data. This approach is very useful when the sensor networks are heterogeneous, as well as when nodes are battery powered. The sensors’ data in a SG database is represented by a unique format that is associated with the physical nodes through the unique node ID, independent of the local sensor network protocol. In this manner, data can be processed and visualized independently of the characteristics of the physical source.

c) Configurator unit and database: The configurator unit is a collection of software modules, where each module is dedicated to a specific type of sensor/actuator network. This unit configures the nodes and networks according to the inputs from applications and users, as well as according to the stored system status in the configurator database.

d) Secure access manager and user database: This component coordinates all the communication between the end users and the IoT server by ensuring privacy and data protection. It only allows authorized users and third-party applications to access the stored information and the network configuration based on the user database, and the users’ access permission for each resource. The network owners have administrative privileges over their networks by default.

3) User interfaces: The user interfaces allow users, application developers and service providers to interact with an IoT server. The user interfaces offer different functionalities to standard and administrative users. Standard users can only access the energy consumption data pertaining to their own households. Administrative users, meanwhile, have higher access privileges and they can also view the configuration and status of the IoT devices, and configure them dynamically. The user interface is divided into three main components: a visualization interface, a configuration interface and a web service API.

a) Visualization interface: It displays the current and past information of household energy consumption. Additionally, it allows authorized users to send commands to actuator nodes attached to home appliances.

b) Configuration interface: It enables the users to remotely manage and configure their networks. Additionally, users can set the data visibility of their household appliances as well as third-party applications access. This interface also allows administrators to remotely register new gateways and configure new network connections. To establish a new connection, each gateway requires the IP address and network name of the message dispatcher, the port number on which the message dispatcher can accept the connections and the network AES security key.

c) Web service API: It opens the platform (IoT server) to service providers and new client applications. APIs offer an easy and unified way to retrieve information collected from heterogeneous sources. Utilities, service providers and third-parties use web service APIs to obtain single, multiple or aggregated measurement data, as well as to notify consumers about dynamic changes in tariffs, of weather related data and alarms. For security and privacy purposes, only registered users and authorized third-party applications can access energy consumption data from an SG database through web service APIs.

F. Summary and Insights

We have surveyed the existing architectures for IoT-aided SG systems. As presented in Figure 10, the major focus of the existing studies is either generic layered architectures or the HAN architectures specifically for controlling and managing home appliances remotely. However, the layered architectures (three-layered and four-layered) are very generic architectures and they do not cover many specific aspects of SG, such as all the networks (HAN, NAN and WAN) and systems (power generation, transmission, distribution and consumption). Hence, it is very important to consider these specific aspects in an architecture for IoT-aided SG systems. Additionally, four-layered architecture is an extension of three-layered architecture by dividing the network layer into field network layer and remote communication network layer. It is very important to analyze why there is a need of four-layered architecture and why we should not have five-layered or six-layered architectures.

The other three architectures (energy efficient, last meter SG and web-enabled SG) are mainly designed for HAN. The energy efficient architecture saves energy by using smart location-based automated energy control framework, the last-meter SG architecture aims at automating the HAN of SG using IoT technology and the web-enabled SG architecture also connects HAN to the web by offering a number of web services on the top of IoT devices. However, these current studies on architectures for IoT-aided SG systems are very limited; there are still no architectures for NAN and WAN of IoT-aided SG systems, and other areas of HAN are also yet lacking architectures. Hence, we strongly recommend future developments in this area.
research on architectures for NAN, WAN and the other HAN areas, which should focus on the individual characteristics and requirements of HANs, NANs and WANs. Subsequently, the individual architectures for HAN, NAN and WAN will need to be combined as a whole for the realization of complete IoT-aided SG systems. Since, IoT and non-IoT communication technologies play a vital role in the realization of IoT-aided SG systems in order to provide connectivity, it is very important to consider communication technologies and topologies in the overall architectures for IoT-aided SG systems.

V. PROTOTYPES FOR IOT-AIDED SG SYSTEMS

Prototypes play an important role in the development of a system in order to test various functions and verify the operation before the actual commercial implementation. Some prototypes have been developed for IoT-aided SG systems as well, however they are very few and there is a need to develop more prototypes for IoT-aided SG systems. In this section, we discuss the existing prototypes of IoT-aided SG systems.

A. A Simple Prototype for Energy Efficiency

A simple prototype for smart energy involving one user was designed in a Leadership in Energy and Environmental Design (LEED)-gold-certificated green office building. It linked electrical appliances in two locations, an apartment and an office in an office building [99]. This prototype is a simplified scenario of the framework presented in Figure 7. The objective of this prototype was to enable a user to dynamically control and manage appliances in two locations. The prototype enables the server to trigger energy policy control process by turning electrical appliances ON or OFF in the two locations after detecting changes in the user’s location. This helps users to effortlessly implement and control their own energy policies in real time, making their energy consumption directly proportional to their actual utilization. Although this simple prototype only involves one user with control devices in two locations, this system could be easily scaled up with multiple users controlling their devices at different locations simultaneously.

Figure 11 presents the structure of this prototype. The hardware includes Kill-A-Watt electric meters [102], WeMo controllers [103], WiFi routers, one server in each location, and smart devices with location sensors that have a GlobalSat GPS module. This prototype requires two software packages. One package handles the data recording of GPS locations and sends that information to the server in National Marine Electronics Association (NMEA) 0183 compliant format. The other package is a configuration and management software for WiFi routers that provides a port mapping service for accessing the server from outside the Network Address Translation (NAT). The server executes Python codes programmed with Common Gateway Interface (CGI) scripts to control the WeMo devices through the Universal Plug and Play (UPnP) protocol. The smart device is able to control the electrical appliances in both locations through the inter-operation of hardware and software.

In this prototype, a smart mobile device (smartphone, tablet or laptop), with a location sensor, sends its location at predefined intervals to two servers in two locations (i.e., the apartment and the office room). The servers inside the NAT or firewall are accessed from outside by means of port mapping technology. The servers calculate the distance of the mobile device from themselves, and if the distance is
within the predefined threshold, they trigger the energy policy control process that instructs the controller to turn the electrical appliances ON or OFF in the two locations according to predefined energy policies. This simple example of automation demonstrates the ambition to move from explicit (but hit-or-miss) user actions to intuitive and sensor-based activation that are more reliable. Further sensing (e.g., weather) and other data (calendrical, habitual behavior) can be combined to refine the automatic activation control.

B. Integration of Renewable and Non-renewable energy Sources at Home

A prototype for integrating renewable and non-renewable energy sources at home using IoT is presented in [85]. This prototype is designed for the HAN architecture presented in Figure 8. The electric meters are connected to non-renewable and renewable energy sources to record the current and voltage readings. This configuration has a direct connection to IoT embedded devices, and hence the IoT embedded devices change the energy source by controlling the source changers connected to the SG supplies of the houses. The web services allow consumers to track energy consumption on various scales, such as daily, weekly, monthly and yearly, as well as to compare the consumption data for different times, and thus enable consumers to configure and switch the scheduling of energy sources (e.g., non-renewable or renewable) in advance.

The consumer also has the ability to reconfigure the current energy source instantly in case of an emergency.

The pilot hardware and software components are as follows:

The hardware includes an ARM cortex M3 processor to design the IoT device. An LPC1768 processor from NXP [104] is used as the ARM processor, interfaced with an Ethernet port, an LCD and an RS232 port. CMSIS [105] is used as a real-time operating system for task optimization, and LwIP protocol stack is implemented to support TCP/IP functionality on the board. The ARM processor interfaces its Universal Asynchronous Serial Transmission (UART) port with MAX232 ICI in order to communicate with its RS232 port. However, the collected data from electric meters is in the form of RS485 port out. Hence, the output from RS232 is converted to RS485 for compatibility and the RS484 MODBUS protocols can then transmit serial data up to 1.2km.

Several electric meters can thus be accommodated by a single controller board through relay controllers (such as H-bridge drivers).

To incorporate the Internet with this prototype, an Ethernet port RJ45 is interfaced to the LPC1768 processor. The Internet connection is established with the help of the LwIP protocol suite in three steps. Firstly, initializing the Internet connection, i.e., mapping a MAC address to the IP address with access to the world wide web (www). Secondly, connecting to the Internet in order to transmit or to receive data. Thirdly, terminating the connection upon completion of a transmission or reception.

The software includes a Graphical User Interface (GUI) for accessing the web services and user account management. A consumer can access web services via the web browser (any sort) of any device connected to the Internet. A consumer initially registers himself, and after the required verification and authentication, the administrative staff adds the consumer's home to the system. Subsequently, the consumer can monitor his home's average power consumption, making it possible to keep track of energy consumption and plan the scheduling of power sources.

C. In-Home Appliance Monitoring Implementation

An in-home IoT-aided SG prototype is implemented in [100], [101] for the architecture presented in Figure 9. This prototype includes a ZigBee network connected to the IoT server through a ZigBee IP gateway. In order to collect the real-time energy consumption of home appliances, smart plugs are deployed between each home appliance and its wall socket to collect the loading information of the each home appliance.

The smart plug is also an actuator node that can turn the load ON and OFF, configured through the user interface.

The communication with the ZigBee network is provided through a Freescale MC13224 SoC. The board includes an ARM7 processor with 128KB of flash, 96KB of RAM and 80KB of ROM memory. For energy measurement, an analog device ADE7953 was used. Load control was implemented using a single-pole bistable 12V relay which can support up to 16A. The power supply unit in the board can supply 12V for the relay and 3V for the ADE7953 1C and MC13224 SoC.

BeeStack, a Freescale ZigBee stack, is used to implement the firmware, running on the smart plug.

Since the smart meter is a ZigBee device, a ZigBee/IP gateway is used for the communication with IoT server. The ZigBee/IP gateway is comprised of a micro controller, an Ethernet interface and a ZigBee RF transceiver. The Freescale Kinetis K60 is used as a micro controller which is based on an ARM Cortex M4 processor with hardware encryption. The message dispatcher is implemented as a multi process application on a Linux machine. It continuously listens to new connections from the gateways.

The data collection unit is implemented using CoMo software [106]. It is designed for fast prototyping of network data mining applications and it is used in large testbed deployments, e.g., PlanetLab [107]. Hence, it is scalable to very large systems with high data rates. The CoMo architecture provides an abstraction between the IoT server and the network interface. It follows a modular approach and it is comprised of several modules. Each CoMo module interprets the packets of a specific type of sensor network that belongs to the households and extracts data for inclusion in either the SG database or a configuration database. The configurator and user databases are implemented with MySQL. After the required authentication, the Tornado implements direct access to the home appliances data using HTTP.
The user interface is implemented as a web interface. The web interface, the secure access module and the configurator unit are based on open source non-blocking web servers, known as Tornado [108]. The graphical interface is based on Twitter Bootstrap [109]. The web interface mainly consists of five functionalities, home appliances’ energy consumption data visualization, registration and configuration of new networks, privileges management, registration of new sensors for home appliances, and sending commands. Firstly, the visualization of energy consumption of the home appliances provides a time range selector and a graph where energy consumption data is plotted as a function of time. The time option allows the desired measurement period to be selected. Secondly, there are dedicated web interfaces that administrators use to register and configure new networks. The network configuration is stored in the configurator database. Thirdly, the administrators can manage privileges by assigning or removing different privileges to different users and third-parties. These privileges include the modification of specific network options (such as the communication channel and the security level), as well as managing sensors’ visibility of home appliances and security. Fourthly, any unregistered home appliances that are sending data through a registered network or gateway are automatically detected by the system. The system then informs administrators about such home appliances, and they decide whether to register these new home appliances or not. Finally, authorized users send commands to the actuator nodes in home premises so that the required actions can be performed.

D. Summary and Insights

As presented in Figure 12, there are not many published prototypes in this area, and they tend to be very simple. For instance, the prototype for energy efficiency (see Section V-A) is a very simple prototype involving one user controlling home appliances in two locations (i.e., at their home and in an office building). Similarly, the integration of renewable and non-renewable energy sources prototype (see Section V-B) and in-home appliance monitoring prototype (see Section V-C) associate the home appliances with the web through web services. Consumers can access these web services through any browser and use them to control their home appliances, to track energy consumption and to switch the energy sources (e.g., renewable and non-renewable). More challenging prototypes would require cooperation of HAN, NAN and WAN, affecting the various subsystems (i.e., power generation, transmission, distribution and utilization) of SG. In addition, combining different IoT knowledge systems with different sensor input systems will yield further intelligent functionality than available today.

From this viewpoint of the prototype literature, it becomes apparent that there are no easily available open-source testbeds and simulation tools to enable developing experimentations and performance evaluation of IoT aided SG systems. For this purpose, [110] is a good source of guidance.

VI. BIG DATA AND CLOUD FOR IOT- AIDED SG SYSTEMS

A. Need of Big Data Management in IoT-aided SG Systems

The integration of IoT technology with SG comes with a cost of managing huge volumes of data, with frequent processing and storage. Such data includes consumers load demand, energy consumption, network components status, power lines faults, advanced metering records, outage management records and forecast conditions. This means that the utility companies must have hardware and software capabilities to store, manage and process the collected data from IoT devices efficiently and effectively [111].

Big data is defined as data with huge volume, variety and velocity (three V’s). The high frequency of data collection by IoT devices in SG makes the data size very large. The variety is represented by the different sensors that produce different data. The data velocity represents the required speed for the data collection and processing. Hence, IoT-aided SG systems can apply the techniques of big data management and processing (such as hardware, software and algorithms).

The frequency of data processing and storage for IoT-aided SG systems varies from application to application. For instance, some applications perform their tasks during a specific time of a day, such as weather forecasting, which can be performed daily at the night time. Other applications perform their tasks all the times, such as real-time online monitoring of transmission power lines, so these requirements need consideration in managing and processing their data [77], [112]. Big data analytics can help to manage real-time and huge data [113].

In SG, the Supervisory Control and Data Acquisition (SCADA) system is the main element of decision making. It collects data from IoT devices which are distributed over the grid and provides real-time online monitoring and controlling. Additionally, it helps to manage the power flow throughout the network in order to achieve consumption efficiency and power supply reliability. Generally, it is located on local computers at various sites of the utility companies. With the growing size of SGs, utility companies face a challenge in keeping SCADA systems updated and upgraded. In order to solve this problem, cloud computing is a good solution to host SCADA systems. Cloud computing enables on-demand access to a shared pool of computing resources, such as storage, computation, network, applications, servers and services [114]–[116].
Fig. 13. Classification of big data management in IoT-aided SG systems into platforms and techniques. The platforms include cloud computing and fog computing while the techniques include MapReduce and stream processing.

B. Platforms

Cloud computing provides a service-driven model which can be categorized into three types, namely Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS) [117]. IaaS offers the provisioning of computer infrastructure as a service, generally via Virtual Machines (VMs), such as Amazon EC2, Flexiscale, GoGrid and Joyent. PaaS provides the support of operating system and software development to the developers to deploy their applications within the Cloud, such as Microsoft Windows Azure, Force.com and Google app engine. SaaS is a multi-tenant platform and can be referred as on-demand services over the Internet. It provides a ready to use application for the end users, such as IBM, Microsoft, Oracle and SAP. Hence, the utility companies can transfer their SCADA systems entirely to the Cloud and utilize the storage, processing and other services offered by Cloud computing. In this manner, the utility companies can get many advantages, such as no maintenance cost and overhead, better collaboration, pay per usage and reduced energy cost [118]. Meloni et al. [119] proposed a cloud-based architecture for SG based on REST API by considering interoperability, reusability and security in their architecture. The authors also presented a case study to highlight the benefits of this architecture.

However, there is a security risk of using Cloud computing for SCADA systems due to the shared storage among several users, which makes it vulnerable to various attacks. Such security concerns are discussed in detail in [120]. Fog computing, a low latency and highly distributed model, extends the paradigm of Cloud computing to network ‘edge’ to overcome this issue. In fog computing, there is no need to transfer data to the Cloud, and locally stored data is processed by devices located at the edge of the network [121]. Hence, fog computing is a good alternative to Cloud computing for IoT-aided SG systems. Jalali et al. [122] explore and evaluate the usage of Fog computing and microgrids together for reducing the energy consumption of IoT-aided SG systems.

C. Techniques

There are two main techniques for big data management, namely MapReduce and stream processing [77]. MapReduce [123] is suitable for static and non-real-time applications of IoT-aided SG systems, such as weather forecasting, while stream processing is suitable for real-time applications, such as online monitoring, self-healing and fraud detection, as well as non-real-time applications. The MapReduce technique is a tool for analyzing large historical data and is frequently used. It splits big data sets into smaller data sets and processes these smaller data sets concurrently on multiple machines using the same code. Stream processing [124] is considered ideal for processing sensor data and big data streams. Its architecture is designed to handle big data in real-time with high scalability and fault tolerance. Hence, stream processing has a great potential for big data management in IoT-aided SG systems [77].

D. Summary and Insights

IoT-aided SG systems involve processing data that have the same characteristics as data that requires Big Data techniques. Figure 13 presents the classification of big data management in IoT-aided SG systems. Big data management is highly suitable
for IoT-aided SG systems due to its huge volume of data and its 'velocity' - the need for real-time processed information. The operation platforms for big data management in IoT-aided SG systems include cloud computing and fog computing. Cloud computing provides on-demand access to a shared pool of computing resources. It is a service driven model which is categorized by IaaS, PaaS, and SaaS. Sending and storing data on the Cloud raises security risk issues, due to the shared storage among several users, which makes it vulnerable to attacks. Hence, fog computing is used to solve this security risk. Fog computing does not require data transfer to the cloud and the data is processed by devices that are located at the network edge. The techniques for big data processing include MapReduce and stream processing. MapReduce is suitable for static and non-real time applications and it analyzes large historical data. It splits big data sets into smaller data sets and processes these smaller data sets concurrently on multiple machines. Stream processing is suitable for both real and non-real time applications and is ideal for sensors and big data streams. It is highly scalable and fault tolerant, and it has a great potential for big data management in IoT-aided SG systems. So far, IoT-aided SG systems do not present new issues for Big Data processing. However, different SG Big Data applications with different data sampling frequencies and data types should be further investigated.

VII. IoT AND NON-IoT COMMUNICATION TECHNOLOGIES FOR SG

There are many IoT and non-IoT communication technologies available for SGs and the users have to select among them, suitable to their needs. There is a lack of proper guidelines for the selection of communication technologies for SGs. Therefore in this section, we have listed and discussed various IoT communication technologies together with non-IoT communication technologies including their characteristics, advantages and disadvantages. Table III provides a summary of each communication technology which is discussed in detail in each sub-section [125]–[127]. From this section, users will have a broader view of available communication technologies for SG and subsequently, they can make better decision for the selection of most suitable communication technology based on their needs. In the rest of this section, we first briefly explain the role and need of communication technologies for SG and subsequently provide discussion on each IoT and non-IoT communication technology.

The IoT and non-IoT communication technologies used in the SG for data transmission between smart meters and electric utilities are categorized into two types, wireless and wired technologies. Wireless technologies have some advantages over wired technologies in some cases, such as their ease of connection to otherwise unreachable or difficult areas, as well as their low cost infrastructure. However in wireless technologies, signal attenuation may occur due to the nature of the transmission path. On the other hand, wired technologies do not have such interference issues and, unlike wireless technologies, their functions do not depend upon batteries.

An SG requires two types of information flows. Firstly, between smart meters and IoT devices, sensors and home appliances, and secondly, between smart meters and utility control centers. The first data flow can be achieved through powerline communications or wireless communications, such as by using 6LoWPAN, ZigBee and Z-wave [128]. The second data flow can be achieved by using cellular communications or via the Internet. However, there are various key limiting factors that should be considered in the deployment process of smart metering, such as operational costs, deployment time, availability of technology, and the operating environment (such as rural, urban, indoor, outdoor). Hence, the choice of technology that suits one environment may not be applicable for another. We discuss communication technologies for SGs in the rest of this section.

A. IoT Technologies

1) Wireless Technologies:

a) Z-Wave: Z-Wave [129], [130] is a low-power radio frequency (RF) IoT communication technology for short range communication which is mainly suitable for home automation [131], [132]. It operates on 1 GHz band and offers a data rate of 100 Kbps with coverage range of 30m. Z-Wave is developed by Sigma Designs [133] and it applies 128-bit AES encryption for ensuring security [134].

Advantages: The main advantage of Z-Wave is that it does not interfere with WiFi and other wireless technologies operating in 2.4 GHz band, such as ZigBee and Bluetooth [134], [135]. It is optimized for reliable and low-latency communication of small data packets. It is also very scalable and can control up to 232 devices [135]. It can also support whole mesh networks without needing any coordinator.

Disadvantages: The main disadvantage of Z-Wave is that since it is mainly designed for small data packets, it is not much suitable for NAN and WAN because NAN and WAN have large aggregated data packets. Additionally, it is a short range and low data transmission rate communication technology. Moreover, there is only one company, Sigma Designs, for developing the chips of Z-Wave, unlike multiple sources for other wireless technologies (e.g., ZigBee) [135].

b) 6LoWPAN: 6LoWPAN (IPv6 over Low-power Wireless Personal Area Networks) [136] is a key IP-based communication technology. It enables IPv6 packets to be carried within small link layer frames efficiently which are defined by IEEE 802.15.4. The key attribute of 6LoWPAN is the IPv6 (Internet Protocol version 6) stack, which has the main role in recent year for enabling IoT. IPv6 provides around 5x1028 addresses for each person in the world, which allows any device or embedded object to have its own unique IP address and to connect to the Internet. It is mainly designed for home automation (including smart metering). Initially, 6LoWPAN was designed to support IEEE 802.15.4 low-power wireless networks in 2.4 GHz band, however it is now adapted to support a number of other wireless networking media, including sub-1 GHz low-power RF [131]. Unlike Bluetooth and ZigBee, 6LoWPAN provides encapsulation and header compression mechanisms [135]. Similar to Z-Wave, it also applies strong 128-bit AES encryption for link layer security defined in IEEE 802.15.4. It offers a data rate of 250 Kbps and coverage range of 10m to 100m.
### TABLE III
**IOT AND NON-IOT COMMUNICATION TECHNOLOGIES FOR THE SMART GRID**

| Tech Wireless Technologies | Protocol | Advantages | Disadvantages | Applicability | SG Application Areas | Data rate | Coverage range |
|---------------------------|----------|------------|---------------|---------------|----------------------|-----------|----------------|
| Non-IoT Wired Technologies | Powerline communication | Cost effective; low installation cost; wide availability; utility’s own ownership and control; dedicated network | Noisy and harsh medium; sensitive to disturbances; signal quality gets affected by the type and number of devices, wiring distance between nodes and network topology; cost of ownership; complexity of management | HAN; NAN | Low voltage distribution; automatic meter reading | 2-3 Mbps | 1-3 km |
| | Digital subscriber lines (DSL) | High speed; low latency; low installation cost; high data rate; high capacity; long range; wide availability | Quality is distance dependent; high installation cost in low density (rural) areas; unreliable | HAN; NAN | Smart metering | 1-100 Mbps | 0-28 km |
| | Optical communications | Long distance communication; ultra-high bandwidth; robustness against radio and electromagnetic interference; high reliability | High deployment cost of fiber installation; high cost of terminal equipment; difficult to upgrade; not suitable for metering applications | WAN; NAN | Physical network infrastructure | Up to 100 Tbps | 10-60 km |
| | Wireless mesh | Low cost; self-healing; self-organization; high scalability; high data rate | Prone to interference and fading; network coverage problem in rural areas due to low density of smart meters; prone to loop problem due to inclusion of multiple relay nodes | HAN, NAN | Monitoring and controlling of DERs; automation and protection of substation automation | Depends upon protocol | Depends upon deployment |
| | WiMAX | Long range; high data rate | Trade-off between performance and distance; costly RF hardware; low frequencies are already licensed and require leasing; high frequencies do not penetrate obstacles | HAN | Real time pricing; automatic meter reading; outage detection and restoration | 75 Mbps | 0-30 km (LOS); 1-5 km (NLOS) |
| | Cellular communications | Wide area coverage; improved QoS | Network congestion due to high density; critical for emergency applications; non-guaranteed service in unfavorable conditions (e.g., wind storms) | HAN, NAN; WAN | Monitoring and operation of DERs; SCADA system | 80-240 Kbps | 10-30 km |
| | Bluetooth | Low power consumption | Low data rate; short range; weak security; prone to interference from IEEE 802.11 WLANs | HAN | Home automation | 721 Kbps | 1-100 m |
| IoT Wireless Technologies | ZigBee | 16 channels each with 5 MHz of bandwidth in 2.4 GHz spectrum; low power usage; low complexity; low deployment cost | Low data rates; limited energy of battery; low processing capabilities; short range | HAN | Energy monitoring; smart lighting; home automation; automatic meter reading | 250 Kbps | 10-100 m |
| | LoRaWAN | Low-power; long range; no interference with different data rates; enhance gateways capability by creating virtual channels; low-cost secure bi-directional communication | Require extensive training and knowledge; short range; low data rate | NAN; WAN | Management of operation and equipment; online monitoring of power transmission lines and tower | 0.3-30 Kbps | 2-3km (urban environment); 15km (suburban environment) |
| | 6LoWPAN | Robust; low-power; support large mesh network topology; can be applied across various communication platforms | Not suitable for NAN and WAN; only one propriety company for making chips; short range | HAN | Smart metering; home automation | 250 Kbps | 10-100 m |
| | Z-Wave | No interference with other wireless technologies; reliable; low latency; scalable | Not suitable for NAN and WAN; only one propriety company for making chips; short range | HAN | Home automation | 100 Kbps | 30 m |

**Advantages:** The characteristics of 6LoWPAN make it ideal for SG HAN including home automation and smart metering [131]. It is very robust and low-power communication technology which can also support a large mesh network topology [131]. Additionally, its standard has the liberty of being applied across various communication platforms (such as IEEE 802.15.4, WiFi, Ethernet and sub-1 GHz band).

**Disadvantages:** The main disadvantage of 6LoWPAN is the extensive training required to work with IPv6 protocol. The end users cannot deploy this protocol easily because it requires extensive knowledge of IPv6 stack and its functionalities. Moreover, one of its disadvantages are similar to Z-Wave, i.e., it is designed for small link layer frames, and it has short range and low data transmission rate communication technology, therefore it is not much suitable for NAN and WAN.

c) **LoRaWAN:** LoRAWAN [137] is a Low Power Wide Area Network (LPWAN) communication technology which is designed for wireless battery-operated devices in Internet of Things [138]. It is mainly designed for wide area network coverage in IoT and it can be applied in NAN and WAN of SG. It provides mobility, secure bi-directional communication and localization services, as well as interoperability. It offers a data rate of 0.3 Kbps to 50 Kbps and coverage range of 2-3km in urban environment and 15km suburban environment. Most of the existing wireless communication technologies have been designed to maximize their peak data rate, however LoRa is
mainly designed for low-power consumption and long communication range by sacrificing its peak data rate [139]. Furthermore, LoRaWAN network server manages the RF output and data rate for each IoT device through adaptive data rate (ADR) approach in order to enhance network capacity and battery life of each IoT device [137]. It is comprised of wide spectrum bands, there is no interference with different data rates during the communication. Furthermore, it creates virtual channels which enhances the capacity of gateways. Additionally, it provides low-power WAN coverage with features required to support low-cost secure bi-directional communication [135].

d) ZigBee: ZigBee is a cost effective, reliable, low-power, low complexity and low data rate wireless communication technology, developed by the ZigBee Alliance. It is suitable for home automation, energy monitoring, smart lighting and automatic meter reading in SGs. ZigBee has been considered as the most suitable communication technology for HANs in SGs by the National Institute for Standards and Technology (NIST) [140]. Many AMI vendors, such as Elster, Itron and Landis Gyr, integrate ZigBee with smart meters for communication with IoT devices that control the home appliances in HANs [71]. ZigBee is also used to inform consumers about their real-time energy consumption.

Advantages: ZigBee operates on the 868 MHz, 915 MHz bands and also uses 16 channels in the 2.4 GHz band (each having 5 MHz of bandwidth). It provides compatibility with the IEEE 802.15.4 standard and offers a data rate of 250 Kbps with coverage of 10-100m. It supports tree, mesh and star topologies and uses 128-bit AES encryption for security. Due to its lightweight nature, ZigBee is a good choice for metering management, it is considered as a good choice for the SG implementation in HANs due to its simplicity, robustness, mobility, low operational cost and low bandwidth requirement.

Disadvantages: ZigBee has some limitations for practical implementations, such as low memory and processing capabilities, high latency and interference with other devices due to its wireless medium because multiple devices operate on the same spectrum [140]. Such interference in the vicinity of ZigBee can damage the communication in the whole SG network [141]. Therefore, interference avoidance and detection schemes must be designed, as well as energy efficient routing protocols in order to provide reliable performance and to maximize the network lifetime.

B. Non-IoT Technologies

1) Wireless Technologies:

a) Bluetooth: Bluetooth is a part of the Wireless Personal Area Network (WPAN) standard, known as IEEE 802.15.1, which is a low power, short range radio frequency communication standard. It provides a data rate of 721 Kbps and operates on the 2.4 - 2.4835 GHz unlicensed Industrial, Scientific and Medical (ISM) band. Bluetooth can facilitate point-to-point and point-to-multipoint communication configurations. It offers coverage between 1m - 100m, depending on the communication configuration. Furthermore, Bluetooth-configured devices are comprised of the whole seven-layered OSI communication stack.

The main advantage of Bluetooth is its low power usage, which is useful for HANs, as well as for online monitoring of substation automation [142]. Its main disadvantages are its low data rate, short range and weak security. Furthermore, Bluetooth configured devices may interfere with WLANs (Wireless Local Area Networks) due to their high influence on the surrounding communication links.

b) Cellular Communications: Cellular networks can be a good choice for communication between smart meters and utility centers in an SG. The use of existing cellular communication infrastructures save the costs and time of the utility centers to build a private and dedicated communication infrastructure for a SG. A number of cellular communication technologies, including 2G, 3G, LTE and WiMAX are available to utility centers for smart metering deployments in SG. Currently, cellular networks have been used in SG by a number of companies. For instance, Echelon’s networked energy services system uses T-Mobile’s Global System for Mobile (GSM) communications for its deployment by integrating T-Mobile’s SIM (Subscriber Identity Module) into Echelon’s smart meters to enable communication between smart meters and the backhaul servers [125]. Since T-Mobile’s GSM network handles all the communication requirements of smart metering in the SG, investments in a new dedicated communication network are not required by the utility centers. Similarly, Telecom Italia, Telenor, Vodafone and China Mobile have also offered their GSM networks for communication in SG.

Advantages: Since cellular networks have existing infrastructure, utilities do not have to incur the additional costs of building the dedicated communication infrastructure for SG. Due to their ubiquity and cost effectiveness, cellular network is the leading communication technology for the SG. Furthermore, since GSM capacity is now progressively freed up due to the migration to VoLTE (Voice over LTE), mobile operators can offer such solutions for a relatively low cost. In SG, the data collection by IoT devices is performed at short intervals, which generates a huge amount of data in short bursts, and so cellular networks provide sufficient bandwidth to handle such data. Moreover, cellular networks also ensure the security of data transmission security in SG systems. Since the cellular network coverage has reached almost 100% in the developed world, cellular networks can provide the best coverage for SGs. Additionally, lower maintenance and deployment costs, and rapid installation make cellular networks a better choice for SG applications, such as AMI, HAN, outage management and demand response management.

Disadvantages: The cellular networks’ services are shared among multiple customers which may cause network congestion and performance deterioration in emergency situations, presenting a severe challenge for mission critical applications of SG which require continuous communications. In unfavorable climate conditions (e.g., wind storms), the cellular networks may be unable to provide guaranteed service, compared to wired networks. The utilities therefore, have to build their own private communication networks in order to fulfill the communication needs of mission critical SG applications.

c) Wireless Mesh: A wireless mesh network comprises of a group of wireless nodes where new nodes can join the
network and each node can act as an router. If any node leaves the network, the self healing characteristic of the network allows it to establish an alternative route through the active nodes. A wireless mesh network was applied in a SG by the Pacific Gas, SkyPilot Networks and Electric Company in a smart metering system. In such a system, each smart device is equipped with a radio module and each device routes the metering data through neighboring meters. In this manner, each meter acts as a relay until the collected data reaches the electric network access point. The collected data are then transmitted to the utility.

**Advantages:** The wireless mesh networking is an effective solution with low cost, self healing, self organization, self configuration and high scalability properties. It enhances the network performance, balances the network load, and provides scalability, and network coverage range [143]. Urban and suburban areas can be well-covered with the help of a multi-hop routing technique. Since smart meters act as relay nodes, a higher number of relay nodes maximizes the network coverage and capacity. Wireless mesh networking is highly suitable for home energy management and AMI applications of SGs.

**Disadvantages:** The major challenges of wireless mesh networking are their network capacity, fading and interference. Wireless mesh networks are difficult to implement in rural areas because the smart meters’ density is not sufficient to cover the whole communication network. Moreover, as data travels though multiple relay nodes, there could be a routing looping problem which would cause additional overhead and affect the available bandwidth [141].

d) **WiMAX:** WiMAX (worldwide interoperability for microwave access) is based on the IEEE 802.16 standard for Wireless Metropolitan Area Networks (WMAN) with the main goal of achieving worldwide interoperability for microwave access. WiMAX has its own spectrum bands for interoperability. It has been assigned the 3.5 GHz and 5.8 GHz bands for fixed communication, while the 2.3 GHz, 2.5 GHz and 3.5 GHz bands are reserved for mobile communications. The spectrum bands 2.3 GHz, 2.5 GHz and 3.5 GHz are licensed spectrum, while the 5.8 GHz spectrum band is unlicensed. It provides up to 70 Mbps data rate and 48km coverage. The licensed spectrum bands are more suitable for long distance communications as they allow for long range transmission and high power.

WiMAX’s main advantages are the long range and the high data rate. It is mainly applied in HANs and AMI, for the real time pricing, automatic meter reading, and outage detection and restoration. Its two main disadvantages include costly Radio Frequency (RF) hardware for WiMAX towers and a trade-off between network performance and distance. Furthermore, high WiMAX frequencies cannot penetrate through obstacles and lower frequencies have been already assigned, and so require leasing from third-parties.

e) **Mobile Broadband Wireless Access:** Mobile Broadband Wireless Access (MBWA) technology, also known as MobileFi, is based on the IEEE 802.20 standard. It provides high mobility, high bandwidth and low latency. It operates on the 3.5 GHz licensed band by exploiting the features of the IEEE 802.11 WLANs as well as the IEEE 802.16 WMANs. It provides a real time data rate of 1 Mbps up to a high speed data rate of 20 Mbps.

MBWA’s main advantages are its high mobility support, high bandwidth and low latency. It can be used in NANs and WANs for SG applications, such as broadband communication for electric vehicles, SCADA systems and wireless backhaul for SG monitoring. Its main disadvantage is that since it is a new technology, there is no communication infrastructure readily available for this technology. Hence, the use of this technology would be costly, compared to other available technologies.

f) **Digital Microwave Technology:** Digital microwave technology operates on the 2 - 40 GHz licensed bands and provides a data rate of up to 155 Mbps. It offers long distance and wide coverage of up to 60 km, and accepts data from ATM (Asynchronous Transfer Mode) or Ethernet ports and forwards it as microwave radio.

The main advantages of digital microwave technology are its long distance coverage and high bandwidth. It can support point-to-point communications for SG applications, such as transfer trips between Distributed Energy Resources (DERs) and a distribution substation [126]. Its main disadvantage is that it is prone to two types of signal fading, namely multipath interference and precipitation. Moreover, it incurs additional latency due to its encryption of messages for security, which makes the messages larger.

2) **Wired Technologies:**

a) **Powerline Communication (PLC):** PLC uses existing powerlines to transmit high speed data of about 2-3 Mbps from one device to another. PLC has a direct connection to the meter, and therefore, it was the first communication technology for electricity meters [141]. In a PLC network, the data from smart meters is transmitted through a PLC to a data concentrator, as they are directly connected to each other. Subsequently, the data from data concentrators is transmitted to a utility control center using other wireless communication technologies (such as cellular networks), as they are not directly connected to each other through powerlines [125].

**Advantages:** PLC reduces the installation cost by using the existing powerline infrastructure instead of developing a private communication infrastructure. The strengths of PLC are its cost-effectiveness (by reusing existing infrastructure), widely available infrastructure, standardization efforts and ubiquitous nature. HAN is one of the largest applications of PLC technology. Since the PLC infrastructure broadly covers almost all the urban areas in the range of a utility company’s service territory, it can be suitable for SG applications in urban areas.

**Disadvantages:** The powerline transmission medium of the PLC technology is noisy and harsh, increasing the challenges of channel modeling [71]. Moreover, the quality of signals are adversely affected by using powerlines in SGs due to various parameters, such as the number and types of IoT devices connected through powerlines, the wiring distance between transmitters and receivers, and the network topology [125].

b) **Digital Subscriber Lines (DSL):** DSL is a high speed digital data wired transmission technology which uses telephony networks land wires. A number of SG projects have
selected DSL as their communication technology. As an example, an SG project was carried out at Deutsche Telekom for the Stadtwerke Emden municipal utility in Germany in which Deutsche Telekom was responsible for providing data communications to electric and gas meters. A communication box was installed at each consumer’s premises, which then transmitted the consumption data to Stadtwerke Emden utility over DSL. Deutsche Telekom offered a number of services in this project, such as installation and operation, analyzing consumption data and data transmission.

**Advantages:** DSL reduces the installation cost by exploiting the existing broadband infrastructure. The main strengths of DSL technology are its wide availability (in the developed world), high bandwidth data transmission and low cost. These strengths make it suitable for electric utilities to implement SGs with smart metering and data transmission applications.

**Disadvantages:** DSL technology requires installation and maintenance of communication cables which makes it difficult to implement in rural areas due to the high cost of installation and maintenance of fixed infrastructure for low density areas. Additionally, the quality of the DSL connection depends upon the distance between the subscriber and the serving telephone exchange, which makes it difficult to characterize the performance of DSL technology. Also, due to its unreliability and down time, it is not appropriate for mission critical applications.

c) **Optical Communications:** Optical communication technologies have been widely used by electric utilities in the last decade by building the communication backbone for connecting substations with control centers. Fiber optic communications play a significant role in SGs. Recently, the usage of optical fibers in SGs has been proposed to provide SG services directly to consumers [144], [145]. Furthermore, the Ethernet Passive Optical Network (EPON) technology enables the use of a standard Ethernet communication protocol over an optical network, and it is therefore gaining considerable attention from grid operators because of its interoperability with existing IP-based networks [146].

**Advantages:** There are three main advantages of optical communication technology. Firstly, it can transmit data packets over long distances (about several kilometers) by providing up to tens of Gbps. Secondly, it is robust against radio and electromagnetic interference, which makes it a desirable candidate for high-voltage environments. Thirdly, a special type of optical cables, known as Optical Power Ground Wire (OPGW), combines the features of optical and grounding communications which allows long distance transmission at high data rates. Hence, OPGW can be used for building transmission and distribution lines [146].

**Disadvantages:** Although optical communications are very favorable for SG, they do have some limitations. The main disadvantage of optical communications is the high deployment cost of the fiber installation and the terminal units. Furthermore, they are very difficult to upgrade. Optical networks, which provide high quality wideband, are not suitable for metering applications, because metering devices are memory-constrained, requiring only narrow band communication. Therefore, these devices are not likely to be connected to broadband networks [146].

**C. Summary and Insights**

In this section, we have discussed several IoT and non-IoT communication technologies for SG. The main motivation of discussing these communication technologies for SG is to provide some guidelines for the selection of communication technologies of SG based on the requirements. For this purpose, we have discussed which communication technologies are preferred for which scenarios, along with their characteristics, advantages and disadvantages. We came to know that most of the communication technologies are designed by focusing HAN. However, there is a new IoT communication technology, named LoRaWAN, which is a very good candidate for NAN and WAN and it is a long range and low-power communication technology. Furthermore, it is important to note that there is no overall the best technology, but certain ones are more suitable to particular SG applications than others. In general, wired technologies such as DSL, PLC and optical fiber are expensive for wide area deployments, especially in rural areas. However, they can maximize both communication capacity and security. Wireless technologies, on the other hand, can reduce installation costs but they have bandwidth and security limitations.

**VIII. Open Issues, Challenges, and Future Research Directions**

In this section, we highlight open issues, challenges and future research directions which are also categorized in Figure 14.

**A. Physical Layer**

1) **Adverse Environmental Conditions and Constrained Devices:** IoT-aided SG systems operate under different environments including some very severe conditions, such as the monitoring of power transmission lines. Therefore, it is important to consider requirements for reliability, availability, compatibility for hybrid communication technologies and signaling coverage at adverse environmental conditions [96]. IoT solutions for self-healing and self-organization should also be considered. As an example, when a set of IoT devices fail, an alternative route should be selected by the self-healing capability, so that the reliability of IoT-aided SG systems should not be compromised.

The limitations of IoT-aided SG systems also include the constrained devices that are used. Such devices may be ruggedized for adverse conditions, but they lack memory and processing power that limits their ability to perform local functions. The lifecycle for such devices tends to be rather long (up to 10 years), so backward compatibility remains a serious issue.

2) **Energy Acquisition:** IoT end devices and sensors operate on batteries in many applications of IoT-aided SG systems. For example, the online monitoring of power transmission lines includes various sensors, video cameras and backbone nodes installed on the transmission towers and transmission lines,
which normally operate on batteries. Therefore the energy acquisition for power consumption of these devices is a serious problem in realizing the application of IoT technology in SG [50], [96]. For this purpose, efficient energy storage sources for IoT devices, and energy generation devices coupled with energy harvesting using energy conversion need to be used designed [57]. Already, the new generation of batteries can boast over ten years of life [147] at reasonable usage. However, there are still limitations on the level of power usage at the device level.

3) Environmentally Safe Devices: IoT devices in some SG applications are deployed outdoors and at severe electromagnetic conditions, such as power generation, transmission and distribution substations. Therefore, it is very crucial to protect the instruments and to consider and embed new technologies, such as dustproof, waterproof, anti-electromagnetic, anti-vibration, low temperature and high temperature in the manufacturing of IoT devices and their chips that will prolong their lifetime under such severe environments [50].

B. Network Layer

1) Communication Networks: Information and communication networks are very important for the realization of transmission and collaboration of IoT devices in IoT-aided SG systems. The information and communication networks can be divided into two main categories based on the range of transmission [96], namely wide area and short range communication networks. In wide area communication network, the long distance information transmission is achieved through IP-based Internet, PLC, OPLC, 2G/3G mobile networks, LTE and satellite networks. In short range communication network, Bluetooth, ZigBee (IEEE 802.15.4) and Ultra-Wideband (UWB) are used. As an example, the wireless sensor nodes in IoT-aided SG systems have the characteristics of low power, low rate and short distance with the limitations of storage and processing capabilities. Hence, ZigBee is an appropriate communication network in this scenario. As IoT-aided SG applications progress from merely informative facilities and appliance scheduling towards automated power management and mission-critical power supply, the reliability and speed of the communication become paramount. As Section VII discusses several IoT communication networks, IoT-aided SG systems utilize a hybrid combination of communication networks at different stages in the same operation, a situation that is not common in other fields. This communication path goes through several ‘legs’, from devices to local network, then to gateways, then to core servers and potentially to the Cloud too, using different protocols each time. This means that more elaborate applications of IoT-aided SG systems need to be assured of solid network support, despite fragmented communication phases, and multiple network providers.

2) Data Fusion: Data fusion is the process of combining data from multiple sources. The IoT devices in IoT-aided SG systems are resource constrained and have limited battery life, processing, bandwidth and storage capabilities. Therefore, it is not efficient for IoT devices to transmit all the data to a gateway in the process of data collection, as it would consume significantly high energy and bandwidth. It is desirable to use data fusion technologies to filter and aggregate only useful data from multiple IoT devices, which will enhance the efficiency of data collection, as well as save energy and bandwidth [96]. The techniques of identifying the significant data, such as smart aggregation, is a new field that will undoubtedly impact IoT-aided SG systems.

C. Transport Layer

1) Congestion: Congestion causes delay and packets loss, which are the important performance parameters for SG [148]. An input from a NAN gateway can be delayed or missed by the control center due to congestion, which may affect important decision making by the control center, thus causing performance degradation or non-fulfillment of the user requirements. It may also be possible that a message could be dropped by a HAN gateway due to congestion and its memory overload if multiple messages arrive to the HAN gateway from a higher number of IoT devices simultaneously. In such scenarios, the
IoT devices have to retransmit the packets on the request of the HAN gateway upon the expiration of the acknowledgement interval at HAN gateway, which contributes to higher delay. Since some SG applications are delay sensitive, it is necessary to minimize the communication delay in IoT-aided SG systems. For many IoT-aided SG systems, it is essential to accommodate a higher number of simultaneous messages from multiple IoT devices without causing a major impact on delay and packets loss. This means not only high bandwidth, but also minimizing the number of messages from multiple IoT devices to each HAN gateway, i.e., careful network design and optimal numbers of nodes and gateways [149].

D. Application Layer

1) Interoperability and Integration of Devices: Interoperability is defined as the ability of two or more heterogeneous networks/devices to exchange information between them, and to use the exchanged information in a common function [57]. The IoT-aided SG system is comprised of a large number of different types of IoT devices and gateways which vary in characteristics, operation, resources (such as computation power, memory, energy, bandwidth, time sensitivity), as well as their implemented communication stacks and protocols (for non IP-based devices). The lack of device interoperability and integration imposes a serious constraint on the development of IoT-aided SG systems. One possible solution proposed in [1] is to convert the networks based on proprietary protocols into IP-based networks for the realization of IoT-aided SG systems. This will enable the SG to get benefits from the seamless integration of various types of networks/devices for achieving interoperability. Moreover, future IoT devices should integrate different communication protocols and standards which operate at different frequencies and allow different architectures to communicate with other networks [57]. Additionally, the interoperability issues need to be differentiated at different levels, such as in the communication layer, the physical layer or the application layer. A holistic approach to services, devices and semantics should be addressed for solving the interoperability in IoT-aided SG systems [57].

2) Huge Data Handling: The integration of IoT technology with SG comes with the cost of more frequent processing and storing the huge volume of data which would impose a higher load on the IoT communication networks. Such data includes energy consumption, consumers load demand, advanced metering records, power lines faults etc. Using high bandwidth and data rates, such as the ones offered by LTE, increases the ability to transport such data but creates bottleneck elsewhere. Consequently, the utility companies should need to design systems with enhanced capabilities to store, manage and process the collected data efficiently and effectively [111].

E. Miscellaneous Issues

1) Need of Standardization: Standardization is important for interoperability, compatibility, reliability and security. Although there have been separate investigations on the standardization activities of IoT [26], [27] and SG [70], there is no standardization activity specifically for IoT-aided SG systems. However, standardization of IoT data collection under OneM2M [65], [66] is in full swing, but the energy industry regards it as an overkill and unsuitable for constrained devices. OMA’s standard for LWM2M (Lightweight M2M) [67] is gaining greater popularity due to its greater simplicity, which is required for such applications.

De facto standards emerge ‘organically’ in the web world by wide adoption of what is usually open source or freely available software components. This may eventually occur for IoT-aided SG systems. However, the security requirements need more urgent solutions.

F. Security Issues

Although IoT technologies have been widely applied in SG, these could lead to various security vulnerabilities. Since the monitoring and controlling in IoT-aided SG systems is performed over the open Internet, it has no more than the Internet-based security, which has inferior security than the managed mobile and fixed networks. The Internet is far more vulnerable to cyber attacks. By manipulating the data either generated by smart objects or sent from the utility, an attacker can affect the real-time balance between energy production and consumption, and cause considerable financial loses to the utility and power assets [150]. For instance, very recently, the management of contingencies in smart grid through Internet of Things have been proposed [151]. Therefore, security considerations for IoT-aided SG systems is a high priority. Such considerations consist of several aspects are discussed below and some calibrated security measures for centralized IoT-aided SG systems are discussed in [152].

1) Resource Constrained: In IoT-aided SG system, several IoT devices and smart objects are resource constrained, specially those that are deployed in great numbers. Since they have limited computational and storage capacities, they cannot run complex security algorithms. This constraint makes the application of classical security solutions (such as public key infrastructure (PKI) and public key cryptography) more challenging [150]. Hence, there is a need to take special care while developing security solutions for IoT-aided SG systems to ensure that the resource constrained IoT devices are able to accommodate the proposed security solution.

2) Privacy: The smart meters and the appliances in the houses could provide information much more than just energy consumption, such as the habits of consumers (wake up, sleeping, lunch and dinner timings), whether they are away from premises, or on vacation. Such information can be used for marketing (e.g., timing of adverts) but in the wrong hands, it can be used for burglaries, for example. Utilities must guarantee that such private user data should not be obtained without the users’ approval and that such data would only be used for the intended purpose [153]. A secure and differentiated access to data for IoT-aided SG systems is proposed in [100] to ensure privacy. In this design, the consumers have complete fine-grained access to their data while the distributors and energy utilities receive only aggregated statistical data and have coarse-grained access to consumers data. Additionally, some other privacy considerations for IoT-aided SG systems are discussed in [154].
3) Trust Management: A certain level of trust establishment is required for two devices to communicate. It is easy to establish a trust relationship between devices which are owned/managed by the same entity, but not where they are managed by different entities, such as the consumers for appliances and operators for smart meters. In a large scale IoT-aided SG system, it is very challenging to establish trust between IoT devices which are owned/managed by different entities [150].

4) Authentication and Authorization: The energy provider has to authenticate each smart meter in order to bill the corresponding consumer. The identity of the IoT device in an SG is also authenticated in order to avoid any misuse of the system. Only the authenticated user or device should be authorized to accomplish the tasks or is granted the required privileges to access the resources. For example, the configuration of a smart meter can only be done by the field agent, who should be authorized and granted privileges [150].

5) Data Integrity: Data integrity is also very important to ensure that the received data from IoT devices (such as smart meters) cannot be modified by an unauthorized party. In IoT-aided SG systems, the IoT devices generally communicate using the open Internet. Therefore, data exchanges can be easily comprised by the attacker. Energy consumption of households can be altered by an attacker and can also modify the data exchanges in SG systems to lower the prices during the peak hours, for example. This would significantly increase the energy consumption of households (such as charging cars) instead of minimizing it which will eventually result in an overloaded power network. Therefore, data integrity in IoT-aided SG systems ensures that consumers are charged according to their exact energy consumption [150].

6) Cyber Attacks: SG involves various physical objects, such as smart meters, cables and transformers that are managed by IoT. Hence, SG is vulnerable to cyber attacks which could subvert the management and cause indirect damage to these assets. Attacks can prevent smooth operations, and interfere with maintenance procedures. Attacks can also prevent the billing process to proceed, and the energy supply to be balanced. The more IoT-aided SG applications are developed, the greater the need to prevent cyber attacks.

7) Scalability: The IoT-aided SG systems consist of a large number of IoT devices and smart objects which are installed over large areas which may comprise of few cities in a country. Hence, scalability is a serious challenge.

8) Confidentiality: SG data should be protected from prying eyes of unauthorized parties. Confidentiality means that the stored and transmitted data is only accessible to the concerned persons. As an example, the energy consumption data of consumers should not be accessible to anyone except the SG’s operator and the energy providers’ appropriate departments.

9) Identity Spoofing: In identity spoofing, an attacker takes an identity of a legitimate user/thing and uses it for communication on its behalf in an unauthorized manner. In IoT-aided SG systems, the identity of a smart meter at someone’s home can be spoofed by the attacker and in this manner, the legitimate user would be charged for energy consumption of the attacker.

IX. CONCLUSION

Smart Grid (SG) is the future grid which solves the problems of uni-directional information flow, energy wastage, growing energy demand, reliability and security in the traditional power grid. The Internet of Things (IoT) technology provides connectivity anywhere and anytime. It helps SG by providing smart devices or IoT devices (such as sensors, actuators, and smart meters) for the monitoring, analysis and controlling the grid, as well as connectivity, automation and tracking of such devices. This realizes the IoT-aided SG system which supports and improves various network functions at the power generation, transmission, distribution, and utilization. In this paper, we have presented a comprehensive survey on IoT-aided SG systems. We have surveyed architectures and applications of IoT-aided SG systems. We discussed existing and potential applications of IoT-aided SG systems. We also presented various IoT and non-IoT communication technologies for SG systems by presenting their advantages, disadvantages, and applicability. Additionally, some existing prototypes of IoT-aided SG systems were surveyed which can serve as a baseline for future research in this area. Since IoT-aided SG systems can generate huge amount of data, therefore, we also surveyed and provided solutions for big data processing in IoT-aided SG systems. We concluded the survey by presenting open issues, challenges, and future research directions for IoT-aided SG systems.

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