Computer Science Review 30 (2018) 1–30

Contents lists available at ScienceDirect

Computer Science Review

journal homepage: www.elsevier.com/locate/cosrev

Review article

Smart grid communication and information technologies in the perspective of Industry 4.0: Opportunities and challenges

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HIGHLIGHTS

- This paper presents a comprehensive presentation on critical smart grid components with international standards and information technologies.
- This study gives an overview of different smart grid applications, their benefits, characteristics and requirements.
- This research investigates and explores different wired and wireless communication technologies.
- This article discusses a number of critical challenges and open issues and future research directions.

ARTICLE INFO

Article history:
Received 16 April 2018
Received in revised form 16 July 2018
Accepted 10 August 2018

Keywords:
Internet of Things
Industry 4.0
Big data
Cloud computing
Smart grid
Wireless sensor network

ABSTRACT

The fourth industrial revolution known as Industry 4.0 has paved the way for a systematical deployment of the modernized power grid (PG) to manage continuously growing energy demand by integrating renewable energy resources. In the context of Industry 4.0, a smart grid (SG) by employing advanced Information and Communication Technologies (ICTs), intelligent information processing (IIP) and future-oriented techniques (FoT) allows energy utilities to monitor and control power generation, transmission and distribution processes in more efficient, flexible, reliable, sustainable, decentralized, secure and economic manners. Despite providing immense opportunities, SG has many challenges in the context of Industry 4.0 (I 4.0). To this end, this paper presents a comprehensive presentation on critical smart grid components with international standards and information technologies in the context of Industry 4.0. In addition, this study gives an overview of different smart grid applications, their benefits, characteristics, and requirements. Also, this research investigates and explores different wired and wireless communication technologies used in smart grid with their benefits and characteristics. Finally, this article discusses a number of critical challenges and open issues and future research directions.

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https://doi.org/10.1016/j.cosrev.2018.08.001
1574-0137/

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1. Introduction

The existing centric approach-based factories around the world are exposed to varying circumstances in manufacturing due to globalization, volatile markets, and technological developments. This variation leads to new challenges in terms of production cost, quality and time. Thus, these aging factories are not fully able to fulfill an ever-increasing demand of the 21st century [1]. To address these challenges, the existing factories will need capabilities for virtual and physical structures, which permit for close cooperation and rapid adoption along the whole lifecycle from innovation to production and distribution in an agile and responsive manner.

Recent advances in ICTs technology concepts have emerged as new communication systems, information processing approaches and future-oriented techniques in manufacturing industrial revolution. This industrial revolution is generally known as Industry 4.0 [2]. The key vision of Industry 4.0 is to make existing factories smart enough to identify the need for a significant reduction in faults and react with short-cycle adaptation for higher productivity to increase economic benefits. Industry 4.0 will serve as a conceptual base for intelligent realizing and controlling physical production processes locally as well as globally using advance ICTs [3]. Therefore, in Industry 4.0, ICTs play a dominant role in strengthening the overall flexibility of manufacturing resources for increasing productivity. Industry 4.0 will allow customers to choose a variety of desired quality level products at a constant price with a high degree of freedom. This will definitely increase the number of competitors and sellers to the buyer's market as well as the life of the people in the living world. However, the high complexity of control systems of an intelligent factory brings new challenges to production reliability, which creates uncertainty on all organizational and technological capability levels and adequate strategies to develop them [4].

The current industrial revolution and increasing electricity price, diminishing fossil fuels and rising concerns about global warming have provoked energy utilities and governments to take solid steps for enhancing efficiency and reliability of their current power grids for high-quality electricity [5]. In addition, to seek alternative renewable energy sources and their reliable integration within the existing PTDs to meet the rapidly changing energy demands of the 21st century [6].

Recently, many renewable energy generators like solar, tidal, biomass and wind generators, which produce a few kilowatts up to some megawatts, are becoming extensively diffused around the world. These large-scale distributed generation systems transformation of the present power systems containing several hundreds of generators, characterized by power, current, voltage and different technologies and topologies.

The whole electrical power system is the integration of these large numbers of geographically distributed sub-systems. The digital integration complexity of these geographically distributed components in the existing power grid makes it very vulnerable, thus requiring intelligent, two-way and secure communication mechanisms in PG [7]. The nomenclatures used in this study are listed in Table 1.

The main focus of this survey article is to explore critical smart grid components, communication technologies, applications, challenges and requirements in the context of SGI 4.0. In Section 2, we provide a detailed overview of SG in the context of Industry 4.0. In Section 3, we provide QoS requirements for SG. In Section 4, we provide a detailed survey of key design components, some standards, requirements and emerging challenges in SGI 4.0. In Section 5, we provide a survey of identifying potential SG applications, challenges and their communication requirements in SGI 4.0. In Section 6, we highlight potential benefits and key observations in SGI 4.0. Finally, the last Section 7 is summarizing and outline future research direction.

2. Smart grid in the context of industry 4.0

In the following, we explain the details of smart grid in the context of Industry 4.0.

2.1. Power grid evolution

Today's power grids are continuing to operate using antiquated technologies and systems. The electricity generation and distribution (EGD) in these PGs can be divided into three different subsystems, namely generation, transmission, and distribution. The PGs generate electricity and for long-distance transmission step-up transformers convert it into high voltage electricity at the transmission substations. Then, a medium voltage electricity is acquired by converting this high voltage electricity at the DG [8]. Finally, the medium voltage is converted into a low voltage in order to facilitate the customers. For several decades, the electricity flow has remained unchanged in PG. However, the PGs subsystems have changed with different paces over time. Therefore, the automation level significantly varies at various components of the PGs. The EGs has transformed into interconnected grids from a set of isolated PGs. These PGs are unified into regional or national EGs to handle the unbalanced supply and demand by employing different duplicated paths for power flow and failures like transmission equipment or generation plants failures.

The entire dispatching electricity coming from several regions is centrally managed by a centrally located control center using computer-aided control and monitoring system generally known as SCADA systems. These systems comprise of different automation equipment's came into life around 1965 and at the control centers evolved into EMS for monitoring and controlling the PG components. The Remote Terminal Units (RTUs) are deployed in PG to collect real-time information with least delay (2–10 samples/s) at a transmission and distribution substations. The EMS uses AGC for optimal power flow, contingency analysis and state estimation [9]. Thus, the existing PG is fairly smart in electricity generation and transmission; however, it requires extensive human intervention due to lacking much automation at the control centers. After the 1990s, some efforts have been made on customer premises and real-time distribution monitoring systems. As a result, some novel applications were developed, such as DA, AMR, and AMI. However, the usage of these applications is not widely spread on the existing PG since they were employed locally only as pilot projects. Thus, this recent development of the PG is assumed too localized and inefficient to address several critical issues.

2.2. Energy management and environmental issues in traditional PG

The operations of the existing PGs are limited and inefficient. In existing PG, because of lack of efficient energy storage or backup capacity, the supply is required to keep up with the need which results in forced just-in-time paradigm [10]. Thus, appropriate energy storage and advanced storage technologies are crucial for PG. Moreover, during the peak load hours, the energy need variations strain the elderly infrastructure-based PGs. It causes electricity cut off or quality issues with availability and reliability, which is really a subject of worry. To cope with the demand, peaker plants based on non-renewable energy sources have to turn on for additional electricity supply [11]. However, this approach is inefficient and uneconomical when the average electricity demand is significantly less than the peak. Also, in the longer run, it may be difficult or even impossible to match the power supply to this peak demand using the peaker plants because of day-by-day increasing energy demands. A small control failure is quite fatal in peaker plants to crash the entire PG [12]. In addition, the existing PGs do not rely on

Table 1
Nomenclature used in this study.

Word	Abbreviation	Word	Abbreviation
AES	Advanced Encryption Standard	JSME	Japan Society of Mechanical Engineers
ASME	American Society of Mechanical Engineers	KEA	Korea Electric Association
ARM	Advanced Meter Reading	LoS	Line-of-Sight
AGC	Automatic Generation Control	MCC	Mobile Cloud Computing
AFCEN	French Association for the Equipment of Electro Nuclear Boilers	MDMS	Meter Data Management System
AMI	Advanced metering infrastructure	MIMO	Multiple Input Multiple Output
AAA	Auditability, Authorizability, Authenticity	MAC	Medium Access Control
AITs	Automatic Identification Techniques	M2MXML	Machine-To-Machine Extensible Markup Language
BD	Big data	MEC	Mobile Edge Computing
BAN	Building Area Network	MBWA	Mobile Broadband Wireless Access
B2G	Building-to-Grid	NIKIET	Designated Russian Code Comparison authority
BGAN	Broadband Global Area Network	NBP	National Broadband Plan
B&P	Business and Policy	NIST-IR	National Institute of Standards and Technology Interagency Report
BPEL	Business Process Execution Language	NIST	National Institute of Standards and Technology
CPSs	cyber–physical Systems	NERC-CIP	North American Electrical Reliability Corporation-Critical Infrastructure Protection
CC	Cloud Computing	NIPP	National Infrastructure Protection Plan
CS	Cyber Security	NGTP	Next-Generation Telematics Protocol
CSA	Canadian Standards Association	OWL	Ontology Web Language
CSPs	Cloud Service Providers	OFDMA	Orthogonal Frequency Division Multiple Access
CORBA	Common Object Request Broker Architecture	PKI	Public Key Infrastructure
SCADA	Control and Data Acquisition	PTD	Power Transmission and Distribution
CDMA	Code Division Multiple Access	PONs	Passive Optical Networks
DDR	Dynamic Data Resource	PaaS	Platform as a Service
DR	Demand Response	PTDs	Power Transmission and Distribution systems
DA	Distribution Grid	RDF	Resource Description Framework
DSL	Digital Subscriber Line	RDFS	Resource Description Framework
DAPs	Data Aggregation Points	REST	Representational state transfer
DEWGs	Domain Expert Working Groups	RSS	Really Simple Syndication
DoS	Denial of Service	RPC	Remote Procedure Calls
DG	Distribution Grid	SSL	Secure Sockets Layer
DOE	Department of Energy	SUNs	Smart Utility Networks
DISA-STIGs	Defense Information Systems Agency-Security Technical Implementation Guides	SGIP	Smart Grid Interoperability Panel
EG	Electricity Grid	SLA	Service Level Agreement
ER	Emergency Response	SATCOM	Satellite Communications
EDDL	Electronic Device Description Language	SWS	Semantic Web Services
EPRI	Electric Power Research Institute	SNRA	Sensor Network Reference Architecture
EMS	Energy Management System	SPs	Service Providers
EMN	Edge of a Mobile Network	SC-FDMA	Single Carrier Frequency Division Multiple Access
FDT	Field Device Tool	TLS	Transport Layer Security
FAN	Field Area Network	T&D	Transmission and Distribution
FCC	Federal Communications Commission	TDMA	Time Division Multiple Access
FDMA	Frequency Division Multiple Access	UDDI	Universal Description, Discovery, and Integration
GPRS	General Packet Radio Service	UMTS	Universal Mobile Telecommunication System
GOOSE	Generic Object Oriented Substation Event	UHF	Ultra High Frequency
GWAC	Grid Wise Architecture Council	VHF	Very High Frequency
H2G	Home-to-Grid	WiMAX	Worldwide Interoperability for Microwave Access
HAN	Home Area Network	WPAN	Wireless Personal Area Network
ISM	Industrial, Scientific, and Medical	WBAN	Wireless Body Area Networks
IaaS	Infrastructure as a Service	WRAN	Wireless Regional Area Network
IEC	International Electrotechnical Commission	WAN	Wide Area Network
IT	Information Technology	WSDL	Web Service Description Language
I2G	Industrial-to-Grid	WSML	Web Service Modeling Language
IEDs	Intelligent Electrical Devices	WSs	White Spaces
IEEE	Institute of Electrical and Electronics Engineering	WSMOC	Web Service Modeling Ontology Compliant
IoS	Internet of Services	WSMO	Web Service Modeling Ontology
ISO	International Standards Organization	WSMX	Web Service Modeling eXecution environment
IAN	Industrial Area Network	3DES	Triple Data Encryption Algorithm
IoT	Internet of Things		

renewable energy resources have resource scarcity and environmental issues. Furthermore, the elderly PG that uses fossil fuels for generating electricity emits greenhouse gases and other pollutants, which are harmful to both health and the environment. In the last, utility companies realize that through modern information management and automation they must shift their dependence to systems-based knowledge rather than the knowledge of their aging workforce. Additionally, the existing elderly power plants are heavily using fossil fuels, including oil, coal, nuclear fission and natural gas for generating electricity. These natural reserves on the earth are expensive and being consumed rapidly since they are nonrenewable. Other, the emitted harmful gases such as carbon dioxide (CO_2), sulfur dioxide (SO_2), nitric oxide (NO) and other pollutants challenges are also present in the PGs. Thus, the energy sector is one of the major sources heavily consuming natural reserves and emitting harmful gases.

2.3. Integration of renewable energy resources and issues in traditional PG

These above-mentioned emerging crises recently have attracted worldwide attention to seek alternative renewable energy resources that are durable, environment-friendly and can endure long-term development of the power industry for reliable and high-quality electricity [13]. The potential resources for renewable or green energy include hydro, geothermal, solar, wind, tidal and biomass. Their reliable and efficient integration with PGs in the process of electric energy generation can omit or significantly reduce the emissions of harmful gases into the atmosphere in order to slow the adverse effects of climate change. In most parts of the world, the wind and solar power are available, however, their contribution to PGs is fairly low. Instead, each of them faces the problem of uncertainty in energy intake in variable environments [14]. For example, PGs powered by solar experiences substantial variations in their energy harvesting capability because of varying weather conditions, seasonal patterns and diurnal cycle in solar energy over time. Consequently, PGs must be equipped with huge rechargeable batteries to supply energy during the nighttime, which requires extra recharging circuits and is usually expensive and increases the cost of production significantly. Consequently, the position and direction of the wind-powered sensor nodes like the orientation of solar cell intensely affect the energy intake and leads to different energy harvesting rates in the PG. In addition, harsh weather conditions like hail and storms could also damage the turbine blades and solar panels. However, the advance communication, control, and sensing functionalities can significantly help the integration of such intermittent energy resources in the PGs [15]. For example, sensors using advance-sensing mechanisms can collect weather-related data and stored in the control room through near-real-time communications that can help operators to timely implement the proper control actions for handling risks.

2.4. Need for modernized SG

All above-mentioned challenges and issues are the driving force behind the transformation of the existing PG into an automated SG paradigm is known as Smart Grid Industry (SGI) 4.0 [16]. In SGI 4.0, the key objectives are to provide intelligent electricity by using advanced ICTs envisioned to offer a variety of advantages in the following areas: emerging economies, renewable energy sources, environmental, efficiency, reliability, security, and safety. Although some novel studies exist [9,17–26] guiding the smart grid challenges, however, unfortunately, they are not addressing the issues in the context of Industry 4.0. The SGI 4.0 paradigm offers a platform, vision, and architecture of high-quality EGD in the smart grid. The key principals behind the SGI 4.0 include decentralization, virtualization, real-time capability, service orientation, modularity, and interoperability. While the fundamental characteristics of SGI 4.0 are data integration, flexible adaptation, secure communication, intelligent self-organizing, optimization, electricity generation process, service orientation and interoperability. The SGI 4.0 decreases the average energy production price by improving the cost situation of the smart grid for economic benefits, i.e., the "Moore's Law" [27]. Moreover, SGI 4.0 will provide environment-friendly, high quality, and competitive power generation solutions by using renewable energy resources. Thus, electricity generation systems (EGSs) to meet varying energy demands, especially during peak hours will be adaptable, more robust, flexible, scalable and reliable to deal with customer demands. In SGI 4.0, the control centers, the transmission infrastructures, and the substations are believed to interact and monitor the electric devices remotely, employ novel technologies and services to improve the power quality and to coordinate with their local devices in real-time and self-consciously manner to reduce lead times. A fundamental architecture of smart grid in the context of Industry 4.0 is shown in Fig. 1. In Fig. 1, initially the IAN, BAN, and HAN containing smart devices like micro solar panels, washers, ovens, air-condition, batteries, PHEVs, etc., are connected to the firewall via WiFi or Ethernet (Two-way communication). The firewall is directly connected to NAN/Local cloud having the various types of services and functionalities. Moreover, the firewall is also connected to WAN cloud through backhaul communication infrastructure which could be Cellular/WiMAX/Satellite/Fiber/PLC or DSL. The WAN cloud having different types of services, including IoS, data storage cloud, decision support systems, technical support, big data analytics, security services, and other various types of functionalities and services provided by different utilities for SG. At the second stage, different types of power generation sources such as nuclear, wind, thermal, solar and hydropower plants are connected to WAN cloud via WiFi or Ethernet, and backhaul communication infrastructure which could be Cellular/WiMAX/Satellite/Fiber/PLC or DSL. At the third stage, different energy utilities are connected to power generation systems for real-time monitoring and control the smart grid. Moreover, these utilities are also connected to end users in order to provide various functionalities and services in a real-time manner, such as real-time energy consumption information, billing information, demand response, etc. In summary, the power grid by employing advanced ICTs can provide smart energy in a QoS manner to meet the growing energy demand of 21st century.

2.5. Sustainability of SG

In SGI 4.0, the smart grid systems are capable of collecting data, communicate with computers for analyzing it and give advice on it to the operator for necessary actions. This self-cognition, self-optimization, and self-customization of the SGI 4.0 will enable different systems of the power grid to operate independently or with less human interventions for high-quality electricity. Thus, in SGI 4.0, the systems, workers, customers and other stakeholders will be interconnected and cooperate closely. This real-time interaction between systems, workers, and customers through the continuous and autonomous exchange of information and data will build a highly flexible power generation model that will greatly improve power efficiency and competitiveness in power industries [28]. This will not only change the traditional methods of electricity generation, but also guide for future improvements in terms of internal complexity and external unpredictable events. However, the multifunction and autonomous equipment's in a large-scale smart grid generate a huge amount of ambiguous data. The existing information exchange environments and approaches are not well suited to handle this increasing data, which dramatically increase the internal complexity of the systems leading to more uncertainties due to atypical events [29]. On the other hand, the communication requirements in the SGI4.0 are increased regarding data rates, bandwidth, latency, efficiency, scalability, flexibility, and reliability. Thus, providing real-time trustworthy information from source to the destination throughout the power generation and distribution process requires a non-traditional ICT infrastructure in the SG.

2.6. Role of information and communication technologies in SG

To this end, the role of ubiquitous information and emerging ICTs infrastructure is very important for the realization of SGI 4.0. In SGI 4.0, the key aim of ICTs is to build a highly reliable and flexible communication infrastructure and allow protocols to enable real-time interactions between producers and consumers in the smart grid [30]. Moreover, in SGI 4.0, all interconnected power generation and consumer systems through the continuous and the autonomous exchange of information and data, cooperate closely to realize a digital and intelligent smart grid. It will allow grid systems to create a 'digital/cyber twin' of the physical world, monitor the process and make smart decisions with machines objects and humans in order to address a dynamic and global energy market. The adaptation of emerging ICTs in SGI 4.0 provides

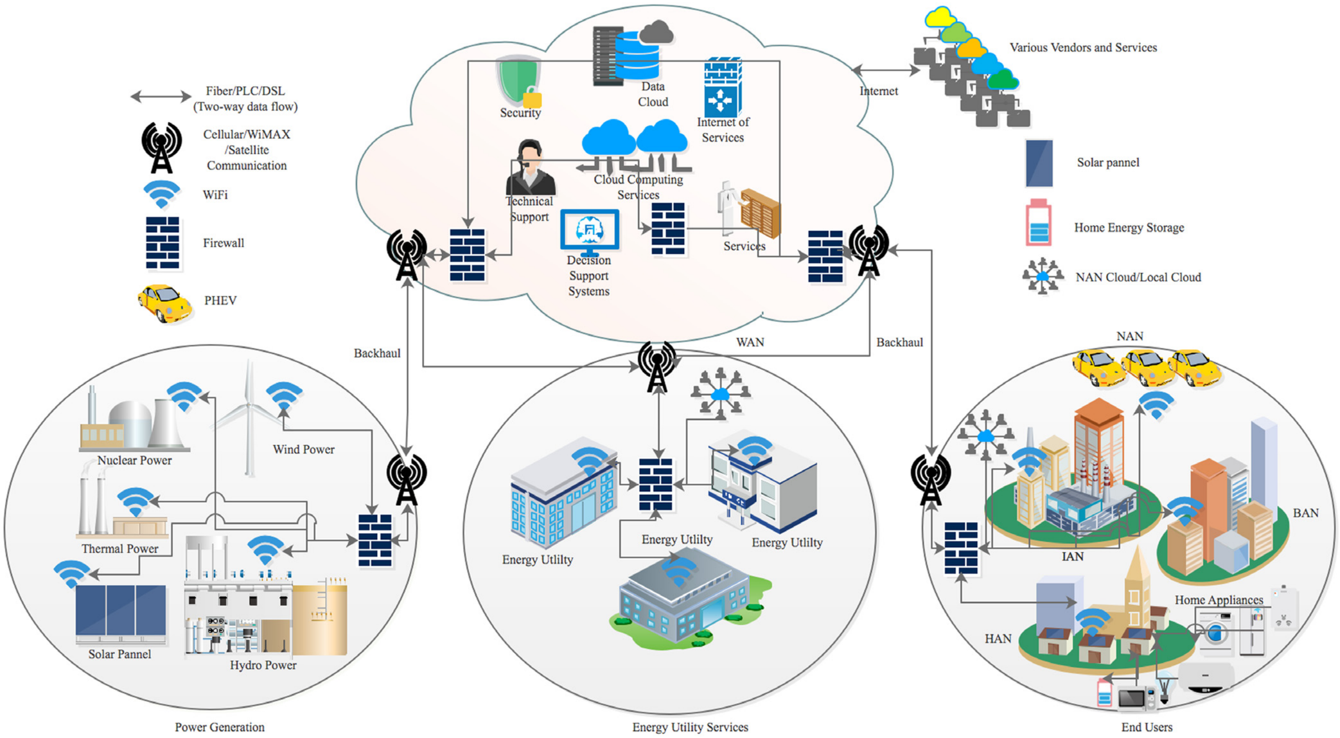

Fig. 1. shows the basic communication and services architecture for smart grid in the context of Industry 4.0.

immense opportunities where system elements make autonomous and decentralized decision for advancing the remote power line monitoring, automated distribution, load management and control, fault diagnosis and detection and automatic meter reading in a real-time manner. In SGI 4.0, the bi-directional information flow between smart meters and smart grid in real time identify the need for current and future energy supply and demand [30]. In SGI 4.0, especially during peak load hours, the distributed control centers, through reconfiguring or adjusting system parameters will be able to provide high-quality electricity without any interruption. Consequently, it also enables efficient utilization of the available energy capacity in a situation when the expected lower energy demand than average by deferring the load which provides an incentive to the consumer in term of reducing electricity bills. Thus, a smart grid using the two-way flow of electricity and ICTs can protect, monitor and respond to changes from power generation to consumption of the whole grid in a cost-efficient manner. In smart grid, the ICTs incorporating technologies such as IoT, IoS, CPSs, BD, and CC are the key enablers of SGI 4.0 [31]. These technologies based on past experiences and learning capacities allow EGSs and electricity consumption systems (ECSs) in SG to vary their behaviors in response to different situations. Thus, it enables real-time adaptive decisions to solve even highly complex problems at the shop floor and worldwide. At this stage, the integration of new technology, namely, artificial intelligence with the ICTs will allow EGSs to learn more from experiences for realizing an interconnected, efficient, intelligent and ubiquitous industrial practice in SG [32]. A detailed explanation of these technologies has been provided in the following sections.

2.7. Human role and job opportunities in SG

In SGI 4.0, though industrial processes are more automated, the human still continues to have a central role to improve real-time grid performance in terms of power quality, productivity, efficiency, and security. Therefore, it is important that workers and engineers need to improve their social, professional, personal and methodical competences to achieve higher power generation efficiency with less cost and fewer resources consumption. In SGI 4.0, a wide range of jobs varying from process monitoring to machine control until power quality verification will be faced by the workers [33]. As a consequence, a look at what kind of skills will be most useful in engineering academic is essential for realizing the advent of SGI 4.0. A computer engineer as IT specialist should have higher mathematical knowledge, core computer programming languages, IoT, IoS, CPSs, CC, simulation tools and web technologies and services, creativity and design skills, experimental skills and hard skills of software, hardware, networks, installation, cyber security, data management, information processing and analysis, troubleshooting, excellent problem solving skills, learning and knowledge of specific software tools. By contrast, the important soft skills with reference to above engineers can be represented by the systemic thinking, proactive and dynamic attitude, adapt to unexpected situations, independent and team-based learning capability, professional communication skills, communication in interdisciplinary groups, innovative, leadership skills and ability to social ethical and professional responsibilities. In SGI 4.0, most of the time spent on simulating, testing products and/or processes and designing, therefore the electrical, mechanical and computer engineers must be comforting working with computers. Beside this, digital skill is another category of skills in energy world is needed by every end user to become digitally literate. This allows end users to use some basic web-based functions to communicate and observer real-time daily energy utilization in homes and factories. For example, in the home, the energy utilization of active machines likes washer, refrigerator, air conditions, etc. It will not only enable to optimize their energy consumption but also prevent electricity theft in homes and factories. Consequently, in the future, the partnerships between higher education institutions and smart grid industry will open new access to science and engineering studies. Therefore, to bridge this gap between the academic and industrial worlds, instant initiatives are crucial.

Table 2
QoS requirements of the smart grid applications (s—seconds; ms—milliseconds; h—hour/s).

Sr.#	Applications	Security	Bandwidth	Reliability	Latency
1	Home energy management (HEM)	High	9.6–56 kb/s	99.0–99.99%	300 ms–2000 ms
2	Advanced metering infrastructure (AMI)	High	10–100 kb/s per node, 500 kb/s for backhaul	99.0–99.99%	2000 ms
2(a)	Meter reading-on-demand	High	100 bytes	>98%	<15 s
2(b)	Meter reading-scheduled manner	High	1.6 k–2.4 kb/s	>98%	<4 h
2(c)	Meter reading-collective manner	High	>=1000 kb/s	99.0%	<1 h
3	Wide-area situational awareness (WASA)	High	600–1500 kb/s	99.0%	15–200 ms
4	Demand response management (DRM)	High	14–100 kb/s per node	99.0%	500 ms-several minutes
5	Substation automation (SA)	High	9.6–56 kb/s	99%–100%	15–200 ms
6	Outage management (OM)	High	56 kb/s	99.0%	2000 ms
7	Distribution management (DM)	High	9.6–100 kb/s	99.0–99.99%	100 ms–2 s
8	Distribution generation (DG)	High	9.6–56 kb/s	99.0%	2000 ms
9	SCADA	High	56–100 kb/s	99.0%	2000–5000 ms
10	Asset management (AM)	High	56 kb/s	99.0%	2000 ms
11	Meter data management (MDM)	High	56 kb/s	99.0%	2000 ms
12	Transmission line monitoring	High	9.6–64 kb/s	90.0%	1000 ms
13	Distributed energy resources and storage	High	9.6–56 kb/s	99.0–99.99%	300 ms–2 s
14	Vehicle to grid (VG)	High	9.6–56 kb/s	99.0—99.99%	2 s–5 min
15	Electrical vehicles (EV)	High	9.6–56 kb/s	99.0–99.99%	2 s–5 min
16	Program/configuration update (FCU)	High	25–50 kb/s	>98%	<5 min–7 days
17	Firmware update (FU)	High	400 kb/s–2000 kb/s	>98%	<2 min–7 days

3. Quality of service requirements and applications in SG

In SG various types of information from power generation to consumer applications with different QoS requirements are efficiently moved through the advanced ICTs. It is expected that by enabling various SG applications will result in the increasing data quantity unit from Megabyte, Gigabyte, and Terabyte to Petabyte. This massive amount of data from the source towards destination must be transferred in QoS manner. Hence interoperable, secure and flexible bi-directional networking technologies that meet each SG component QoS requirements are essential for the successful realization of SGI 4.0. Table 2 [6,34] shows the QoS requirements for various SG applications. In this study, we have highlighted below some of the basic quantitative and qualitative requirements must be satisfied by the ICTs infrastructure in a variety of SG applications in SGI 4.0.

3.1. Quantitative requirements

3.1.1. Latency

Latency is a measure of data transmission delay between SG components. It is one of the essential constraints since data needs to transmit immediately. For instance, in some mission-critical SG applications like WASA or DR compared to AMI or HEMs latency may be not tolerated. Hence, the networking solutions used for time-critical applications must satisfy the minimum delay requirements.

3.1.2. Bandwidth

The low, medium and high radio frequencies have their specific role based on the application requirements in SG. For short distance communication like in HEMSs, the high and medium frequency ranges can be used due to their wider bandwidth leading to higher data rates. On the other hand, low-frequency ranges can be used for high-quality long-distance communication in various smart grid applications. The lower frequencies compared to higher frequencies can avoid the LoS problems and can easily penetrate through linear and non-linear objects.

3.1.3. Data rates

The smart grid applications are generating various types of data like text, pictures, audio, video and many others, at different rates. Thus, the choice of an appropriate communication technology is essential for achieving a reliable and accurate application specific data transfers in HANs, NANs, and WANs.

3.1.4. Throughput

Throughput is the sum of data transferred between smart grid components in a specific time interval. Throughput used by the SG for communication depends on the application characteristics. For instance, the throughput required by the SG for AMI or DR communication is different from the WASA or TLM.

3.1.5. Reliability

Reliability is an attribute defines how successfully communication systems timely exchange messages according to its specifications. Therefore, it is extremely important that the communication nodes always be reliable for successful and timely message exchanges in the SG. The reliability based on the specifications varies in the SG applications.

3.2. Qualitative requirements

3.2.1. Data accuracy

Data accuracy is an essential data quality index that is directly related to the accuracy of the SG components. The data accuracy has an impact on the applications efficiency, performance and economic benefits.

3.2.2. Data validity

It is an important factor showing that how to retrieve useful information from the massive ocean of data coming from different SG components. In order to provide various services to customers in a more efficient manner, this data validity should be improved.

3.2.3. Accessibility

It means the customers must be offered equal opportunities to access SG application services without discrimination.

3.2.4. Interoperability

It is obvious that various types of communication technologies and protocols will be combined to provide efficient data exchange between diverse SG components. Therefore, the interoperability is essential in both networks and SG applications for guaranteeing standard data exchange with the same meaning.

3.2.5. Security

To protect the critical data from physical and cyber security attacks is one of the biggest issues in the SG. In all SG applications, the end-to-end secure two-way communication is essential for preventing any vulnerability to SG assets.

4. Key components of SG in the context of industry 4.0

The key components of smart grid in the context of Industry 4.0 are shown in Fig. 2 and discussed in the following sections.

4.1. IoT

IoT is a key enabling technology for the next generation industrial revolution and is associated with the development of SGI 4.0. In SG, the IoT has several potential benefits in various applications, such as smart homes, smart buildings, smart cities, smart security and several others [35]. The fundamental principle of IoT is to offer users seamless interoperability and advanced connectivity between machines, humans, services, disparate networks and in particular control systems for enabling real-time transfers of knowledge among organizations and inside organizations. In SGI 4.0, with the advent of IoT the decisions will not be only dominated by suppliers and stakeholders, but also involve consumers more in decisions about customization and power quality [36]. At the basic level, the IoT connecting various types of smart grid physical things that are able to sense, interact, process and interconnect to the Internet as a ubiquitous network. This enables real-time data collection and sharing of smart grid systems rely on the cyber layers, such as data systems and software to carry out monitoring and control logic intelligently from any remote location worldwide [37]. The efficient and effective use of this information and knowledge changes the relationship among energy suppliers, consumers, and stakeholders in SGI 4.0. Thus, the use of IoT in SG allows making intelligent systems, management decision support systems, and predictive diagnostic systems in order to increase the power generation capacity and thus result in significant financial benefits [38]. In SGI 4.0, the numerous building blocks of IoT architecture comprise of radio frequency identification, sensors, actuators, context-aware computing, cloud technologies and various wired and wireless communication technologies for intensive interconnectivity. These objects through a uniquely assigned address scheme can interact and cooperate autonomously with other traditional devices like tablets, smartphones, personal computers, etc., using web services over the internet for the purpose of collecting and exchanging data [39,40].

4.1.1. Data standards

The IoT relies on application layer which uses the collected and transmitted data from lower layers for forming a DDR base to provide tactical understanding. The application layer relies on IoT to business (IoT2B) and IoT to consumer (IoT2C) categories [41], which are appropriate for the Internet of Thing-based all general business necessities, including power and energy sector. The key technology and common standards are the two basic categories of IoT standard structure. The most common data standards comprise of BITXml (XML-based protocol), EDDL, FDT/DTM (Device Type Manager), M2MXML, NGTP, ONS (Object Naming Service), OPC (Open Process Control), oBIX (Open Building Information Exchange) and PML (Physical Markup Language). The most common software frameworks contain ArchestrA, DRM (Data Relationship Management), IDM (Intelligent Data Manager), MDM (Master Data Management), OSGi (Open Service Gateway Initiative), SaaS (Software as a Service), SOA (Service-oriented Architecture) and Sedona [42,43]. On the other hand, the IEC international standards such as IEC 61804–3, IEC 61804–4, IEC 61804–5 and IEC 61804–6 (EDDL) are used to define the equipment parameters and field instrumentation digital communication characteristics [44–46]. The IEC 62453 (FDT) is used for the communication and configuration interfaces standardization between the host system and field equipment [47]. Finally, to support a number of different equipment's from any supplier, the EDDL technology creates a single engineering environment by enabling host system manufacturers. All these common standards ensure the uniformity and simplify the job of all stakeholders in various business domains including power and energy sectors.

Fig. 2. The key components of SGI 4.0.

4.1.2. Protocols

Specifically, the applications of IoT technologies are offering various services where end users can monitor their real-time electricity consumption via online web pages in SG. From the web pages, data is transferred into connected smart grid industrial cloud through wireless or wired networks. At the application layer, for reliable and secure information transformation between your browser and the website, one of the most widely used application-level protocol for IoT is a Hypertext Transfer Protocol Secure (HTTPS), which is an advanced version of the purely textual protocol hypertext transfer protocol (HTTP) [48]. The American Standard Code for Information Interchange (ASCII) level protocol allows highly confidential online encrypted communications between your browsers, such as Internet Explorer, Firefox, and Chrome and the website. HTTPS pages typically use either transport layer security (TLS) or secure link layer (SLL) protocol based on a PKI (Public Key Infrastructure) mechanism for secure encrypted communications. The KPI system typically uses a public key and a private key to encrypt communications [49]. Every time, the website sends its SSL certificate contains the public key to a user request an HTTPS connection to a webpage for the secure session. Then, based on the shared secrets initiated by SSL a uniquely secure connection is established between the user and the website. Generally, most of the smart grid applications, such as smart metering system, home energy management, demand, and supply, asset management, etc., generate a huge amount of data, periodically. Thus, each time during transferring too much outline information it includes headers with the actual information content on the web. Moreover, during handshaking or key sharing process a cyber attack may break the connection between your browser and the website. In addition, for embedded systems that are equipped with limited power (these devices for processing microAs of data during transmission and reception and having power-ups of some hundreds of milliampere-second (mAs) and hardware resources (e.g., computational capacity and reduced memory) are facing problems during processing and transferring this huge amount of data related to specific applications. This presents a clear danger and the adoption of this ASCII level protocol may not be the best choice in order to preserve huge of amount of data coming from various IoT-enabled SG applications. Therefore, a lightweight and secure protocol that allows devices to communicate effectively with the reduced size of the packets of data exchanged is essential for the IoT-enabled SG application to empower SGI 4.0.

4.1.3. Challenges in IoT

Thus, both workers and consumers by using such as technology have improved access to this data and information on defined domains. This valuable information received from consumers allows workers to monitor, manage and optimize systems control for improving the goal of a near-zero defect state in order to fulfill the energy supply and demand of the growing world. At this stage, it is also important to note that the implementation architecture of IoT needed for SG could be entirely different than traditional IoT used for smart home appliances, smart health monitoring equipment or fitness devices [50]. The use of IoT technologies in these smart applications can improve users quality life and experiences. However, in the event of malfunctions usually, their services become unavailable without creating emergency or danger situations. On the contrary, in IoT enabled SG, wrong decision-making due to services failure or unplanned events manifestation can endanger people's lives. Hence, a distinctive reliability and sensitivity are required for the IoT technologies used for SG applications rather than traditional IoT technologies and services. Therefore, when designing and implementing the IoT technologies, the designers and engineers must take into account these requirements need for diverse smart grid applications. Thus, an IoT-enabled connected and highly efficient, reliable and secure communication architecture against failures and hacking is essential for various SG applications to empower SGI 4.0. In addition, there are other several challenges, including how are devices named and organized, track and monitoring, performance measurement and optimization, enable reliable communication between devices, privacy and security across billions of things and how to maintain the connected devices?.

4.2. CPS

The other key enabler of the SGI 4.0 is CPS. Generally, a CPS closely intertwined software and physical objects and allows different components to exchange information by interacting with each other via IoT [51]. In SGI 4.0, the modern IoT enabled ICTs connects all relevant components to observe real-time information for monitoring, control and maintenance purposes. A CPS contains various trans-disciplinary methodologies, including computer science, design and process science, manufacturing systems, mechatronics and mechanical engineering and cybernetics theory [52]. Hence, a strong integration between control systems and industrial processes using systems engineering is crucial for the realization of CPSs. The embedded systems are one of the key technical methods in CPSs. These embedded systems are consisting of various types of software and hardware that tightly integrate the physical objects with their computational services in a myriad of ways [53]. More precisely, the eponymous aspect of CPSs is the integration of physical asset and cyber components through which different components interact with each other in order to exchange information in a deterministic, reliable and extremely fast way. However, different from the traditional embedded system, a CPSs-enabled system in SG usually designed with cyber twined and physical input and output services. Thus, CPSs with feedback loop mechanisms monitor and control the physical processes by interacting with the embedded computers and networks [54]. In CPSs, the embedded computers and networks serve as headquarters for monitoring and controlling the feedback loops and performance of the physical processes in the SG. Consequently, the CPSs provide highly synchronized information related to the physical shop floor and the virtual computational space which leads to the new degree of control, efficiency, transparency and surveillance in the SG. The CPSs full potentialities in various SG applications can efficiently manage distributed processes by using data processing and analyzing, controlling the actuators and connecting to digital network services via multi-model human–machine interfaces. Thus, it helps to avoid any problems related to the energy infrastructure if appropriate action is taken instantaneously [55].

4.2.1. Architecture of cyber–physical systems

The fundamental architecture of CPS consists of two parallel networks, namely physical network and cyber network to efficiently control the various processes in SG. The amalgamation of both comprised of the structure of the interconnected components and the reliable communication links among these embedded devices. Typical CPSs in SG, use sensor-based communication to collaborate with various power generation systems (PGSs) and process data from industrial processes in order to provide different services and functionalities. This multitude of parallel and interlinked sensors and actuators rely on knowledge-based computational and engineering principles to provide new ways of human–machine interaction for controlling real-world physical processes intelligently [56]. Therefore, a large number of different types of sensors, such as light sensors, force sensors, touch screens and multi-function sensors play important roles in CPSs used for the SG. In CPSs, the micro-controllers are expected to control these sensors, actuators as well as RFID (Radio Frequency Identification) at the perception layer. To achieve the final goal of micro intelligence, this perception is used at the application layer. Thus, at perception layer the fundamental objective is to enable things with a sense of vision and intelligence while interacting with the physical world. The perception layer concerns utilizing some common sensors in IoT-enabled smart grid ecosystem for detecting motion, acceleration, vibration, weight, humidity, temperature and location. In SG, the CPSs with several wireless sensor networks (WSNs) can be used for real-time and reliable decision-making in decentralized manners for different services [57]. These devices by detecting events or changes in quantities and qualities send output to the control centers for the necessary actions. On the other hand, the RFID or DMCs technology due to their smart sensing abilities are used to identify various objects in SG. After identification, these objects through specific forms of interconnectivity can connect and interact with each other in real time. This results in creating an enormous volume of data from their sensing behaviors or movements. The relevant data from these objects either directly stored in associated clouds or passed through the decentralized self-configured workstations. The use of RFID technology not only helps the end user daily life operations, but also captures data from these utilities to enable a self-learning production. This self-learning production system instinctively adjusts its parameters for achieving product management on a real-time basis if the quality deteriorates.

4.2.2. Data exchange standards

The CBRN (Chemical Biological Radiological Nuclear), EDXL (Emergency Data Exchange Language), IRIG (Inter-Range Instrumentation Group), TEDS (Transducer Electronic Data Sheet), TransducerML and SensorML are some basic sensor data exchange standards focusing on the definitions of ISO/IEC [58,59]. These standards are focusing on the AIDC (Automatic Identification and Data Capture) method that is a global application for both IoT-enabled sensors and RFID (IEEE 802.15) technology. The key aim of AIDC technology is to provide real-time information access to the systems. Recently, IEC and ISO have developed some basic standards, such as IEC/ISO 19762:2016 that specifies definitions and terminologies for AITs [44]. Some other common standards have been developed for RFID technology. For example, ISO/IEC 15459 series describes the common rules, groupings, individual products and product packages, identification for registration procedures, individual returnable transport items and individual transport units [60]. The ISO/IEC 18000, ISO/IEC 15963–2009 series describes different unique frequency ranges and numbering systems for the identification of RFID tags [61,62]. These standards allow users to choose appropriate RFID devices based on their needs. The ISO 10374:1991, ISO/TS 10891:2009, ISO 18185 and ISO 6346:1995 series defines the communication, coding and freight containers electronic seals for RFID applications [63]. These standards endorse that the RFID tag in a variety of smart grid environments can operate efficiently. Moreover, the ISO 17366:2013, ISO 17365:2013, ISO 17367:2013, ISO 17363:2013 and ISO 17364:2013 standard series define the data hierarchy and technical aspects for RFID applications in the supply chain management [64,65]. Some other standard series like IEC/ISO 29179:2012, IEC/ISO 29176:2011, IEC/ISO 29178:2012, IEC/ISO 29173-1:2012, IEC/ISO TR 29172:2011, IEC/ISO 29143:2011 and IEC/ISO 29175:2012 have been defined to support the mobility and data capturing flexibility of AIDC and RFID [66–72]. Some other standards such as IEC/ISO 29182 standards specifies SNRA requirements for developing smart WSNs [73]. The ISO/IEC/IEEE 21451, IEC/ISO/IEEE 21450:2010, IEC/ISO 30128:2014, IEC/ISO 20005:2013 and ISO/IEC 30101:2014 series helps users to create intelligent WSNs [74–79].

4.2.3. *Challenges*

All these above-mentioned standards due to their collaborative information processing and open interfaces help users to build a more reliable and intelligent sensor network for various smart grid applications. Thus, the CPSs using advanced control algorithms are expected to manage and control the smart grid in a decentralized, autonomous and in real-time fashion. This will enable real-time data and information exchange between consumers and power plants leading to higher-quality EGD with lower costs in SG [80]. However, the integration of a large number of complex and heterogeneous subsystems in CPS applications in SG is costly and needs additional domain-specific methods, models and tools to the development process. Moreover, due to aligning every service element with all physical and ICT elements of the CPS brings several unique challenges in designing, developing, control methodologies, certifiable systems and security. In addition, the other challenges for practitioners and scholars are how to implement CPSs in time and space for various SG applications. These challenges, including the following four aspects are, cooperation between different systems, modeling and model integration, integration and verification and testing of CPSs are essential for various SG applications.

4.3. *Big data*

The smart grid is becoming more complex and more knowledge-intensive with an aggressive push toward the IoT and CPSs technologies in SGI 4.0. As a result, the data is becoming more and more accessible and ubiquitous in SGI 4.0. In SGI 4.0, the data mainly accumulates due to pervasive integration of the following various objects, such as sensors, actuators, controllers, radio frequency identification, web-based applications, transactional applications and interactive servers used for various smart grid applications, such as electricity price data, metering data, energy using data, grid systems health data, demand and response, advanced control and monitoring and others. In the coming future, it is expected that the amount of data will continuously grow with the increasing number of CPSs used in advanced electricity generation and distributing in the smart grid. This huge amount of heterogeneous industrial data stored in the distributed clouds will be available in real time via IoT technology [81–83], locally or globally. Nevertheless, up till now this valued resource of information is yet often overlooked [84]. Thus, advanced integration, collection, processing, analysis, presentation and storage systems for big data which link all the entities and data needs of the industrial process are main challenges for the realization of SGI 4.0.

4.3.1. *Big data characteristics*

This massive amount of analog and digital data has main five '5V' characteristics, namely value, variety, veracity, volume and velocity [85]. The value or variability is related to the consistency of the data, the variable contains type or nature of the data, the veracity comprises of quality of the captured data, the volume includes a quantity of generated and stored data and velocity comprises the speed at which the data is generated and being processed [86].

4.3.2. *Big data analytics*

One of the key aims of data analytic techniques is to identify patterns and interdependencies from a pool of data to support intelligent decision-making for industrial processes in the smart grid. There is no doubt this will allow power generation industries to monitor and analyze the performance of their processes, diagnose and define inefficiencies and even prediction of potential events in a more efficient way [87]. Thus, with the advanced big data analytics (BDA) the EGD processes can be revealed transparently and controlled and managed in a more efficient way in SGI 4.0.

4.3.3. *Big data structure*

In SGI 4.0, the big data coming from human, machinery, environment and manufacturing process can be divided into three basic types, naming structure data, semi-structured data and unstructured data. The data coming from power generation and distribution devices equipped with sensors, actuators, controllers, radio frequency identifications, etc., are classified as structured data [88]. The data coming from the website due to end users' activities are organized as semi-structured data. In the last, the unstructured data is based on the operating characteristics of personnel or systems that can be denoted by a variable quantity of images, audio, video surveillance, etc [89]. This unstructured data, e.g., videos of power generation systems, helps to analyze the efficiency of the operators and environment safety in the smart grid. Herein, the operator is considered as a 'target', then by employing the techniques of the noise eliminating, information reintegration and enhancement an advanced target recognition and tracking model of target motions can be constructed [90]. Consequently, by employing clustering analysis and feature extraction of the target motion trail, the motion trails and motion parameters of the target can be realized for designing an analytical model that helps to realize the target behavior with high efficiency. Thus, multi-source heterogeneous spatial industrial data will be formed, needs characterization to extract valuable knowledge and information that will most likely gain significant competitive advantages in the smart grid. In big data characterization, the unstructured and semi-structured information is converted into a structured format for reducing data barriers since the data have a different source, dimension, format and other factors. Generally, to make knowledge interpretable semantic web technology is used for semi-structured data, such as XML and by employing ontology concepts with tagging or annotation this semi-structured or unstructured data becomes standardized [91].

4.3.4. Big data attributes

In addition, the big data further categorized into two main attributes, namely time attribute and special attribute. In time attribute, one of the key objectives can be monitoring of the electricity generation process by using a different type of ubiquitous sensors installed on multiple machines to collect huge data size beyond traditional scales with different sampling frequencies. For example, during the electricity generation process in smart grid, the system vibration signals with frequency range between 10 kHz to 100 kHz can be collected. Meanwhile, the corresponding temperature of the systems can be acquired with a frequency smaller than 100 Hz in order to evaluate the health condition of the smart grid [92]. Thus, in different time scales both diverse signals can be extracted efficiently. On the other hand, in spatial attribute several spatially independent power generation systems are integrated and the output is regarded as the sum of each system. For example, the energy consumption of independent resources, such as air conditioning, illumination, generator, step-up transformer, step-down transformer, electricity cables, pylons, turbine, boiler, furnace, etc., can be represented as overall energy consumption of the smart grid. During energy consumption analysis, the consideration of spatial attributes of this information can make the complex system more clear and transparent [93]. The integration of these two aspects is called the spatiotemporal property of big data.

4.3.5. Challenges in BD

The characterization of big data with unique spatiotemporal property can provide more accurate and transparent information to intelligent power generation systems, which may assist to reduce total cost and improve power quality in the smart grid. Generally, the processing of big data comprises of dimensionality reduction, performance evaluation, and prediction, data formatting, etc. Revealing the numerous characteristics of big data by employing advanced data mining techniques offers several benefits in smart grid, such as ensuring predictive maintenance, achieving near-zero downtime, improving overall system performance, sustainable innovation and more. However, the analyzing of larger and too complex datasets requiring, an integrated big data processing environment to reveal the unknown correlations, hidden patterns identification, customer preferences, market trends and other valuable business information is challenging. In addition, the other main challenge is how to store and retrieve this big data with respect to applications priority in a robust manner?. In this context, the adoption of cloud computing may be beneficial in the smart grid. Moreover, the reliability and safety in intelligent decision-making at the right time for the right purpose is another challenging issue in the smart grid. This big data will continue to play an increasingly important role to provide predictive maintenance for improving system reliability or designing new solutions in highly complex, automated and flexible industrial systems in the SG. Thus, emerging and effective big data technologies, such as data deep mining, stream data processing, data clustering, cloud computing, envelope analysis and machine learning are crucial to pursuing the goal of efficiency, scalability, economics, and harmony in SGI 4.0. The development of these advanced analytic techniques for dealing with an abundance of operational and shop-floor data will be challenging in SG for various applications. Under these facts, the big data environment has become a hot spot for both academic research and practical application in SGI 4.0.

4.4. Cloud computing

In SGI 4.0, a vast volume of analog and digital data is generated by several IoT-enabled CPS sources, which requires a big data storage, cleaning, mining and high-performance computing techniques to enhance sustainable innovation of the smart grid [94]. In this context, the idea of clouds originated from a search engine platform, offers a new way of providing high-performance data storage, computing resources and services at low cost for various SG applications. The cloud is an advanced hope-inspiring technology for enabling EGD model to transform resources into services by employing the support of virtualization, CC, IoT and service-oriented technologies that are scrupulously shared and circulated [89]. The cloud currently is an important platform that provides a highly stable connection between the network and application layer components for utilizing these resources and services efficiently. Therefore, it is regarded as an intelligent, parallel and the networked model which covers the entire lifecycle of EGD from its design, production, testing, and maintenance, intelligently in the smart grid. In the clouds, the virtualization technology enables CC with highly dynamic allocation, resource sharing, flexible extensions and several other features of the computational layer [95]. Consequently, the CC technology offers a number of various types of services to users depending on application need such as software, hardware, storage, security and access to computers and systems use in SG. These computational services and scalable resources from the cloud can be accessed on-demand, anytime from anywhere on the Internet for all types of smart grid end users. The existing studies in CC have been listed in Table 3.

4.4.1. Cloud computing services and characteristics

Generally, an ideal cloud for SG applications must have five basic characteristics, including on-demand self-service, resource pooling, quick elasticity, wide network access and measured service. Moreover, to provide a uniform and ubiquitous access to end users for services sharing, private, public and hybrid clouds are essential for SG applications [117]. In private cloud, each SG utility rely on the SG application's requirements has its own internal data center which works like a private network. This private cloud is assumed a highly secure, reliable and confidential model that does not allow other utilities to access its immediate services. The SG services only can be accessed via SLA or by outsourcing the private cloud to an external service provider who has the right to manage and control all infrastructures. In public could, the deployment models for SG applications works like a public network. Unlike the private cloud, the resources for various types of SG application are shared where users pay per use of smart grid services based on the conditions offered. The end users can access SG services that are located in different utilities, locally or globally, via the Internet. However, it requires cloud service provider agreement for accessing services [114]. The entire services in public cloud are standardized and fully managed by the service provider in order to satisfy diverse SG application's requirements. The hybrid cloud model is the integration of both private cloud and public cloud in which SG services are processed, analyzed and combined in the private cloud and then shared to all other utilities by employing public clouds.

4.4.2. Cloud computing infrastructure

In addition, SaaS, PaaS, and IaaS are the three basic delivery models for easy access to various application services in SG. The key aim of the IaaS is to provide database, networking, storage, operating system and specific architectural requirements on the cloud for various smart grid applications to meet high efficiency while handling extensive workloads. The performance of IaaS can be enhanced significantly for SG utilities by enabling integration of various types of resources from different vendors in CC [120]. This will allow CSPs to modify, repair and maintain information and architecture of the SG applications and utilities on an immediate basis. The PaaS offers an environment for deploying various types of SG applications, however, without taking the responsibilities to control or manage the fundamental cloud infrastructure. The PaaS

Table 3
Existing studies in Internet of Thing (IoT), CPS (cyber–physical System), IoS (Internet of Services), BD (Big data), CC (Cloud computing), CS (Cyber security) and CTs (Communication technologies).

Sr. #	IoT	CPS	IoS	BD	CC	CS	CTs
1	Wollschlaeger et al. [36]	KoutsouKos et al. [96]	Wanyama et al. [3]	Jose and Ramakrishn [83]	Sarkar et al. [97]	Wang and Lu [98]	Gungor et al. [99]
2	Trappey et al. [42]	Gai et al. [100]	Trappey et al. [101]	Zhang et al. [85]	Gai et al. [100]	Sun et al. [7]	Koenig et al. [102]
3	Majeed et al. [38]	Trappey et al. [44]	Theorin et al. [103]	Yan et al. [92]	Sookhak et al. [89]	Wei et al. [104]	Jamil et al. [105]
4	Sofić et al. [41]	Khalid et al. [56]	Sung [106]	Klievink et al. [82]	Kim and Kim [107]	Langer et al. [108]	Faragher and Harle [109]
5	Kshetri et al. [40]	Bangemann et al. [47]	Wan et al. [110]	Santos et al. [84]	Tao et al. [111]	Basharat et al. [112]	Song et al. [113]
6	Faheem and Gungor [16]	Liu et al. [53]	Majeed and Rupasinghe [38]	Coletta and Kitchin [93]	Stojmenovic [114]	Thames and Schaefer [115]	Emmanuel and Rayudu [116]
7	Faheem and Gungor [1]	Shakshuki et al. [54]		Sookhak, Gani, Khan and Buyya [89]	Rusitschka et al. [117]	Von Solms and von Solms [118]	Erol-Kantarci and Mouftah [119]
8	Rani et al. [50]	Khan et al. [52]		Lam et al. [86]	Bai et al. [120]		Galli et al. [121]
9	Abbas et al. [122]	Jazdi [55]		Wang et al. [88]	Fazio et al. [58]		Ghavimi and Chen [123]
10	Trappey et al. [44]	Sanders et al. [51]		Khan et al. [81]	Bhardwaj et al. [95]		Li et al. [124]
11	Lee et al. [35]			LaValle et al. [87]			Hirschman et al. [125]
12	Aijaz and Aghvami [37]			Boyd and Crawford [90]			Robalo and Velez [126]
13	Farooq et al. [39]						Mahmood et al. [127]
14	Wang et al. [43]						Alonso et al. [128]
15							Feng et al. [129]
16							Bennett et al. [130]
17							Shaukat et al. [131]
18							Nisar et al. [132]
19							Swain and Das [133]
20							Khedr et al. [134]
21							Chakraborty et al. [135]
22							Cena et al. [136]
23							Al-Maqri et al. [137]
24							Faruk et al. [138]
25							Bouhafs et al. [139]
26							Sum et al. [140]
27							Weyrich et al. [141]
28							Batista et al. [142]
29							Rehmani et al. [143]
30							Mahmood et al. [144]

by an order of magnitude simplifies the process of software development for the SG utilities and especially focusing on the service functionalities. This allows SG utilities to build concentrate applications without considering the solid development environment because some of the details are hidden from the end user in PaaS, unlike IaaS. In the last, SaaS through a web browser provides SG application services to authorized users [95]. These services running on a cloud infrastructure via the Internet are installed on the power utility's systems hardware. The cloud vendor is responsible to gives permission only to authorized users for accessing various services through their installed application program interfaces since the vendor has complete control over the applications in terms of security, update, manage, maintain and capabilities. Thus, it offers the advantage of better efficiency, reliability, and security of the SG systems.

4.4.3. Cloud computing virtualization

Recently, cloud computing due to its relative innovation and exploding development has gained an increasing attention in both academia and industry. The several modernized virtualization concepts based on CC have been developed for EGD and SG applications, including Mobile Computing (MC), Fog Computing (FC) and Edge Computing (EC). The key aims of these novel virtualization technologies are to enhance CC in terms of mobility, location-awareness and fluctuating latency. MC helps to improve response efficiency of the network by enabling processing closer to the devices [100]. In MC, the data storage and computing power move outside of the mobile devices and into the cloud. On the other hand, the EC extends FC in terms of some analytics, processing, communication and decision-making to end devices in SG. Also, FC offers some several similar opportunities in MCC and MEC. In MEC, to achieve better performance, the CC capabilities to the EMN are bringing nearer to the mobile objects [97,145]. Thus, to reduce complexity MCC could be seen as a bridge that fills the gap between computing resources and processing requirements of various SG applications. For example, smart meters are used to track the real time-consumer power usage that helps to estimate demand sites and supplier mismatch in the SG. However, handling up to several hundred thousands of consumer information for meaningful decisions is very difficult for SG meters since it involves massive information retrieving, analyzing and processing capabilities. This requires semantic information, stream processing in a distributed manner, machine learning, pattern mining and various software tools and techniques for reliable decision-making. To this end, the use of cloud computing platform can easily manage these entire transactions and provides reliable and scalable communication environment at low cost in SG. Therefore, it is anticipated that clouds will be the next revolutionary integral part of the SGI 4.0. As a result, several vendors have started to offer cloud-based solutions in which systems can monitor and control processes of various SG applications [117,120].

4.4.4. Computation standards

The computation layer enables all above-mentioned CC services and resources for SG applications and bridges the service's decision to the application layer. The computation layer offers some hardware standards, such as Arduino, BeagleBone, Cubie-board, FriendlyARM, Gadgetter, Intel Galileo, Mulle, Phidegts, Raspberry PI, T-Mote Sky, UDOO and WiSense. The software standards, including Andriod, Contiki, LiteOS and TinyOS. The ISO/ IEC 27033 series minimizes information security risks and ensure the security of information and network [146–148]. The IEC/ISO 29180:2012 series has been used for ubiquitous SNs for ensuring the security [101]. The sensor-related hardware, software and security technologies can be run in the CC environment for offering different services for SG applications.

4.4.5. Challenges in CC

The cloud computing-enabled AMI can significantly improve the balanced power supply and demand in both peak and non peak hours. Moreover, several critical interaction issues between the users and power utility provider, e.g., for demand-side management application can be successfully addressed with CC technology and approaches to improve the customer needs and shaping of the load in SGI 4.0. The advances in CC technologies will enable various smart grid enterprise and analytic applications to achieve power generation, distribution and consumption-related undertakings reaction times of just several milliseconds. As a result, more and more data-driven services for EGD systems will be deployed in the clouds for real-time sharing across sites and company boundaries. However, the reliability of cloud computing is affected by several critical challenges, including the location of the data, mixing of data, compatibility, redundant data management, disaster recovery and insufficient cloud security policy. There are also many other challenges related to cloud computing, such as data loss or delete, data location, data lock-in, data segregation, data integrity and theft, characterizing structured, restitution of data, bandwidth limitations, cloud interoperability, fault tolerant, energy-related issues and modeling invisible factors. Thus, cloud computing and advanced data mining techniques are essential in order to increase the capacity and scalability of resources for various SG applications.

4.5. IoS

The evolution of IoT for the combination, utilization and retrieval of rich information resources already has shown the direction of the future Internet. The IoS is a key enabler of IoT and another main pillar of SGI 4.0. The idea of IoS is similar to the IoT, however, unlike IoT, the IoS is applied to services rather than physical entities [103]. The IoS infrastructure uses the Internet as a medium to offer and sell services for gaining a competitive advantage over competitors in energy markets. Consequently, the vision of IoS under IoT perspective is to allow everything as a service on the Internet to explore hidden energy markets. This includes different types of software, hardware, standards, tools and platforms for developing SG applications and delivering services to customers [149]. With respect to that, the CC technology is the key foundation of the IoS deployment to service energy utilities. The IoS in CC acts as a bridge between service providers and customers to provide the technical basis for creating industrial business networks. Considering these advanced business networks models, the entire EGD enterprises will work together under the umbrella term SGI 4.0 [110]. Thus, the energy utilities will be able to design and provide novel value-added application and services and make them easily available for the customers through web technologies. This enables participants to utilize and offer both internal and cross-organizational services via IoS for proving high-quality universal services [150]. Therefore, the advances in IoS will bring new opportunities that profoundly change the way of services to customers in the SG, worldwide.

4.5.1. Web 3.0/4.0

One of the most important undertakings is the description of services for the IoS in SGI 4.0. In today's IoS for SGI 4.0, experts with technical sophistication developed the content or functionality of the services that are mostly set up by technically unsophisticated end users [38]. The web-based platform is emerging that permit end users who do not have the specific skills of web programming to create, manage and publish content of various types of SG application services for customers. With the recent advances in web-based technology, the energy utilities with more and more emerging applications will be able to exchange information instantly and interconnect their functionalities between end users and suppliers in real time. This will ultimately improve the power quality, productivity, customers and utility relationship as well as flexibility regarding the external requirements dynamics [151]. Therefore, in the near future, the web-based resources will be consumed rapidly by both energy enterprises and end users in the SGI 4.0. All these functionalities and services will be summarized under the web-based platforms Web 3.0/4.0 [152]. In the context, the envisioned IoS in SGI 4.0 has three major categories, including stakeholders, applications and technology. The description of exact functions of consumers and intermediary players and the characteristics of resource providers are the main responsibility of the power industry stakeholders. The key paradigms of application development and the types of available resources for applications management are the main components of applications, e.g., AMI, DR, ER and others. Finally, the messaging protocols, resource composition and resource interfaces are the fundamental components of technology deals with. However, the traditional IoS designed for IoT do not seek and consumer electronic services, but mostly used to gather information from applications, e.g., AMI, through the web-based resources. Hence, modern web-based services are essential under the web-based platforms Web 3.0/4.0 for SG applications.

4.5.2. *Protocols*

Generally, the terms service, web service and e-service sometimes have the similar concept which is widely used for referring. These terms by employing a uniquely identified URI are used to identify an autonomous software component, which can be accessed through specialized Internet protocols (IPs) like HTTP, Simple Object Access Protocol (SOAP) or XML [153]. The IoS using these web services as technological entities use to combine and correlate different operational processes and IT aspects into SG service descriptions. The SOAP defines the message data format to be sent between requesters and service providers and build abstract layers by providing a basic messaging framework. The REST is an architectural style which enables seamless interaction between web clients and arbitrary web resources thereby exchange XML-based messages. The Uniform Resource Identifier (URI) allows web users to identify unique resources and operations [154]. By using HTTP verbs and resource identifiers, end users may invoke REST-based services and demands the transfer of specific information which can be provided in the form of an XML-file. The web-based protocols or web-based programs are used to make available the web services which are basically e-services for consumers. The opportunity for alternative concrete technologies becomes more open for e-services by separating the technical and logical layer specifications of a service. Presently, the IoS offers SOA, RPC and RESTful web services as basic services for the various SG applications in SGI 4.0 [155].

The SOA web services follow SOA architecture relies on "message" as a basic unit of communication, thereby referred as "message-oriented" services. In SOA web services, WSDL is used to provide loose coupling since the focus is on the "contract" [150]. The WSDL describes the technical aspects such as data types, method names, arguments, Internet addresses, ports and implementation aspects like how a web service can be remotely invoked and accessed over the web. In SGI 4.0, the SG applications depend on WSDL-based interface standard are intended to encapsulate as standardized services of application access in IoS. To this end, information interfaces already have been observed as a first advanced development which enables stateful composition of a huge number of services in a proficient fashion. However, to attain this in a more realistic manner bring several unique challenges, including structure, semantics and wide agreement on standards for exchanging information in the course of these energy utility processes. The RESTful web services use HTTP to perform well-known operations, including DELETE, PUT and GET. The main purpose of RESTful web service is to interact with stateful resources. Last, the RPC web services use RPC programming functions and methods for searching entities. In addition, some researchers allow integration of CORBA into web services [156].

In SGI 4.0, the proprietary portals are used to access smart grid information and applications from the web. In this context, the most widely accepted standard HTML is used to represent the information uses some meta-information. This meta-information is usually machine-readable due to non-standardized assembly. However, the website owners recently decided to use XML-based files that follow the RSS standard to support rapid contents aggregation from arbitrary sources instead of publishing energy utility data in a static HTML-based fashion on the web. Moreover, easily deployable and widely accepted languages like BPEL are anticipated to prevail in the envisioned IoS [157]. In addition, in web technology, the semantic annotations rely on RDF, RDFS and OWL meta-languages. RDFS is the extended RDF vocabulary which intended to describe taxonomies of certain classes and properties [158]. This concept is further extended by ontologies which use an OWL. To this end, the SWS by using semantic annotations enrich traditional web service technology to provide a composition of program functionality and automated discovery. The recent research in SWS has yielded WSMO framework associated with WSML representation language family and using the execution environment WSMX prototype implementation of WSMOC [159–161]. The UN/EDIFACT standard may be used for point-to-point message exchange interfaces for SG applications [162].

Presently, the publicly available SG applications service registries are foreseen by readily available UDDI standard based web services stack. The UDDI standard offers services to users through human-readable interfaces [163]. However, due to very limited functionality at technical experts level the traditional UDDI standard is not adequate to satisfy the user's service requirements in SGI 4.0. Realizing the facts, some efforts already have begun at intermediaries level for advancing the role of traditional UDDI-based implementations to offer richer resource registry functionality [164]. Some of these advances provide transparency and sophisticated navigation functionality for users. A high degree of transparency is offered by the intermediaries to users in order to find dedicated web resources for different smart grid applications. It does not only provide statistics about resource information, availability, and performance of the end users but also contain references to services [165].

4.5.3. *Opportunities and challenges in IoS*

The IoS will allow end users to efficiently access various functionalities or contents by leveraging a plethora of non-functional and functional resource attributes created by others. Thus, it significantly enhances the predictability and reliability of resource provision and utilization and decreases uncertainty in a worldwide energy utility economy that empowers the realization of SGI 4.0. With respect to that, the advanced types of intermediaries are essential for facilitating the emergence of the Internet of Services towards the smart grid utilities. The intermediaries besides guaranteeing the predictability and dependability of electronic services also act as rich service registries for power utilities. The independent institutions that enforce and control the compliance of both consumers and resource providers should have to be established. This will allow power industries to offer and consume mission-critical resources and functionality to individual requirements through the web over the next-generation Internet. However, formal rules, enforcement mechanisms and the proper establishment and application of informal constraints are necessary to reduce transaction costs in the ever-increasing SG services and boost energy economic for all new players. In addition, innovative approaches for the development of smart grid applications must rely on modern agile methodologies such as xtreme programming (XP), instead of traditional V-model or Rational Unified Process (RUP) model [166,167]. Moreover, the other challenges for IoS, including interfaces compatibility, browser compatibility, screen resolutions, web technologies, equipment deployment, authenticating security, tracking user activity, guarding data so that end users see what they like to see, standardization and many others. Thus, more advanced platforms and tools, which allow users to compose resources on the web from almost arbitrary locations with little technical expertise are crucial for various types of SG applications.

4.6. Cyber security

In SGI 4.0, various types of seemingly independent systems, including IoT, IoS, CPS, CC, and applications are interconnected with diverse underlying CTs, ownership and management yielding high complexity in the SG. As a result, the probability of unintended access and flaws increase the possibility of security breaches and data leaks which may lead to large-scale catastrophic failures in the SG [112]. Moreover, it is quite clear that a large amount of raw data collected from heterogeneous devices and end users through these systems may also contain a variety of known and unknown vulnerabilities on the user's personal and behavior profile. The exploitation of these vulnerabilities may allow attackers to launch various attacks for compromising AAA, non-repudiation, and confidentiality of the SG systems [168]. For instance, a cyber attack in metering systems can manipulate data due to lack of reliable user authentication system. Also, due to massive malicious attacks and intrusion on data storage center and data backup measures may result in data recovering failure or data management chaos leading to inappropriate grid systems control. Furthermore, an attacker with the vulnerabilities might penetrate in a network and cause load conditions alteration after gaining full access to control software destabilizes the power grid in unpredictable ways. Therefore, the two-way communication among customers, generators, substations, distribution systems and power equipment must employ these crucial information security problems in SGs. Moreover, presently in PTD and EGS networks, several endpoint devices are placed in an insecure environment openly, which make them jeopardize to malicious physical attacks. Thus, the cyber security not only focuses on unintended compromises of valuable information in a case of natural disasters, equipment failures or user errors, but also deliberate attacks from terrorists, disgruntled employees and industrial espionage in SG. The cyber attacks will not only yield cascade effects on significant losses of the grid technological and financial benefits, but also hurt the energy concerns reputation [98]. Hence, it is essential that the energy utilities need to increase awareness and ensure security on new failure modes in SG systems before they become large-scale problems. Besides, an increasing SG security from malicious attacks and unauthorized accesses can be realized by improving the capacity available for monitoring and updating network configuration during operations.

4.6.1. Internal and external attacks

Presently, internal attacks and external attacks are two types of performer-oriented attacks rely on location in the power grid. In internal attacks, a node or a group of malicious nodes act legitimate and directly establishing links with neighboring nodes and slowly inflict havoc of the network. The compromised nodes generate the wrong type of routing information or malicious nodes with a valid signature using their private keys and transmit it to other nodes in the network. Consequently, inside attacks once trusted by the network, the malicious nodes parade as legitimate nodes then can launch different attacks to damage the network by suppressing important information from reaching the base station. Therefore, to handle and identify the internal attacks is more difficult compared to external attacks since it occurs due to trusted nodes in the SG systems network [104]. On the other hand, the adversary exhaust the resources of a node or a group of nodes in external attacks which results in advertising wrong routing information. Unlike internal attacks, these malicious nodes in external attacks do not belong to the network. These types of attacks are injecting fake or unnecessary packets causing additional overhead and congestion, which interrupt the performance of the SG systems network.

4.6.2. Active and passive attacks

In addition, active attacks and passive attacks are two different categories of external goal-oriented attacks in SGI 4.0. Inactive attacks, an attacker usually monitors, observes and modifies the data to assume control over the network for interrupting the functioning of the power grid [169]. There exist many types of active attacks, including alteration of data, black hole/sinkhole, fabrication, false node, hello flood, jamming, message corruption, node malfunction, node subversion, node replication, sybil, spoofing, selective forwarding, wormhole and DoS [115,118]. On the contrary, in passive attacks, an attacker unceasingly monitors and gathers systems sensitive information without interfering or interrupting the network operations. There exist many types of active attacks, including traffic analysis, selfish misbehavior, snooping and eavesdropping. Thus, many network users due to disclosure of malicious data become inept to track the passive attacks [96].

4.6.3. Layered attacks

In addition, there are various types of layer-orientated attacks targeting different layers of the network protocol stack in various SG applications. At the physical layer, the common attacks, including eavesdropping and jamming channels and interference which may lead to DoS attacks [170]. The malicious eavesdropping attacks mainly have two types, namely jamming and eavesdropping. The malicious jamming attacks often happened due to untrusted equipment or devices may pass the authentication in SG systems. On the contrary, the malicious pining attacks are due to masquerading as legitimate nodes to access private information in the network. On the data link layer, the common attacks consist of selfish misbehavior, malicious misbehavior, and traffic analysis. Basically, these attacks by violating the established communication protocols targeting the functionality of link layer protocols. At the network layer, the common attacks are, link spoofing, routing table flow poisoning, information disclosure, route cache poisoning, resource consumption, byzantine, packet replication, wormhole, sybil, black hole and rushing attacks [171]. The key aim of these attacks is to disturb the routing functionality of the protocols at the network stack. The common attacks on the transport layer, including session hijacking and flooding which consume node resources by flooding it with connection requests. In the last, unauthenticated application and policy enforcement attacks on the application layer result in data corruption or invalidation. In addition, on the multi-layer, the common attacks, including DoS, distributed DoS, synchronized loading, jamming and impersonation attacks. Lastly, the data leakage can occur on secure sockets and transport layers due to lack of true vulnerability.

4.6.4. Standards

According to EPRI, the cyber security of EGD systems is one of the emergent requirements in the future transition of electrical distribution grids. Presently, some standards bodies like IEEE, Industry Standard Architecture (ISA), NIPP, NIST, IEC, and NERC-CIP, are working on the development of scalable, secure and consistent communication systems for various smart grid applications in SGI 4.0 [172]. Since these standards bodies will drive the SG security requirements the collaboration with them is extremely important to ensure a highly reliable and secure SG deployment in the future. Up till, more than 75 SG standards have been identified by NIST mainly focuses on interoperability, architecture, reliability, cyber security, system maintenance and communication technologies for realizing the vision of the smart grid. In this context, a roadmap NIST report 1108 on SG interoperability was published by NIST [173]. It defines, specifies and guides the power utilities about implementation standards, conceptual reference model, the vision of the smart grid, security assessment procedures, expected functions and services, application and requirement of communication networks and the priority action plans for the implementation of smart grid. The basic information security issues have been addressed in NIST report 7628 for the SG [173]. The NIST report 7628 aims to identify the information security issues in SG. It mainly presents specifies of the security requirements, explains the security architectures and specifies critical security challenges in the SG. Moreover, the key management, cryptography, privacy, and vulnerability analysis have been discussed in the context of security strategies for SG.

The NIST report 7628 particularly focuses on the communications reliability and security for the automated energy management in SG [174]. The IEC 62351, IEC TC57 and WG13standards discuss the reliability and security issues in the SG construction [175–178]. Particularly, the IEC 62443 series provides comprehensive security protection as well as security to control systems in SG [179]. The SGIP and Cyber Security Coordination Task Group (CSCTG) were established by NIST that includes participants from various standards organizations, manufacturers, regulatory organization, federal agencies and academia [107,180]. The key aim was to support the development of standards under the energy independence and security across all the smart grid domains and components. The Codes and Standards Working Group (CSWG) draft document NIST-IR 7628, is continually evolving [108]. The CSWG interacts regularly with Standards Development Organization (SDO), ASME, AFCEN, CSA, JSME, KEA, NIKIET and particularly World Nuclear Association's (WNA) for co-operation in nuclear reactor design evaluation and licensing for energy purposes.

The NIST, USA DOE's and GWAC have approved DEWGs for H2G, B2G, I2G, T&D and P&P [181–188]. Moreover, there are some other securities and energy-related standards such as NIST SPs, FIPS (Federal Information Processing Standards) 201, ISO 17799 and DISA-STIGs can be applied on SG [189]. The ISO/IEC18883 is designed for secure communication interface; certificate management and authorization management may be used to provide reliability in SG [190]. The IEC 61850 standard is appropriate for communications, the American National Standards Institute (ANSI) C12.20 standard can be used for metering accuracy; the IEEE 1588 is for equipment clock synchronization and time management in SG [191]. The M441 standard provides interoperability, reliability, and security for the deployment of smart metering systems. Many of the above standards are mainly focusing on communications security in terms of privacy, authorization and authentication technologies [192]. The FIPS has permitted AES standard and 3DES solutions for providing high performance and strong security may be used for various types of SG applications [193]. However, NIST expected that by 2030 the 3DES solution would likely become insecure, as there is a risk of compromising the systems in SG [23]. Thus, AES might be the preferred solution expected to have long lifetimes for new components in SGs.

4.6.5. Challenges in CS

Taking into account above-mentioned facts, it could be realized that the security is very challenging and fruitful research area in SG. The terrorists, industrial espionage, and the inadvertent compromises are the attacks currently smart grids is facing. In addition, the smart grid due to employing two-way communication compared to traditional power grid become more prone to cyber security attacks since it directly exposed to malicious users. Therefore, the fundamental question is how to provide physically and virtually security to millions of micro and macro CPSs for reliable and healthy cooperation between them in a timely manner?. This requires extensive research for the development of new tools and techniques to realize the vision of a secure smart grid industry 4.0. Generally, the cyber security offers several benefits in SG like identify cyber risks and respond fast; deep inspection of the data, industrial assets and know their cyber security risks; high availability and support to customers and power utilities; host identity verification to protect control and data integrity; instantly prevent users and systems data theft; protect intellectual property and confidential information of users and systems in SG and many others. However, realizing the vision of a new democratic, sustainable and secure SGI 4.0, some novel security techniques as well as software and hardware tool are essential. The 'profile-then-detect' method may be useful to identify the DoS attacks. In addition to the cyber security, the anomaly detection, and risk assessment, analytical methods must be taken into consideration to enhance the ability to deal with the faults, detecting and handling security breaches for improving the automation level in SGI 4.0.

4.7. CTs

The CTs is the key component that forms the basis for SGI 4.0. The key aim of the CTs is to provide a sophisticated, reliable and fast communication infrastructure that enables the automated exchange of information among the huge amount of distributed CPSs in SGI 4.0. This real-time exchange of meaningful information from the entire production and consumption floor will allow energy utility companies to monitor, control and manage grid operations in a more efficient, reliable and flexible manner [99]. The advancements in CTs will form the interface between the physical and the virtual worlds for exchanging instant industrial information is seen as a real game changer for grid industrial networking in SGI 4.0.

4.7.1. Private and public communication infrastructure

Presently, the CTs infrastructure can be separated into private or public in SGI 4.0. The fundamental aim of both CTs at the communication layer is to provide intelligent self-awareness and increasing reliability for various SG applications in SGI 4.0. The public network, such as Internet offers several alternative communication paths because of its already existing shared communication infrastructure for remotely monitor and control the SG. However, the design and implementation of these CTs in a two-way manner is extremely challenging due to security and diverse QoS requirements of various SG applications [116]. This requires integration of various types of communication networks, ubiquitous computing and cyber security in SG. Therefore, it is extremely important that utilities should understand the various QoS requirements of smart grid applications before deploying the communication infrastructure for the SGI 4.0. To this end, a detailed performance analysis of public versus private network in terms of cost and benefits can help energy utility companies for the SG applications deployment.

4.7.2. Categories of data transmission at communication layer

The WAN, NAN, and HAN are basic transmission categories of communication layer in SGI 4.0. The main three tiers, namely core backbone, backhaul distribution and the access point are located between these networks. The various types of networks like wired or wireless or fiber networks are used to provide communication between core backbone utility center and backhaul aggregation points in the SGI 4.0. In SGI 4.0, the links between the core utility systems and grid are established through WAN which consists of two basic types, namely backhaul and core networks. The backhaul network combines and interconnects NAN to the core network which combines and connects the metro networks of utility and substations. Thus, the WAN combines multiple NANs as a backbone communication network for conveying aggregated data from end users to control center of the power utility. Consequently, it facilitates system planning, protection, and operation for real-time monitoring and control of different SG applications. This particular covering various EGD domains containing a huge portion of delay sensitive data needs high reliability over long-distance two-way communications among distinct DAPs in SG.

These DAPs, including energy resource stations, substations, control centers, electricity generation plants, distributed PTD grids and many others. Thus, the transmitted data between the control center and wide area networks are anticipated to be several thousands of terabytes. The data rates for smart grid control, monitoring and security applications at various DAPs in wide area network can change between 10 and 100 Mb/s, with covering a very large area of tens of kilometers [172]. The WAN provides connectivity to customer premises for supporting numerous applications within HAN, BAN, and IAN. Therefore, functionally of the WAN remains a hub for the e2e SG network as it connects all of the domains for enabling grid-wide control, monitoring and protection applications at the power layer. However, the data rates from 10 Mb/s to 1 Gb/s with a range of nearly several hundreds of square miles supporting thousands of supported devices are suitable for the low latency smart grid for monitoring, control and security applications in wide area networks. In WAN, underlying the wired technologies like the DSL and PONs are prime candidates due to their long-distance coverage with high data transfer rates can be employed between the control station and substations in SG. However, PON has more superiority than DSL due to extremely low network latency and high data rates. Through some wired technologies like IP/Multiprotocol Label Switching (MPLS) and Synchronous Optical Networking (SONET), the Metro Ethernet can be implemented as a core network in SG [194,195].

The NAN sometime indicated as a FAN covering the domain of distribution and transmission in SG. In customer domain, various endpoints in the NAN are supporting diverse smart grid applications, such as power quality monitoring, DA, OM, and others. Generally, a NAN is comprised of diverse applications, including pricing, distribution automation, meter reading, demand response management, electric service prepayment, smart metering, updates regarding firmware and several others. Many of these applications are equipped with various smart sensors for gathering information to support functions like sharing consumption data with in-home displays, supporting air conditioners or cycling heaters switching off during peak load hours. A NAN clustering network that may cover several square kilometers which consist of a few hundred to thousands of nodes (e.g., smart meters) depending on the communication technology and smart grid topology (distributed or centralized) used, may need data rates ranging from 100 kb/s to 10 Mb/s. The substation and distribution automation applications using the IEC 61850 standard achieve interoperability between M2M and IEDs communication within NAN. The delay requirements for mission-critical applications information based on the IEC 61850 protocol may vary between 3 and 10 ms in the SG. Consequently, the NAN usually covers the area around 1–10 square miles with data rates up to about 10–1000 kb/s, higher than HANs. Thus, HAN requires less coverage area, low data rates and secure communication links having power consumptions in the SG.

The fundamental purpose of HAN is to provide connectivity to any specific service point of the home through the backhaul of a utility service provider in NAN. More precisely, the communication link in customer home premises such as solar panels, plug-in electric vehicles, small-scale wind turbines, smart meters and power consumption control tools, storage devices would be the main responsibility of HAN. The various types of CPSs equipped with sensors, Z-wave, Ethernet, Bluetooth and Zigbee-based WSNs and RFID are linked to a centrally controlled HAN gateway through highly reliable, robust and low bandwidth NAN channels [105,109,122,196–198]. In addition, the smart grid applications are operating using two common types of CTs, namely wireless and wired networks as given below.

4.7.2.1. Wired communication technologies. Currently, most of the SG critical applications are relying on wired networks using copper or optical fiber technologies. These networks perform better in terms of extremely low interference, reliability, security, and bandwidth with high data rates in SG. Generally, the data rates for Ethernet (IEEE 802.3) are varying from 1 Gb/s to 10 Gb/s for length 100 m to 30 m using Cat5 to Cat8 copper cables are suitable for HANs/IANs/BANs [199]. In addition, the wired technology, namely DSL is used to convey digital information over telephone lines from customers' premises to control center with maximum speed up to 1 Gb/s over a distance around 500 m [113]. The symmetric and asymmetric DSL are two main categories of DSL having different download and upload speed can be used in NANs.

The other main competing wired technology is a power line communication (PLC) that enables bi-directional communication by transmitting modulated carrier on the existing power line cable for automation of the power grid. The existing PLC can be categorized into narrowband power line communication and baseband power line communication in SG. The narrowband power line communication operates between 3 kHz and 500 kHz bands which is further categorized into a high data rate narrowband PLC and low data rate narrowband PLC [121]. The first technology operates between 2–250 MHz and provides up to several hundred Megabits per second (Mb/s). On the other hand, the second technology provides data rates up to 10 kilobytes per second (kb/s) using a single carrier and 1 Mb/s when multi-carriers are used [168]. The PLC in smart grid environments is most useful for the applications such as remote monitoring, advanced metering infrastructure, and many others.

Lastly, the data rates for fiber optics are varying from 1 Gb/s to 40 Gb/s with specific length [129]. For example, the data rates from 10 Gb/s to 100 Gb/s for the length of 40 km to 1 km in single mode fiber and from 10 Gb/s to 100 Gb/s for the length of 1 km to 100 m in multi-mode fiber are suitable for control and monitoring applications in SGI 4.0. In addition, fiber optics with higher data rates up to 1 Tb (Terabits)/s are under development [102] can be used as a backbone between WANs and NANs. In SG, to connect substations with utility companies control centers, the optical communication (OC) is used as a backbone network in the electric grid environment due to various advantages like extremely low latency, immune to electromagnetic interference, high data rates and range up to several hundred kilometers [200]. The optical communication can be categorized into active and passive optical networks. In first technology, manageable active devices are used which can support nearly 80 km depends on the switch used. On the contrary, in second technology passive devices like couplers and splitters are used which can facilitate 32 customers with distance range between 10 km and 20 km [168]. The Ethernet passive optical networks, broadband passive optical networks, and gigabit passive optical networks are three variants of passive optical networks. The key benefit of using the passive optical network is the use of special electrically powered devices at the source and destination ends like used in the fiber-to-home network.

4.7.2.2. Wireless communication technologies. In SG, the communication technologies options, including GPRS UMTS, LTE (Long-Term Evolution), 5G (Fifth Generation), WiMAX, SATCOM, Wi-Fi, TVWS

(TV White Space), MBWA, WRAN, DASH 7, Z-wave, WPAN, WBAN, ZigBee and Bluetooth [123–126].

The UMTS generally recognized as 3G provides high data rates about 22 Mb/s in the uplink and 168 Mb/s in the downlink can be used for SG applications in both NAN and WAN. The technological advancements in cellular communications have led to shifting 2G (GSM) to 4G (LTE) with high throughput from 14.4 kb/s to about 100 Mb/s [127]. The LTE provides 80 Mb/s at the uplink and around 300 Mb/s at the downlink with 20 MHz frequency band and 4 × 4 MIMO antennas [128]. The LTE-Advanced at 70 MHz and 4 × 4 MIMO antennas provide throughput about 1 Gb/s at the peak downlink and 500 Mb/s at the uplink transmission [119]. On the other hand, the LTE-Advanced at 10 km range provides 1.5 Gb/s at the uplink and about 3.3 Gb/s at the downlink for an increasing number of concurrent active users [130]. Typically, LTE utilizes OFDMA in the downlink and SC-FDMA in up-link in order to achieve power efficiency and scheduling flexibility. About in 15 min a huge amount of information is generated between utility and smart meters requires higher data transfer technology. In this context, the 3G (Third Generation) or 4G (Fourth Generation) can provide desired data rates over large geographical locations. Therefore, the IEEEP2030/D7.0 standard approves 3G as a backhaul network [131]. In addition, LTE and LTE-Advanced are suitable and can be employed in both wide are networks and neighborhood area networks for various SG applications, such as AMI, DR, and OM. Recently, 5G (Fifth Generation) wireless communication technology is being developed to support higher data rates and low latencies for long-distance communication. The 5G interfacing with WiFi, Bluetooth, and LTE will provide universal high coverage and seamless user experiences will be suitable for AMI and several other SG applications in WAN and NAN. For 5G, the latency below 10 ms, reliability and density up to 100 devices per meter squares will be most challenging to support near real-time control and monitoring applications in SG.

The microwave technology provides secure and high-speed wireless connection for sending and receiving a huge amount of industry information, including text, audio, video, and many others. The microwave technology typically uses a high-frequency beam of radio waves for point-to-point communications. This small wavelength beams using convenient antennas are directed to narrow beams that may directly point to the receiving antenna. Similar to low-frequency radio waves, the microwave equipment near to each other can use the same frequencies without causing harmful interference in the networking. The microwave technology provides a very large information carrying capacity and portability. Over the past 20 years, this technology resolved fundamental problems for rolling out economical mobile infrastructure. Consequently, the more than 50% base stations around the world's mobile utilities are employing microwave technology for providing efficient and reliable point-to-point networking. The microwave signals can be categorized into three main categories, namely extremely high frequency, super high frequency and ultra-high frequency operate at 30–300 GHz, 3–30 GHz, and 0.3–3 GHz frequency bands, respectively. The microwave technology can provide data rates up to 3 Gb/s and more on 4–42 GHz licensed frequency bands with distance coverage more than a 100km constraint to suitable antennas and sites [201]. The microwave technology for SG applications like distributed energy resources, distribution feeder protection relays, DR, AMI, is appropriate in NAN. The WiMAX IEEE 802.16 standard in a radius approximately 50 km supporting high data rates about 70 Mb/s and a data rates about 100 Mb/s with distance coverage about 10 km in the rural environments [26,132]. The WiMAX version 802.16 j takes into account multi-hop and multicast techniques is particularly reserved for mobile users to access services remotely [133]. The WiMAX standard IEEE 802.16m offers high data rates about 100 Mb/s and 1 Gb/s at higher and lower speeds, respectively [134,168]. Therefore, it appears to be most suitable for various SG applications using both WAN and NAN technology.

In the past decades, the cellular communication has been proved as a mature data transfer technology. The satellite communication in a remote location could also be considered as a redundant and communication backup technology for reliable information collection in SG. It was employed previously for SCADA systems. The key advantage of SATCOM is to offer services to remote areas where other communication technologies fail to provide services. Typically, satellite systems are operating between 1 GHz and 40 GHz bands. Recently, the Global Satellite Engineering and Stream Technologies have successfully demonstrated the long-range WAN over the Iridium network made of Low earth orbits (LEO) satellites. The Iridium network covering the whole earth with 66 satellites with low latency networks due to using L-band. The Iridium NEXT has been launched in 2017 started to provide services with data rates up to 1.4 Mb/s. The LEO satellites are typically located between 500 km and 1500 km above the Earth and achieve long-range communication with latencies around 300 ms. On the other hand, the minimum round trip time of the GEO satellites is noticed 500 ms. The LEO systems are using SATCOM operated on the battery can be viable, although not yet utilized, solution for the SG. In recent, the SATCOM also begins to offer its communication services can be used in WANs and NANs. In addition, Inmarsat has launched BGAN for M2M communication with service availability of 99.9%, data transfer rates around 500 kb/s and latency below 1 s. Moreover, Nanosatellites provide data transfer rates nearly 9.6 kb/s are suitable for low latency and data rates SG applications.

The IEEE 802.11 xx series known as Wi-Fi comprises of license-free ISM bands. It consists of low-cost radio interfaces spans a range of wireless CTs with data transfer rates between 54 Mb/s and 150 Mb/s in Wireless Local Area Networks (WLANs). Typically, IEEE 802.11 xx standard series uses unlicensed frequency band between 2.4 GHz and 5 GHz which are freely available. The variant IEEE 802.11s (Mesh) allows a self-configurable wireless mesh network for solving the coverage issue to enable high-speed AMI applications in NAN [135]. The variant IEEE 802.11n provides communication coverage up to 70 m for indoor and about 250 m for outdoors is appropriate for SG applications [136]. The IEEE 80.11e variant of IEEE 802.11 due to QoS requirements is substantial for SG applications [137]. The IEEE 802.11 enhanced version IEEE802.11s covers multi-hop applications while the variant IEEE802.11e is appropriate for the vehicle to grid. The other variant of the IEEE 802.11 series contains low-power Wi-Fi (IEEE 802.11 ah). The IEEE 802.11 ah with a minimum throughput of 100 kb/s using different channels ranging from 1 to 16 MHz at unlicensed 900 MHz bands have long-range distance up to 1 km [202]. Table 4 [19,116,131,168] shows the communication technologies with their specific data rates, power consumption, deployment cost, segment, latency, and applications.

The cognitive radio is a promising technology to solve bandwidth scarcity issues in wireless networks. It allows secondary users to use free vacant licensed spectrums in dynamic, efficient and reliable manners. However, priority is given to primary users over secondary users for transmitting data in the network. Thus, it prohibits unauthorized interferences to authorized users as the primary users acquire spectrums. For SG applications, the cognitive radio architecture can be used in TVWS is suitable for NAN. The other variant of the IEEE 802.11 series comprises of White-Fi (IEEE 802.11af) also know as super Wi-Fi enabling WLANs to operate in TVWS cognitive radio channels [138] from 54 MHz to 790 MHz. Previously, the VHF and UHF frequency bands ranging from 54 to 216 MHz and 470 to 698 MHz has been employed for licensed wireless microphones and television broadcasting. However, due to recent advances from analog to digital TV broadcasting have led

Table 4
Communication technologies with their specific data rates, power consumption, deployment cost, smart grid segment, distance coverage, latency and applications.

Technology	Communication standards	Data rates	Power consumption	Deployment cost	SG segment	Distance covered	Latency	SG applications
Cellular	2G	Very low	Low	Low	HAN/NAN	Long distance	High	HA, PHEVs, DS, AMI
	2.5G	Very low	Low	Low	HAN/NAN	Long distance	High	HA, PHEVs, DS, AMI
	3G	High	Medium	Low	HAN /WAN//NAN	Long distance	High	DA, AMI
	3.5G	High	Medium	Low	HAN /WAN//NAN	Long distance	High	DA, WASA, AMI
	4G (LTE)	High	Medium	Low	HAN /WAN//NAN	Long distance	Medium	DA, WASA, DR
	LTE-Advanced	Very high	Medium	Low	HAN /WAN//NAN	Long distance	Low	WASA, SCADA
	5G	Very high	Medium	Low	HAN /WAN//NAN	Long distance	Low	Core/Backhaul, DR, DA
WiMAX	IEEE 802.16	Very high/High	High	Medium	HAN /WAN//NAN	Long distance	Low/Medium	DA, AMI
	IEEE 802.16j	High	High	Medium	NAN/WAN	Long distance	Medium	DA, AMI
	IEEE 802.16m	High	High	Medium	NAN/WAN	Long distance	Medium	DA, AMI, DER
Satellite	LEO	Medium	High	High	HAN/NAN/WAN	Long distance	Medium	AMI, DA, SCADA
WRAN	IEEE 802.22	Medium	Medium	Low	NAN/HAN/BAN/IAN	Long distance	Medium	PHEVs, SCADA, AMI
WiFi	IEEE 802.11	Low/Medium	Low	Low	HAN/NAN	Medium distance	Medium/High	AMI, DER, DRM
	IEEE 802.11s	Medium	Low	Low	HAN/BAN/IAN	Medium distance	Medium/High	PHEVs, AMI, HA
	IEEE 802.11n	Medium	Low	Low	HAN/BAN/IAN	Medium distance	Medium/High	PHEVs, AMI, HA
	IEEE 802.11e	Medium	Low	Low	HAN/BAN/IAN	Medium distance	Medium/High	PHEVs, AMI, HA
	DASH 7	Low/Medium	Low	Low	HAN/BAN/IAN	Low/Medium	High	AMI, DER, HA
	802.11af	Medium	Medium	Low	BAN /HAN /IAN	Medium distance	Medium	AMI, PHEVs
MBWA	IEEE 802.20	Medium	Low	Low	BAN /HAN /IAN	Medium distance	Medium/High	PHEVs, SCADA
WPAN	IEEE 802.15.4 (Zigbee)	Low	Low	Low	BAN /HAN /IAN	Short distance	Low/Medium	DER, HA, AMI
	IEEE 802.15.4g	Low	Low	Low	BAN /HAN /IAN	Short distance	Medium/High	HA
Z-wave	IEEE 802.15.4	Low	Low	Low	BAN /HAN /IAN	Short distance	High	AMI, HA
Ethernet	IEEE 802.3	High	Medium	High	BAN /HAN /IAN	Short distance	Low/Medium	AMI, HA
WBAN	IEEE 802.15.6	High/Very high	Low	Low	BAN /HAN /IAN	Short distance	High	HA
RFID	802.15	Low	Low	Low	BAN /HAN /IAN	Short distance	Low	Object identification
Bluetooth	IEEE 802.15.1	Low	Low	Low	BAN /HAN /IAN	Short distance	Low/Medium	HA, AMI
Fiber optical	Fiber	Very high	Medium	High	NAN/WAN	Long distance	Low	Core/Backhaul
DSL Cable	Digital line subscriber	High	Medium	High	NAN/HAN/WAN	Long distance	High	SCADA, AMI
PLC	Powerline communication	High	Medium	Medium/Low	NAN/HAN	Long distance	Low	AMI, DA

HAN (Home Area Network), BAN (Business Area Network), IAN (Industrial Area Network), NAN (Neighborhood Area Network), WAN (Wide Area Network) Data rate range: Very low (1 kb/s to <250 kb/s), Low (250 kb/s to 1 Mb/s), Medium (>1 Mb/s to 10 Mb/s), High (>10 Mb/s to 1 Gb/s), Very high (>1 Gb/s); Distance range: Short (1<500 m), Medium (500<5 km), Long (>5 km) Latency: Low (micro (μ) s<60 ms), Medium (60<120 ms), High (>120 ms) to free a wide range of VHF and UHF unused broadcast channels which may also represent a valid option for the wireless networks in SG. To this end, it enables wireless services for secondary devices (unlicensed) require highly desirable spectrum (vacant channels) over a large area that may bring several advantages in bandwidth utilization for AMI system in NAN.

The MBWA technology relies on IEEE 802.20 standard which integrates the advantages of both IEEE 802.11 and IEEE 802.16 series and provides data rates between 1 Mb/s and 20 Mb/s. Due to high throughput, fast mobility and low latency it covers a wide range of SG application like PHEVs, SCADA systems, and many others. The IEEE 802.22 is standard for WRAN using TVWS offers broadband access to customer premises equipment in rural hard-to-access environments. Typically, a base station is used for managing the medium access to avoid interference to primary user and communication coverage to the secondary user in rural environments. Thus, both IEEE 802.22 and IEEE 802.11af standards are using TVWS with cognitive radio technology. The empty channel access in these technologies can be granted using TDMA, FDMA, and CDMA mechanism. In addition, these communication technologies without a line-of-sight path effect have greater link reliability and a longer range compared with Bluetooth, ZigBee, Wi-Fi and other radio frequencies relying on microwave bands. Therefore, these frequency bands approved by the FCC and NBP can be utilized in SG for various applications, e.g., AMI, particularly wireless communication enabled advance smart meters. Thus, a vast volume of distributing control signals and information services data is transmitted between the smart devices in HAN and service providers in a WAN.

The ISO/IEC 1800–7 standard is typically called DASH 7 technology used in WSNs operates on 433 MHz having data rates up to 28–2400 kb/s and distance coverage extendable to 5 km. The DASH 7 technology requires a latency around 2.5–5 s and a wake-up signal of 30–60 μW is appropriate and can be used for monitoring and plug-in hybrid electric vehicle applications in SG. Moreover, it provides an alternative to ZigBee for SG applications [24]. The Z–wave was developed by Z-wave alliance offers an alternative to ZigBee wireless technology. The Z–wave requires is low cost and simple technology which provides data rates up to 0.1 Mb/s at frequency band 900 MHz. The Z-wave due to its low bandwidth requirements is suitable for home automation applications [203]. The Ethernet technology with low data rates around 100 kb/s and short coverage distance nearly 100 m can also be used to support the IAN, BAN and HAN applications.

The IEEE 802.15 (WPAN) defines the physical layer and MAC layer standards based on the IEEE 802.15.4 (ZigBee) standard for SUNs to implement low power wireless communication network technologies having data transfer rates about 250 kb/s with distance covering nearly 10 m for various SG applications [139]. The IEEE 802.15.4g extends the IEEE 802.15.4 and provides long-range communication for various home automation (HA) applications in HAN. The SUNs infrastructure potentially connects millions of fixed endpoints over large geographically diverse networks [140]. Currently, for various smart grid control and monitoring applications the standards like Wireless-HART, ISA 100.11a and ZigBee are appropriate for low power communication between IoT-enabled CPSs [141,142,204]. Recently, ZigBee-based low powered WSNs have got worldwide attention for various SG monitoring and control applications. The developed ZigBee protocol operating bands for Australia and USA is 915 MHz, for Europe is 864 MHz and 2.4 GHz worldwide. Consequently, the throughput for the USA and Australia is 40 kb/s, for Europe, is 20 kb/s and 250 kb/s is worldwide [131]. The standard IEEE 802.15.1 is known as Bluetooth provides short-range distance coverage of 1–100 m for point-to-point communication and data rates up to 721 kb/s. The blue tooth can find its applications in the BAN, IAN, HAN and particularly for a substation in the SG. The IEEE 802.15.6 (WBANs) standard designed for local and metropolitan area network operates at 1 THz and provides data rates minimum 1 Gb/s for distance coverage up to 10 m and low data rates with varying distances. This IEEE 802.15.6 can be used in the BAN, IAN, and HAN. Moreover, the cognitive radio architecture can be used in Zigbee-based WSNs to acquire QoS communication is suitable for HAN, BAN, and IAN. The RFID is a key enabling technology which provides real-time information collection and sharing in the SG. The use of RFID technology in HAN, BAN, and IAN will enable visibility and traceability of various components located in a specific coverage area for seamless operations. In HAN, the RFID tags and readers are deployed to detect and fed back to the RFID systems on a real-time basis.

Thus, the real-time objects detection like smart meters, solar panels, plug-in electric vehicles, small-scale wind turbines, power consumption control tools, storage devices and home appliances in customer premises would be the main responsibility in HAN. Lastly, the use of IEEE 802.11a/b/g and IEEE 802.11n/ac technologies due to their coverage and higher data rates for different services are also appropriate in HAN.

4.8. Challenges for SG communication

The smart grid communication in terms of the geographical coverage region is categorized into HAN, NAN, and WAN. The different types of communication technologies like wired communication, wireless communication, cellular communication and power line communication used in these networks have their own challenges in SGs. The wired solutions are one of the best options for home area networks to support high data rates at extremely low interferences for SG applications. The wired optical communication provides high data rates al extremely low interference and therefore can be a good candidate for the HANs, NANs, and WANs. However, the scalability and high installation cost are main issues of wired communication technologies.

The wireless technologies are preferred due to their high flexibility and scalability for wide area communications. However, due to adding more wireless access points and routers for providing scalability in wireless technologies increase the total installation costs of the network. In addition, wireless communication is suffering from limited bandwidth, data rates, downlink communication, multicasting, self-healing capabilities, highly complex network design and poor penetration unless required high transmission power and large antennas are other main challenges. Moreover, the wireless communication due to the harsh nature of the smart grid environments like high voltage electrical equipment, obstacles, etc., is facing severe interference issues [143]. Furthermore, the wireless equipment are mostly expensive and not readily available, especially for SG monitoring applications.

In cellular communication technologies due to the failure of a base station may result in full or partial service lost because of treelike topology networking. In emergency situations, the cellular networks data exchange performance is decreasing rapidly with the increasing services shared by customer market. In cellular networks, besides the inter-cell interference the coverage may be increased by increasing the signal power, however, the high data transmission rates remain same for SG applications. In addition, the power utilities cannot directly interact with the applications over the communication network since cellular network providers are responsible for the services. Consequently, the time critical application data and control cannot be delivered directly to end users unless cellular networks implement data backup and data prioritization process. The communication overhead, designing the signaling protocol, multi-cell environment, cross-layer optimization, smart antenna configuration and end-to-end co-cooperative communication could be assumed as open issues in SG. The main problems with power line communication, including interference, channel congestion, signal attenuation, data packets loss due to systems open circuit ends, reflections due to impedance mismatches at discontinuities and time-varying low-pass behavior channel conditions.

The uninterrupted communications increase the success factor of reliable data transmission in SG. In SG, each sub-network having its own CPSs equipped with different capabilities and requirements. Thus, how to ensure the uninterrupted communications and interoperability between the CPSs becomes a challenging task requires universal developing guidelines, common models, architectural rules and standard protocols for secure communications between CPSs in SG. The smart grid will employ different types of ICTs due to heterogeneous application environments. The different interoperability standard solutions used for ICTs may result in damaging the effective deployment of smart grid. Thus, interoperability is a challenging task for both the ICTs and CPSs. In addition, these technologies should support interoperability in a more realistic manner rather than theoretical interoperability. Although some communication standards exist to guide the implementation of CPSs, the globally harmonized standards for ensuring interoperability among CPSs are essential in the smart grid. These standard frameworks will contribute to fulfill the distinct requirements offered by specific smart grid applications.

In home area networks, a great challenge is how to interwork different manufacturers devices using various standards like Ethernet, Bluetooth, Zigbee, and WiFi?. Moreover, the various devices in SG generate data at different rates having different levels of time requirements. The home area networks and neighborhood area network must fulfill the real-time data exchange requirements for each application in SG. However, the main challenge is how to transmit data of thousands of home appliances reside in a region over a neighborhood area network having limited bandwidth and low-speed transmission characteristics? On the other hand, the communication between neighborhood area networks and wide area networks are established based on the base stations. Therefore, the demands in large coverage wide area networks eliminate the use of the ISM bands in SG. In addition, the ambiguity in existing standards operating in ISM bands and their further revisions will raise a lot of regulatory issues [144]. Moreover, this co-existence may also result in an increased power and interference related issues in the smart grid. Therefore, the standard organizations must define policies to carefully answer them.

The long-distance communication between home area networks and neighborhood area network can also be accomplished by TVWS in SG. However, the service reliability is the main issue of TVWS. This is due to the existence of an incoming primary user which postpones the operations of the secondary user using TVWS. The multi-channel utilization and dynamic frequency switching algorithms may provide the solutions to the reliability problems. However, the use of licensed bands to mitigate the unreliability remains to be an open issue. The observed information from the various smart grid control and protection applications in wide area networks is required to deliver reliably in the control center and necessary control actions must be implemented within a few milliseconds. In this sense, the optical communication or a wireless technology like 4G advanced or 5G could be helpful due to their low latency. However, a large number of CPSs in smart grid will generate several thousands of terabyte data periodically. To carry this big data is a secure and reliable way in wide area networks with distinctive priority will be a major challenging task for any communication technology in SG.

The network performance is highly depended on the implemented topology in the HAN, NAN, and WAN. Some technologies because of the regional differences work superior in some regions than in others, e.g., in most of the European countries, the PLC technology works efficiently maybe not appropriate for some Asian countries because of extremely high voltage-centric grids. Thus, how to employ multiple ICTs to resolve interconnection issues within a region and even within a utility company is another challenging issue. The other main problem is how to optimize the links between diverse HANs connected to NANs and NANs connected to WANs. Moreover, due to unique challenging environments, the existing schemes cannot be directly implemented in SG. Hence, designing new or modifications in the existing data gathering, packet size optimization, secure communication and authentication schemes are essential for SG applications to meet their functional requirements. Furthermore, the smart grid will have various types of energy resources such as wind turbines, biomass, biofuel, solar panels, tidal energy, geothermal, hydropower and nuclear energy. The main issues with renewable energy resources integration are efficiency, power quality, reliability and voltage profile and integration of storage devices. Moreover, due to highly complex and dynamic energy in nature how to balance the energy usage of different power sources is one of the main challenging issues need to answer in the perspective of SGI 4.0.

It is believed that the next generation power grid with backward compatible with all existing ICTs, including hardware, software, interfaces, legacy systems, and networks. However, without allowing substantial advancement in the deployment of new technologies this compatibility cannot be accomplished for SG applications and CPSs. Consequently, the deployment of technologies with critical functions and then discontinue those devices because of newer technology is not a good option to manage the smart grid. Thus, how to choose the appropriate core technologies that meet the future smart grid needs and have a long product life to make backward compatible must consider an open issue. Herein, it is important to note that the backward compatibility with new smart grid standards compared to its old version and are entirely different and therefore must not be confused by some parties of concern.

The energy utilities should make investment decisions on IoT-enabled CPSs with a very long lifespan since the smart grid is not a manufacturing industry where CPSs due to shorter lifespan is being replaced after every one or two years, but the one with 20 or 25 years life cycles. Thus, the trial-and-error approaches used in the grid can be avoided by well planning since the people with skills recognize well how to make them survivable in the subsequent years. The different countries, states, and consortiums are other political issues in place for the new technologies implantation in the SG.

5. Smart grid applications

In the following sections, we have explained the detail of various smart grid applications and challenges.

5.1. Demand response (DR)

The demand response is also known as demand-side management, the overtime changes in electricity consumption are managed by temporarily altering the loads on the distribution grid. In demand response, the energy utilities based on energy consumption curves provide information to customers and encourage them for shifting some of their existing electricity usage times [205]. Generally, the users in a residential district are more sensitive to the electricity price; therefore, the demand response in the residential district usually performed due to flexible, controllable, interruptible, deferrable and shiftable appliances. For example, postponing the usage of the assay home appliances like washer, ovens, dryer and decreasing the air conditioners level, water heater, dimming lighting levels, etc., in peak demand hours helps utilities to facilitate some other service areas like industries, hospitals, universities, etc. The customers by scheduling their electricity usage in synchronized manner help power grids to manage short-term peak power conditions and may achieve the benefits of low price signals. Thus, the demand response can reduce overall plant and capital cost investments in the long term by lowering peak electricity demand and improve the reliability of the power grid that avoids the need for network upgrades and inefficient operations. Moreover, the demand response helps to reduce greenhouse gas emission, the risk of system security, blackouts, network congestion, market economic efficiency and many others.

5.2. Advanced metering infrastructure (AMI)

The AMI is an important component of the SG. The infrastructure of advanced metering comprises of various physical and virtual components, including advanced sensors, monitoring systems, smart meters, software, communication technologies and data management systems like MDMS and others [206]. The key enabler of demand response management is the smart metering infrastructure which allows real-time interaction between the energy utility and customers due to employing advanced bi-directional communication capabilities. The smart meters on real-time basis shares customer energy consumption information in much more detail with power grid to balance seasonal variations of electricity demand and supply. The data collected from customer metering device usually stored in a central database used for various purposes. The energy utilities using different types estimation, editing and validation systems and tools analyze this collected data for optimizing operations, electricity costs and end-user customer service. The electricity consumers in a residential district may be immediately informed by the energy utilities about the consumer load information, billing details, outage detection, power quality, the timing of peak load hours and economic benefits. Thus, customers can take advantage of dynamic pricing due to varying energy price at different times in a day using AMI. A fundamental architecture of AMI is shown in Fig. 3.

Fig. 3 shows the basic architecture of AMI. The smart meters via WiFi or Ethernet (blue dotted lines) are connected to data collector unit which is connected to the backhaul network. The backhaul could be Cellular/WiMAX/Satellite/Fiber/PLC or DSL (green dotted lines). This backhaul network is connected to the MDMS via system controller. The MDMS is connected to various types of services provided by the energy utilities like billing, customers care, metering events, grid events, DA, DR, and OM. In addition, there are various types of connection and device-based cyber attacks (dotted red lines) at each stage during message transmission and reception by the end users.

5.3. Substation automation (SA)

One of the fundamental components of the power grid is a substation. The automation of distributed systems is growing instantaneously since the power grid capabilities expand dramatically with increasing capacitor banks, transformers along the feeders and control of relays for the efficient grid performance [207]. The potential equipment used in substation automation, including sensors, actuators, switches, circuit breakers, potential transformers, current transformers, input–output devices and merging unit IEDs. To this end, the substation automation systems are responsible to monitor, control and protect various types of devices in substations. It provides integral functions for collecting several types of data in distribution grid automation. The substation automation systems after analyzing data perform actions that allows robust electricity forwarding to the transmission lines from the generators. The substation automation systems fully monitor and control the instant performance and operation conditions of the substations through communication networks. Hence, a highly secure, scalable and reliable routing network is essential to avoid potential power disruptions and outages. This will enable the integration of new automation functionalities in the existing substation automation architecture in a highly dynamic and reliable manner. Thus, the substation automation systems with the integration of advanced technologies will be able to provide real-time analysis, maintenance, monitoring, control, protection and fault management a local level of the distribution substations in the smart grid.

5.4. Wide area situational awareness (WASA)

The key aim of wide area situational awareness is to monitor, protect and control the power grid systems, distributed across large geographic areas by employing various ICTs technologies. In wide area situational awareness systems, a massive amount of current state data is collected from the electric substations and transmission network in the power grid [22]. This gathered information helps to improve the performance of various PG units and also mitigating the impact of cascading blackouts and disruption in a timelier manner. Typically, the transmission system monitoring and control services are realized by measuring the instantaneous voltage at line current, buses and frequency through digital devices called synchronized phasor measurement units. These intelligent devices help to locate the exact sequence of events causing blackouts and failure due to sharing consistent data with the global positioning system. However, the synchronized phasor measurement units installed within the generation and transmission domain are considering unidirectional power flow to monitor and control the distribution segment of existing power grid. Therefore, it is necessary to deploy synchronized phasor measurement units at distribution points for enabling two-way power flow and instant system monitoring in the smart grid. In addition, the wide area situational awareness systems based on the information usage may be categorized into wide-area control, monitoring and protection systems. The wide area control systems and wide area monitoring systems require high data capacity links in order to fulfill the latency requirements in SG.

5.5. Home energy management (HEM)

The home energy management systems permit the customer to control, monitor and manage the power consumption of their home appliances to advance the electricity supply and consumption [208]. The home energy management systems architecture essentially comprises of smart appliances, advanced control systems, smart meters and in-home displays. The main purposes of the home energy management systems are to provide smart use of energy, data dimension and transmission for various types of home appliances. The home's appliances typically consist of three types of elements, namely energy management gateway, energy management unit and a group of sensor and controllers that feed the energy management unit. The energy management gateway provides an interface to connect home electric appliances with utilities AMI using secure and reliable communication technology. The energy management unit controls power usage, generation and storage in the home and connects to energy management gateway for providing the gathered information. The instant measurements of these home appliances are then forwarded to a central database of the utility company. Thus, the customers are informed about their home appliances power consumption behavior, various kinds of query support and intelligent advice generation in-home displays after performing some statistical analysis by the utility company. In addition, home energy management systems will allow customers to continuous interaction with their home

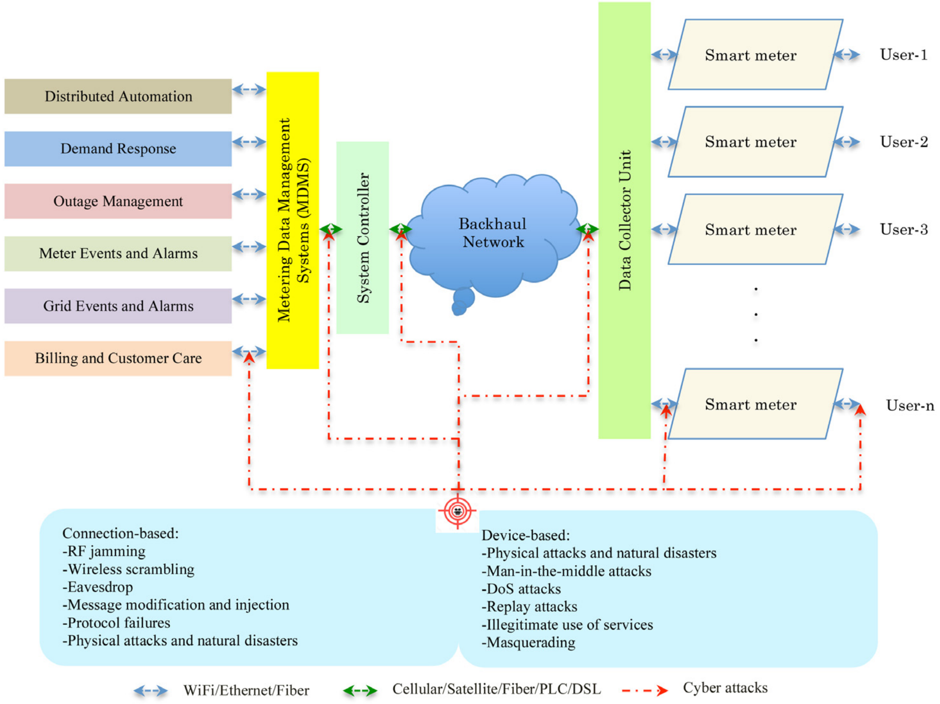

Fig. 3. System architecture of AMI. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

appliances locally or outside world. This will enable customers to rearrange their day-to-day electricity consumption that will result in optimizing their high quality of lifestyles due to reducing electricity bills.

5.6. *Transmission line monitoring (TLM)*

TLM is one of the most important transmissions and distribution application of the SG. Typically, the electricity from power generation plants is transmitted and distributed to customers via power lines. The power lines are vulnerable to lighting strikes, overheating and icing since they may span over a long-distance to supply energy in both populated and urban areas. Hence, to ensure satisfactory power quality and service the rapid detection of transmission and distribution systems anomalies is essential in the SG [209]. To this end, one of the most popular methods for automated TLM is to deploy wireless sensor nodes along transmission lines. The sensor nodes deployed for TLM have the capability to exchange the measurements in real-time with neighboring nodes through wireless communication. Typically, in TLM a multi-hop linear wireless communication network model is formed among sensor nodes. The relay nodes forward the collected events data to the central collection site in a multi-hop manner that is connected to the neighbor area network or wide area network. The data central collection site is directly connected to the base station with low latency, high bandwidth and low-cost links. Hence, the utility company for maintaining the quality of the electricity performs instant actions on the defective side.

5.7. *Outage management (OM)*

The failure at power stations, damage in transmission lines or short circuits may result in loss of electricity supply for a short or long-term period of time is known as a power outage [20]. Hence, to avoid system outage crises for the continuity electricity delivery between electric utilities and customers require outage identification, management and restoration systems in SG. The various advanced functions can be achieved through interfacing the outage management system with SCADA, AMI, CIS and geographic information/facility management/automated mapping systems. The reliable integration of SCADA systems over the single network offers a number of QoS solutions that help to reduce management overhead on control centers. Moreover, the recent improvements in AMI enable it as one of the most promising candidates for OM systems that may improve the outage management processes like outage management service reliability, restoration notification and outage notification and advanced customer services. Generally, there are many traditional ways in which electricity outage is reported manually like customer calls, sending e-mail, etc. However, depending on communication technology, the integration of AMI can improve OM in the smart grid. For instance, the AMI smart meters will send outage notification message or last-gasp report to OM systems before the customers as maybe they are at work or sleeping. The accuracy in the restoration of notification functionality is another advantage of the integration between AMI and OM systems that minimize the manpower required for collecting and analyzing outages for the reports.

5.8. *Plug-in hybrid electric vehicles (PHEVs)*

In the near future, the fossil fuels-based traditional transport systems are expected to replace or enhance by electric transportation due to environmental pollution. To this end, the current research efforts have been directed towards hybrid electric vehicles with advanced batteries and storage systems, despite the one-way focus on designing and enhancement of vehicle subsystems [210]. The hybrid electric vehicles are powered by a rechargeable storage, including cars, buses, trucks and many others. The rechargeable electric storage in vehicles will be connected to energy ports having charging facilities available at home and in public places [211]. These energy ports backend will be connected to the smart grid for electricity flow. Even, currently some research studies are also focusing on designing and implementation of hybrid electric airplanes instead of relying on fossil fuels as a pilot project of the 21st century. The PHEVs possibly can reduce the energy demand in peak load hours due to dynamic charging facilities are known as vehicle-to-grid flow. To this end, the intelligent energy management systems play key roles in decisions making about the vehicle-charging process and thus can be deployed within the utility control room or installed separately for instant control and monitoring in the SG. This will help energy utility and customers about when a PHEV need to charge its battery or supply energy to the grid if there is too much demand on the smart grid. Consequently, PHEVs will definitely curb emissions, decrease the price of transportation, new services and new markets with several types of job opportunities and thus improve our daily lives.

5.9. Distributed energy resource (DER)

Currently, the DERs have tremendously increased in the smart grid. DER to generate the electricity at load end will enable integration of micro conventional and nonconventional energy resources. The distributed energy resources consist of solar panels, biomass, wind power and kinetic energy [212]. The integration of energy harvesting from solar panels is strongly recommended for the smart grid. The biomass due to its clean environmental effects is another attractive long lasting electricity generation solution for the smart grid but acquires lower utilization. Lastly, the wind power worldwide is a fastest growing energy harvesting solution compared to all other renewable energy resources is a pretty smart candidate due to its decentralized nature for the SG integration. These renewable energy resources due to low carbon emissions, better sustainable and reliable electricity at low cost are becoming more popular than conventional power grid. The renewable energy resources due to improvement and advancement in power electronics technology have a strong potential to feed an increasing need for energy.

5.10. Power storage system (SS)

Generally, there are three different types of distribution generation storage technologies, namely physical, mechanical and chemical. During the period of uncertainty, the storage technologies between the source and load act as a bridge. The storage technologies include the application domain of renewable energy resources, grid systems and end users [212]. The storage technologies in renewable energy resources-based electricity generation mitigate the uncertain during storing the surplus energy or supplying energy back to the smart grid. The surplus energy provided by the renewable energy resources could be stored in energy storage devices. This stored energy can be used in the smart grid if needed to supply electricity with more efficiency, reliability and capacity. For an electric vehicle, the required energy ranges from 10 to 200 kW, which usually can be supplied from fuel cells or attached rechargeable batteries. In electric vehicles, despite liquid fossil fuel, the other source of energy harvesting is kinetic energy during continuous movements. The energy harvesting from kinetic source has two different types first from the moving tiers and second push down the energy harvesting plates fixed on the road by moving the car. In the first type, the harvested energy can be directly stored in vehicle rechargeable batteries. While in the second type, the harvested energy can be directly proved to the smart grid. Thus, electric vehicle acts like a mobile DER can be used to supply energy itself as well as to the power grid. Hence, the power generated from these renewable energy resources will help smart grid in terms of power quality, increasing power generation, power system reliability and backup capacity during peak times.

5.11. Asset management (AM)

To ensure a QoS for customers and regulators at both the transmission and distribution levels bring several new challenges to electric utilities. The asset management offers several opportunities to address these issues, such as scheduling of field crews, work order process optimization, tracking, management, automation and field assets [213]. The asset management systems with new information communication and monitoring systems will help to manage the risk of failure, proactive maintenance, system performance, total uptime, overall asset health, replacement and maintenance costs and reliability impacts. There are many micro assets such as wind turbines, photovoltaic arrays, electric and hybrid vehicles and classic asset classes like meters, transformers, switches, breakers, poles, etc. and advance asset groups like hardware, communications systems, software, firmware and storage capabilities. The reliability and availability of these assets are essential for the real-time operations of the grid. Thus, an intelligent and self-healing power grid can optimize utilization of assets and increase reliability by using AM systems.

5.12. Challenges for SG application

There are several main issues with the deployment of smart grid applications. For instance, in AMI, smart meters for storing the data logs requires integration of supplementary memory, the benefits offered by utility companies may not be passed to customers by electricity distributors and retailers, fabricating smart meter readings, secret encryption keys, manipulate all calculations by using unauthorized program and attackers may use an unauthorized program to take the control over secure applications. In DER, each DER storage system may require different control and monitoring technique result in the dump and slow response. Therefore, the reliable integration of the rechargeable batteries and power grid with these renewable energy resources is challenging and requires a properly integrated control structure and modern communication technologies. There other main issues with DERs are interfacing with transmission system, implementation of energy storage, consumer protection, operator remuneration, market entry, tariff regulation, market role, and standardization. In addition, the power quality, voltage profile, stability, uncertainty of load profile and unavailability of remote command functions in micro DERs are other issues. In DR, the smart grid for managing real-time energy-use must employ advanced automation, monitoring, and control technologies, which helps to coordinate electricity use with power system operation for making demand response less hindering for the customer.

In addition, interfacing the hybrid distributed energy systems, integration of various energy storage technologies, natural disaster, etc., are other main challenges for the reliable demand response implementation in the smart grid. The main issues with dynamic pricing and substation control, including the expectation of a high-quality ICTs with fast processing, the massive flow of data, throughput, low latency and optimal power consumption management of communication infrastructure itself [20]. In SA, the substation automation systems with the integration of advanced technologies will be able to provide real-time analysis, maintenance, monitoring, control, protection and fault management a local level of the distribution substations in the smart grid. In TLM, the fundamental issue for acquiring real-time measurements is reliable communication among sensor nodes in the linear sensor network. The failure of a single or a set of nodes over the long-distance transmission lines may result in entire data loss due to buffer overflow of the end node or become invalid due to not reaching on time at the control center. Thus, an appropriate positioning mechanism for sensor nodes along the long-distance transmission lines is essential for their reliable energy transmission and distribution in the smart grid. The other main issue is the limited battery lifespan of the sensor nodes over transmission lines. The energy of sensor nodes depleted quickly due to instant and long-distance communication, particularly those located near to control center site. Thus, the energy harvesting schemes are essential for TLM. In addition, a buffer overflow or memory overrun of sensors located in the middle or near to the controlling center site is another main challenging issue. In sum, to address these issues the development of novel systems, software, tools, and techniques are essential for secure and reliable TLM.

In WASA, the main challenge is to establish robust, reliable, and secure links between synchronized phasor measurement units and phasor data collector within the specific latency in the smart grid. Although plug-in vehicles will accompany environmental and economic benefits, the aggregate power consumption load of large-scale PHEVs adopted by utilities may result in new peak energy need with the existing peak energy requirement at a given time. This might result in blackouts or voltage instabilities due to adding extreme stress on the power grid. Thus, during charging the continuous monitoring of PHEVs through energy management system is essential for preventing overload on the smart grid. To this end, the intelligent energy management system may play an important role in decisions making about the vehicle-charging process and thus can be deployed within the utility control room or installed separately for real-time monitoring and control in the SG. This will help energy utility and customers about when a PHEV need to charge its battery or supply energy to the grid if there is too much demand on the smart grid. In PHEVs, it may also be possible that the charging process is refused or delayed by energy management systems during peak demand hours. Then how to cope with this problem is another challenge for SG. This situation can be avoided by designing online charging scheduling approaches for PHEVs. In addition, for PHEVs, designing an appropriate high-to-low and low-to-high voltage converter for grid-to-vehicle and vehicle-to-grid charging must consider an open research issue. In addition, to realize the vehicle-to-grid/grid-to-vehicle control operations for real-time decisions require a reliable communication platform in SG. The main issues with storage technologies are interfacing, reliable integration, high cost and separate control techniques. All these issues are important and require extensive research before their reliable implementation in SG. Hence, extensive studies are required to address all above-mentioned issues to cope an increasing energy demand of the 21st century.

6. Potential benefits and key observations in SGI 4.0

Potential benefits and key observations about SG can be summarized as follows:

- A significant reduction in energy consumption can be achieved due to shaving the energy consumption behaviors of consumers in the smart grid.
- The smart grid by integrating renewable energy resources can reduce the greenhouse gases and helps to meet the incessantly rising energy demand, worldwide.
- The implementation of various smart grid applications can provide user-friendly services to customers which in turns will bring economic benefits to both energy utilities and customers.
- The wireless solutions like 4G (LTE-advanced) and 5G are preferred due to low latency, higher data rates and large coverage area in WANs for SG applications.
- The satellite communication services due to extremely long-distance coverage may be beneficial for the smart grid applications with flexible latency and data rates requirements in WANs.
- The fiber optics and microwave solutions are extremely suitable as a backbone network between the NANs and WANs due to low interference, latency and higher data rates for SG applications.
- The TVWS-CR technology can be beneficial for providing QoS-aware communication at the power generation, transmission and distribution stages of the SG in NANs.
- The WiFi solutions are preferred for the SG applications having flexible data rates and latencies requirements in IAN/BAN/HANs.
- The advanced cloud computing and data mining techniques are essentials to extract valuable information from the big data for designing new systems or maintenance purposes.
- The physical and virtual security solutions at all levels are essential to ensure the reliability and sustainability of the power grid systems and applications.
- The developments of QoS-aware data gathering routing protocols are essentials for the practical deployment of the smart grid applications.
- The reliability performance analysis is vital for optimizing electricity quality problems in SGs.

7. Conclusion and future work

Industry 4.0 has revolutionized the aging industry to encounter the incessantly rising worldwide need for capital and consumer goods. Industry 4.0 provides immense opportunities for developing novel sustainable products with more service functionalities to the customer. Industry 4.0 is being more efficient and effective in the today's market due to efficient, adaptable, reconfigurable, flexible and decentralized manufacturing paradigm. Currently, energy utilities are facing a strong demand to increase their PG electricity generation, distribution, and transmission capacity by realizing SG. Consequently, the introduction of Industry 4.0 in SG has shifted the energy market trend, evolution of intelligent devices, emergence of new technologies and power generation, distribution, and consumption to a more efficient, adaptable, reconfigurable, flexible and decentralized manner. In the context of Industry 4.0, smart grid by employing advanced ICTs, IIP and FoT offers various services to satisfy the customer needs and economic benefits. However, the integration of these components to achieve secure and reliable power generation to consumption functionalities and services in an economical manner is very challenging for SG. In this survey, we first provided a brief introduction of SGI 4.0. Next, we have presented an overview of different smart grid applications, their benefits, characteristics, and requirements. Then, we have comprehensively focused on critical smart grid components, such as IoT, IoS, CPSs, CC, BD, CS and CTs by considering international standards and information technologies in the context of Industry 4.0. Subsequently, we have investigated and explored different wired and wireless communication technologies used in smart grid with their benefits and characteristics. Also, a number of critical challenges and open issues in smart grid regarding the components, technologies, and applications have been discussed. Lastly, the observations and possible future research directions have been presented. As a future research work, one direction is to perform reliability analysis for optimizing the links between HAN to NANs and NANs to WANs for various SG applications. Second, researchers may investigate the appropriate topologies suitable for HANs, NANs, and WANs. Third, research may design new or modify existing routing protocols for secure and QoS-ware data gathering from various SG applications.

Acknowledgments

The work of Muhammad Faheem was supported by the International Doctoral Fellowship (IDF) program from UTM, the work of Md. Asri Ngadi was supported by the Research Grant from UTM, and the work of V.C. Gungor was supported by the TUBA-GEBIP under Grand no. V.G./TUBA-GEBIP/2013-14.

Conflict of interest

The authors declare no conflict of interest.

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