Cloud Computing Applications for Smart Grid: A Survey

Samaresh Bera, Sudip Misra, *Senior Member, IEEE*, and Joel J.P.C. Rodrigues, *Senior Member, IEEE*

Abstract—The fast-paced development of power systems necessitates smart grids to facilitate real-time control and monitoring with bidirectional communication and electricity flows. Future smart grids are expected to have reliable, efficient, secured, and cost-effective power management with the implementation of distributed architecture. To focus on these requirements, we provide a comprehensive survey on different cloud computing applications for the smart grid architecture, in three different areas—*energy management*, *information management*, and *security*. In these areas, the utility of cloud computing applications is discussed, while giving directions on future opportunities for the development of the smart grid. We also highlight different challenges existing in the conventional smart grid (without cloud application) that can be overcome using cloud. In this survey, we present a synthesized overview of the current state of research on smart grid development. We also identify the current research problems in the areas of cloud-based energy management, information management, and security in smart grid.

Index Terms—Smart grid, cloud computing, micro-grid, smart meter, load-shifting, real-time pricing, dynamic demand response, survey

1 Introduction

A smart grid is conceptualized as a combination of electrical network and communication infrastructure. With the implementation of bidirectional communication and power flows, a smart grid is capable of delivering electricity more efficiently and reliably than the traditional power grid. A smart grid consists of a power network with 'intelligent' entities that can operate, communicate, and interact autonomously, in order to efficiently deliver electricity to the customers. This heterogeneity in architecture of a smart grid motivates the use of advanced technology for overcoming various technical challenges at different levels. Any smart grid infrastructure should support real-time, two-way communication between utilities and consumers, and should allow software systems at both the producer and consumer ends to control and manage the power usage [1]. To manage millions of smart meters in secure, reliable, and scalable ways, utilities must extend this communication network management system to a distributed data center. In this respect, *cloud computing* is envisaged to play key roles of motivation in the design of the future smart grid. Cloud computing is an emerging technology advocated for enabling reliable and on-demand access to different computing sources that can be quickly provisioned and released in a cost-effective way to the service providers [2], [3]. Using cloud infrastructure, a customer can gain access to their applications anytime, and from anywhere, through a connected device to the network.

1.1 Motivation

With the development of the state-of-the-art smart grid systems, it needs the support of bi-directional communication facility, and processing of the information in real-time as well. Additionally, energy demand from the users changes dynamically in different time-periods (such as on-peak, off-peak, and mid-peak), which in turn requires dynamic availability of the communication facility (such as bandwidth, processing units, and storage devices). Therefore, there is a need to integrate a common platform with the smart grid which is able to support the smart grid requirements as follows:

a) Energy management. The existing power grids need optimal balancing of electricity demand and supply between the customers and the utility providers [4]. Smart grids are capable of addressing this requirement. Such features in a smart grid is realized by the integration of various energy management systems (EMS) such as home energy management (HEM), demand side management (DSM), and building energy management (BEMS) [5], [6]. A smart grid allows various renewable energy sources (such as solar and wind) to have efficient management of supply and demand.

b) Need to support multiple devices in a common platform. In a smart grid environment, multiple devices are implemented. These multiple devices are home appliances, smart meters, micro-grids, substations, sensor nodes, and communication-network devices [7]. A suitable protocol architecture needs to be implemented to support these multiple devices in order to have reliable, and efficient electric supply.

c) Information management. Information management is an important aspect in the smart grid architecture [8], [9]. In

- *S. Bera and S. Misra are with the School of Information Technology, Indian Institute of Technology, Kharagpur 721302, India. E-mail: {samaresh, smisra}@sit.iitkgp.ernet.in.*
- *J.J.P.C. Rodrigues is with the Instituto de Telecomunicações, University of Beira Interior, Portugal. E-mail: joeljr@ieee.org.*

Manuscript received 31 Jan. 2014; revised 6 Apr. 2014; accepted 20 Apr. 2014. Date of publication 30 Apr. 2014; date of current version 8 Apr. 2015.
Recommended for acceptance by J. Lloret.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TPDS.2014.2321378

typical city environments, millions of smart meters are deployed in the distribution sites. These smart meters generate massive data for real-time communication with the utilities. A proper data management mechanism is necessary to be deployed for handling such massive data.

d) Layered architecture. A smart grid is a combination of different layers—network, communication, electricity distribution, transmission, and generation [10]. The smart grid is expected to support the overlay communication network on the underlay electricity network.

e) Heterogeneous architecture. The heterogeneous architecture is a special characteristic of a smart grid. Demand response (DR), distributed generation, resource scheduling, and real-time pricing model contribute to the heterogeneity of a smart grid [11].

f) Security. Effective authentication and authorization techniques are required for the preservation of users' privacy. Some security aspects in a smart grid are data outage, threat detection, and cyber-physical attacks [12], [13]. A proper privacy policy needs to be implemented to motivate customers' participation [12], [14].

Additionally, cloud computing is a useful technique which can fulfill the requirements of the smart grid in real-time adequately, while having the following characteristics [15], [16]:

- Optimizing energy costs enabling online monitoring and control of all grid assets.
- Providing different software applications to the users in the smart grid (such as customers, service providers, third parties) for supporting payment according to energy consumption.
- Reduction in carbon emissions through grid access of large wind, hydro, and solar power plants [17].
- Active management of demand and supply curves.
- Providing unlimited data storage for storing customer data.
- Supporting customers with data access from the cloud.

1.2 Contribution

In this paper, we provide a systematic overview of integrating cloud computing applications in smart grids, in three aspects—*energy management*, *information management*, and *security* in the smart grid architecture. For energy management in smart grid, different cloud computing techniques proposed in the existing literature are discussed briefly. Consequently, we discuss several issues to apply the cloud computing techniques for energy management with some future research directions. On the other hand, smart grid is the combination of electrical and communication network. Therefore, communication network plays an important role for reliable energy management. We discuss the information management schemes for smart grid using cloud infrastructure. Additionally, we also discuss the security issues in smart grid which can be addressed using cloud computing. Several future research directions are explained in terms of energy management, information management, and security in smart grid. In summary, our objective in this paper is to offer the following:

1) A comprehensive overview of smart grid and cloud computing in terms of energy management, communication, and security.
2) A clear concept of cloud computing applications in smart grid.
3) An identified list of key problems that can be overcome using cloud applications.
4) Some future research directions in terms of cloud applications in smart grid.

The rest of the paper is organized as follows. We give a comprehensive overview of smart grid and cloud computing in Section 2. We briefly describe the cloud computing applications in the context of energy management in smart grid in Section 3. In Section 4, we survey the application of cloud computing for communication and information management systems. In Section 5, we address different security aspects in smart grid, which can be overcome with the implementation of cloud computing applications. Smart grid with and without cloud-based applications are compared in the context of some existing literature in Section 6. Finally, a conclusion is provided in Section 7.

2 Overview of Smart Grid and Cloud Computing

2.1 Smart Grid

A smart grid can be conceptualized as an integration of electric power grid with the bidirectional communication network system [18]. With the integration of information and communication technology, modern smart grid is capable of providing electricity to the end users in an increasingly efficient manner. A smart grid architecture spans primarily three different technical domains—generation system, transmission side, and distribution side [19]. The generation side consists of traditional power plant generation. The transmission side is responsible for delivering electricity to the distribution side (customers). An important characteristic of a smart grid is controlling electricity consumption at the customers' ends by establishing different optimization methods [20], [21]. To achieve this goal, smart metering and micro-grid are the most important components that have been incorporated in the smart grid architecture.

Smart metering. Smart metering is one of the most emerging technologies used in smart grid to obtain information about customers' real-time energy consumption. It is also capable of controlling the advanced metering infrastructure (AMI) systems [22]. AMI is supported with bidirectional communication mechanism to obtain real-time energy consumption at the customers' ends remotely. A smart meter is a device deployed at the distribution-end, and capable of recording the energy consumption by the customers. Customers and utilities are benefited with smart metering infrastructure. For example, a customer can estimate his/her energy consumption during the whole day for cost-optimization, and utility is able to maintain real-time monitoring for the supply-demand curve.

Micro-grid. In the concept of the smart grid architecture, the power distribution side is divided into subgroups similar to the step-down transformers. These subgroups have self-generation capacity such as combined heat power, wind generation, and solar generation. Additionally, they

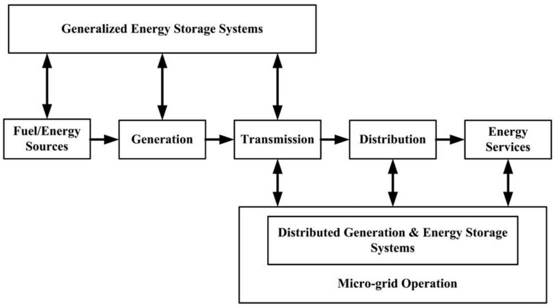


Fig. 1. Smart grid with centralized and decentralized generation, and storage systems.

can control and distribute electricity to the end-users. These subgroups are known as micro-grids. A micro-grid is the integration of low-voltage electricity systems with self-generating facilities. A subgroup has an independent power supply and control system to provide electricity to the end users [23], [24]. In the presence of an intrusion in the entire system, a micro-grid acts in the islanding mode. In such a situation, a micro-grid is able to control the power flow autonomously. Due to the fluctuation in renewable energy sources, the primary distributed energy resources are converted into distributed generation using the micro-grid operation. Some of the advantages of a micro-grid are listed as follows:

1) Electricity distribution facility is converted to decentralized from centralized.
2) A micro-grid increases the local reliability, and energy management mechanisms.
3) Improved real-time monitoring system can be achieved.
4) In the presence of any kind of intrusion, it acts in the islanding mode, and supplies electricity in secure and efficient ways to the end users.
5) All the micro-grids can interact with one another and exchange energy, when there is an excess or deficit of it.

Fig. 1 illustrates a smart grid architecture with the generation, transmission, and distribution components. The traditional power plants, and renewable energy sources are treated as generation side of a smart grid. Electricity is transmitted to the distribution side from the generation side using transmission lines. Finally, the distribution side is responsible for distributing it to the end users.

2.2 Cloud Computing

Cloud computing is an emerging computation model that provides on-demand facilities, and shared resources over the Internet. Cloud computing, based on large storage and computational devices, acts as a utility provider [25], [26]. Cloud computing provides three distinct types of services—*Platform as a Service (PaaS)*, *Software as a Service (SaaS)*, and *Infrastructure as a Service (IaaS)* [3], [27], [28].

Infrastructure as a service. IaaS is the infrastructure service model that includes storage and virtual machines. Load balancing in cloud computing is performed using IaaS. Users can install access to required software through virtual machines. These virtual devices provide on-demand facility to the customers [17], [29], [30]. The IaaS service offers hardware platform to the users on-demand basis. Therefore, users can access the online hardware platform as on-demand basis to fulfill their requirements. Additionally, the IaaS service also supports vertualization of resources on which a guest user can run his/her own operating system [29].

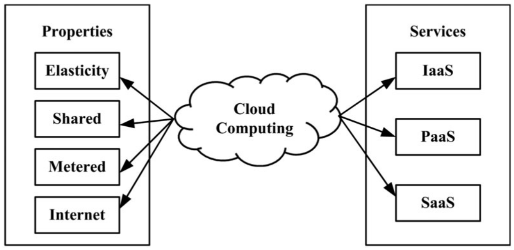


Fig. 2. Cloud computing infrastructure.

Platform as a service. PaaS is responsible for the development and delivery of programming models to IaaS. Users can access such programming models through cloud and execute their programs [29]. PaaS is responsible for the runtime execution of users' given task. Therefore, the PaaS service completes the requirements of building and delivering of Web-applications without downloading and installing required software as well.

Software as a service. SaaS supports all the applications in the cloud environment. This feature of cloud computing is accessible through Web-browsers. The SaaS service provides the modeling of software deployment where users can run their applications without installing it on his/her own computer. However, this service is limited to the users, i.e., only existing set of services is available to the customers.

On the other hand, cloud can also be categorized, depending on the deployment models, as—*private*, *public*, *community*, and *hybrid* [3].

- *Private cloud*. The cloud is owned by a private organization, and information is shared only within the organization. The purpose of this type of cloud application is to serve its own business applications.
- *Public cloud:* On the other hand, public cloud is owned by a service provider, and used by public for their purposes.
- *Community cloud*. Community cloud is similar to the private cloud with some additional features to provide services to a group of organizations who have similar type of requirements.
- *Hybrid cloud*. Hybrid cloud is the extension of cloud computing with private, public, and community cloud computing techniques [28]. The private, public, and community clouds are integrated together to perform several tasks which are capable of handling the requirements of private, public, and community organizations.

In Fig. 2, cloud services and properties are shown. Additionally, we also show the categorization of cloud computing application in Fig. 3. The advantages of using a cloud computing model are as follows [31], [32], [33], [34]:

- *Elastic nature*. Cloud computing supports elastic nature of storage and memory devices. It can expand

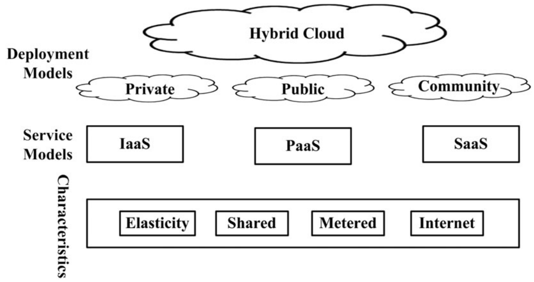


Fig. 3. Classification of cloud computing applications [3].

and reduce itself according to the demand from the users, as needed.

- *Shared architecture*. Cloud computing also supports shared architecture. Information can be shared among the users after meeting the privacy issues, and, thereby, reducing service costs [35].
- *Metering architecture*. Cloud computing offers metering infrastructure to customers [36]. In the metering system, cost optimization mechanisms are offered to users, enabling them to provision and pay for their consumed resources only.
- *Internet services*. Cloud computing can be implemented in the existing Internet service system. Thus, it supports the existing network infrastructure.

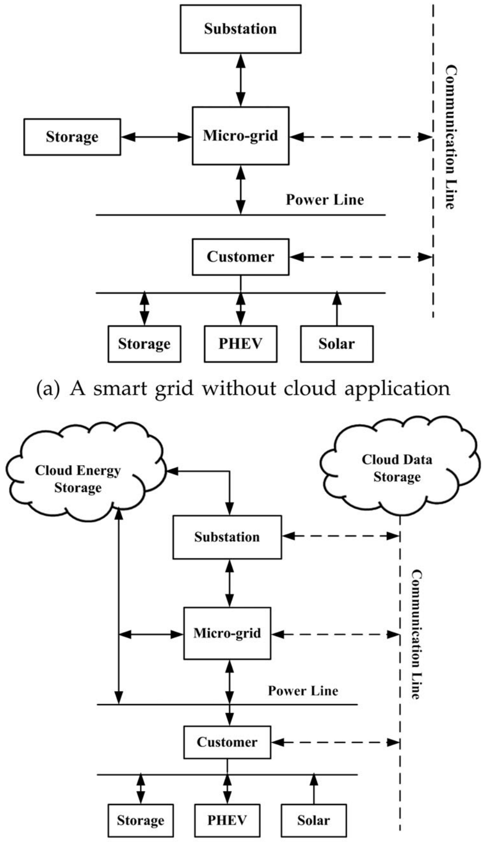
3 Cloud Applications for Energy Management

Energy management is a major concern in smart grid environments. In the past several years, researchers addressed this issue by incorporating the implementation of different components such as Home Energy Management System (HEMS), building energy management system, dynamic pricing, and load shifting [37]. Therefore, the objective of the smart grid is to support cost-effective and reliable energy management in real-time. In this section, we provide a brief overview of the application of cloud computing for smart grid energy management. First, we address different problems using existing approaches for energy management without cloud applications in smart grid. Then, we discuss how these problems can be undertaken with the implementation of cloud computing. Finally, we conclude this section while proposing some future research directions on various aspects of cloud applications for smart grid.

3.1 Problems with Existing Approaches without Cloud

The heterogeneous architecture of smart grids, demand response, and micro-grids are the main building blocks in the smart grid architecture.

Demand response. In smart grid, stand-by generators are used in order to support the heavy load in on-peak hours. These generators are typically based on fossil fuels, and, thus, they increase carbonization of the environment. Therefore, implementation of virtual energy sources are useful than the physical ones. This mechanism is known as Demand Response—a mechanism by which the customers can actively participate in balancing the supply and demand curves [38], [39]. In the presence of demand response mechanism, customers can schedule their appliances during off-peak hours to minimize the energy consumption cost, which in turn minimizes the load on the micro-grids during on-peak hours. Customers can take adequate decision while they have grid, storage, and self-generated energy as well to minimize the energy cost with the help of demand response mechanism. On the other hand, virtual energy storage is also one of the useful techniques for reliable energy supply. In the presence of virtual energy storage platform, the micro-grids can store their excess energy, while other micro-grids can consume the storage energy to fulfill their customers' demand.



(a) A smart grid without cloud application

(b) A smart grid with cloud application

Fig. 4. A conceptual view of smart grid with and without cloud applications.

In Fig. 4a, a conceptual view of the conventional smart grid (without cloud) is shown, where customers are serviced by micro-grids. A micro-grid has some self-generation unit such as solar, and wind generation. All the different components (substations, micro-grids, and customers) can communicate with utility providers over the communication network. On the other hand, in Fig. 4b, the integration of cloud applications in the smart grid architecture is shown. The cloud applications can be served as virtual energy storage [40], and data storage devices. In such a scenario, smart grid components communicate with the cloud instead of doing so with one another directly, and taking necessary decisions for energy management.

In the conventional smart grid architecture (without cloud), several problems, as detailed below, are addressed by researchers [31], [32], [33], [41], [42].

- The master-slave architecture causes extensive exposure to cyber attacks such as the distributed denial-of-service (DDoS) attack from the compromised nodes in the demand response model [31]. In such master-slave architecture, the utility provider acts as a master and the customers act as slaves.
- Single failure in master-slave architecture is one of the biggest concerns in the existing approaches in which cloud is not used.
- The maximum number of customers that can be served is limited due to the limited server capacity.
- Demand response is performed in an utility's energy management systems (EMS). As limited memory and storage are available, it will be a challenging problem for energy management when the number of customers increases.
- Adequate management and control is necessary, while a micro-grid provides services in islanded mode, as different issues (such as stability and voltage regulation) are to be met by the micro-grid itself [42].
- In the conventional approaches(without cloud), using sensor nodes and intelligent devices, an early warning system can be integrated with the grid. However, due to limited energy and bandwidth resources, real-time implementation is quite difficult.

These are some of the fundamental issues with the existing approaches in the smart grid architecture, as reported in the literature [31], [32], [33], [41], [42].

3.2 Solution Concept with Cloud Applications

For several years, researchers proposed several solution concepts for demand response and micro-grid management [31], [32], [33], [41], [43], [44], [45].

Kim et al. [31] proposed the concept of Cloud-Based Demand Response (CDR) for fast response times in large scale deployment. In this architecture, the master/slave demand response model is proposed, in which the smart meters and the home EMS act as slaves, and the utility acts as the master. In such a scenario, the CDR leverages data-centric communication, publisher/subscriber and topic-based group management, instead of IP-centric communication. Two cloud-based demand response models are proposed as follows: (a) data-centric communication and (b) topic-based group communication. Secure, scalable and reliable demand response can be achieved by using the CDR approach. However, the demand-response model discussed in [31] has an overhead problem with the implementation of private cloud for a small-sized network. Some of the overhead problems are the implementation cost, and the selection of appropriate strategy. Even for a small-sized network, all the features of cloud computing platform should be supported in order to have reliable, and secure electricity distribution in a smart grid, and, thus, implementation cost of cloud applications is higher than the existing methods for a small-sized network. So, there is a need for developing such a demand-response model using cloud-based applications that will facilitate both the large and small-scale network.

Energy management can also be addressed with the implementation of dynamic pricing. Xuan Li and Lo [32] proposed two smart grid related issues: (a) peak demand and (b) dynamic pricing. With the integration of cloud, requests from customers are scheduled which are to be executed depending on the available resources, priority, and other applicable constraints. During peak hours, the messages from smart meters are more than those in the non-peak hours [32]. However, in such a scenario, incoming jobs from users are scheduled according to their priority, available resources, and applicable constraints. With the integration of dynamic bandwidth allotment mechanism using cloud application, these issues can be addressed conveniently. During the peak-hour, the allotted bandwidth is higher than that in the non-peak hour, so as to serve all the incoming jobs simultaneously.

Virtualization is one of the most efficient techniques for cost reduction, resource optimization, and server management [41]. Cloud computing can be implemented in the form of different strategies of the micro-grids. Rajeev and Ashok [41] proposed a framework for integrating cloud computing applications for micro-grid management in the form of different modules such as infrastructure, power management, and service. The infrastructure and power management modules are used for task scheduling and micro-grid power management, respectively. The different operators publish their service description using the service module. With the implementation of cloud computing, the external computing devices can be integrated with the internal ones. Thus, the number of supported customers increases, as suggested by Rajeev and Ashok [41]. In such a manner, integrating virtual energy sources with the existing energy storage devices, and the energy exchange mechanism can be achieved among the micro-grids to meet the energy requirements from consumers.

The smart grid infrastructure needs to be deployed globally. Scalable software platform is needed in order to rapidly integrate and analyze information streaming from multiple smart meters simultaneously, in order to balance the real-time demand and supply curves. Yang et al. [33] advocated that cloud platforms are well suited to support such huge data and computationally-intensive, always-on applications. In such applications, scalable requirements of resources are offered by the cloud applications to build a software infrastructure to support such dynamic and always-on applications. In these environments, cloud platforms work as intrinsic components due to the diverse benefits they offer, as mentioned below:

1) Cloud acts elastically to avoid costly capital investment by the utility during the peak hours.
2) Real-time energy usage and pricing information can be shared, so that the customers can get benefited from the real-time information.
3) Some data can be shared with a third party by using cloud services, after meeting the data privacy policies for developing intelligent applications to customize consumer needs.

The implementation of specialized data abstraction for data streams generated from the different components is one of the key technologies for real-time monitoring to take decisions at different instances. On the other hand, third-party vendors are allowed to participate in such real-time

TABLE 1
Comparison of Cloud Computing Applications for Energy Management

Cloud Applications	Smart Grid Features			
	Demand Side Management	Micro-grid Management	Load Shifting	Dynamic Pricing
Demand Response (as in [31])	✓	✓	✓	✓
Peak demand and dynamic pricing (as in [32])	✓	✗	✓	✓
Micro-grid management (as in [41])	✗	✓	✓	✗
Real-time monitoring (as in [33])	✓	✗	✗	✗
Power monitoring and early-warning system (as in [43])	✓	✗	✓	✗
Information interaction using Mobile agent (as in [44])	✓	✗	✓	✗
Dynamic Demand Response (D^2R) (as in [45])	✓	✓	✗	✗

monitoring system. So, defining an effective privacy-policy is perceived to be a secure mechanism, while allowing the third-party vendors for the real-time monitoring process.

Cloud-based services are used for communication and management schemes in the smart grid by Ji et al. [43], while providing the facility of power monitoring and early-warning system as well. In such a scenario, service-oriented architecture (SOA) and enterprise service bus (ESB) are used for providing the real-time support. In this approach, flexible, efficient, on-demand, and scalable smart grid power monitoring system can be built. The authors proposed that SOA relies on publishing applications as a service. Standard Web services, interfaces, service registry, service finding, and service access are implemented into a single cloud application using SOA. With the implementation of cloud applications, resource management, task management, and security management activities can be performed using the ESB architecture for smart grid energy management [43].

With the fast development of smart grid, implementation of higher storage and processing capacity of power system is needed. In such a scenario, a mobile agent is used to serve the information interaction mechanism in the cloud computing infrastructure [44] to fulfill the requirements of the smart grid. This mobile agent combined with cloud computing acts as an intermediate device among different levels in the smart grid. Different types of mobile agents such as Data Mobile Agent (DMA) and State Mobile Agent (SMA) can cooperate with one another to fulfill users' requests. The work in [44] proposes that the use of a mobile agent is more suitable for power system using cloud computing platform due to the smart grid's heterogeneous architecture. In the smart grid architecture, multiple users as well as multiple energy sources participate together. In the conventional smart grid system (without integrating cloud), an energy source with multiple user energy consumption units (agents) is studied by Rad et al. [46]. Using this mobile agent, it is important to understand how energy information interaction can be done while considering multiple users and sources.

In a recent paper [45], cloud computing is used as *Software as a Service* for smart grid cyber-physical systems. In this work, the authors discussed about dynamic demand response (D^2R) to perform intelligent demand-side management and relieve peak-load. In such a scenario, D^2R acts as an intelligent decision making tool to increase the reliability of smart grid. In such a model, the implementation of a cloud-based software platform is envisioned to be useful to support all the portable devices of different layers in a smart grid. The advantages of dynamic demand response (D^2R) are as follows:

- Demand is periodically forecasted.
- According to the demand and supply information, proper strategy is selected in order to achieve a reliable and efficient smart grid architecture.

We present the comparison of different cloud-based applications for smart grid energy management in Table 1 using different features of a smart grid, as addressed by the authors in [31], [32], [33], [41], [43], [44], [45].

Further, in Table 2, we present a summary of different energy management mechanisms, as suggested by the authors [31], [32], [33], [41], [43], [44], [45], with some directions for future research.

3.3 Future Research Directions with Some Research Challenges

Cloud computing applications are one of the most useful techniques for the future smart grid development. Beyond the previously discussed cloud applications, various future opportunities for cloud-based energy management are discussed below with some of the research challenges.

TABLE 2
Summary of Cloud Computing Applications for Smart Grid Energy Management

Application	Cloud Computing Applications	Future Research Directions
Demand Response (as in [31])	(a) Data-centric communication — first time response and large scale deployment. (b) Topic-based group communication — according to priority based.	• How to overcome the overhead problem with the implementation of private cloud for small size network.
Peak demand and dynamic pricing (as in [32])	Customets' requests are scheduled to be executed depending on the available resources, priority, and other applicable constraints.	• Use cloud application to dynamically increase bandwidth capacity during peak hours to avoid congestion.
Micro-grid management (as in [41])	External computing devices are integrated with the internal computing devices to minimize the computational delay	• Micro-grid to micro-grid interaction through cloud. • Establish virtual energy source as depicted in [40], and exchange energy between micro-grid and virtual energy source.
Real-time monitoring (as in [33])	Advantages of scalable and elastic resources to build a software infrastructure to support dynamic and always-on applications for smart grid.	• Efficient and reliable streaming of real-time monitoring with unique needs of energy information applications through cloud. • Provide specialized data abstractions for data streams. • Define a proper data privacy policy when allowing third party to share information.
Power monitoring and early-warning system (as in [43])	SOA and ESB for resource management, task management, and security management	• Design a proactive cloud energy management method that will give an early warning system to all the micro-grids.
Information interaction using Mobile agent (as in [44])	A mobile agent with the help of cloud computing applications is used for exchanging real-time information for energy management	• Increase efficiency using cloud computing mobile agent for multiple user-requests simultaneously.
Dynamic Demand Response (D^2R) (as in [45])	• Intelligent demand-side management and relieve peak-load using cloud application • Demand response is operated within the micro-grid	• Built a software platform which supports all the portable devices from different region. • Define demand response model externally in the cloud and integrate it into the internal micro-grid operation. • Integrate a D^2R model that will support all the programming applications.

1) Implementation of private cloud computing applications for smart grid that will support small-size networks. In such a scenario, a group of users is served by the private cloud, which improves the privacy preserving smart grid architecture. However, it is also a challenging issue to support such multiple small-size network due to their heterogeneous activities.
2) It is useful to give flexibility to the micro-grids to operate with/without the real-time information. Therefore, exchanging energy information between cloud and micro-grid is a big challenge, though micro-grid acts in the islanded mode. In the presence of intrusion, allowing islanded micro-grids to exchange energy from/to the cloud energy storage device is an important issue.
3) Introducing cloud energy devices to maintain demand and supply curve during peak hours. However, there is no well-established framework that will support the virtual energy storage systems. Therefore, proposing a framework that will support such a virtual energy storage device is a research challenge, while allowing all the entities (in the smart grid) to take part of this.
4) Similar to the above, allowing electricity exchange from micro-grid to cloud energy device and vice-versa can reduce the variation of supply-demand curve, when there is an access and deficit of energy, respectively. Therefore, online and real-time optimization, planning, prediction, and control of energy management for future smart grid using cloud applications is a trivial task without adequate infrastructure.
5) Introducing a virtual power flow controller for reliable and efficient smart grid operation. The optimization of power flow is one of the key technologies in smart grid [47]. A power flow controller is responsible for optimized electricity flow in the islanded micro-grids. There is a need for developing an optimized power flow controller that will work in any mode such as the normal mode, and the islanded mode, and also in the presence of any fluctuating power generation equipment.

6) Integrating PHEVs with cloud energy storage to relieve the demand from micro-grids. During peak hour, charging of PHEVs increases the load on smart grid [48], [49]. In such a scenario, customer has to pay high price for charging their PHEVs. With the implementation of cloud energy storage services this issue can be effectively addressed.

4 CLOUD APPLICATIONS FOR COMMUNICATION AND INFORMATION MANAGEMENT

As we have seen in the preceding sections, a smart grid consists of bidirectional electrical as well as communication flows, primarily enabled with the help of advanced sensor network technology. The smart meters are also deployed at the customers' end to communicate with the service provider in order to exchange real-time information. Due to this architecture, massive data are generated from both the utility and end-users sides. The management of vast amount of such data is challenging using the traditional data management approaches due to the different constraints (such as processing unit storage, and memory). Consequently, cloud computing applications are one of the best methods to control such vast data in order to have a reliable, robust, and efficient smart grid environment [50], [51], [52].

4.1 Need for Cloud Applications for Information Management

In a typical city environment, millions of smart meters are deployed at the distribution side. To successfully handle such massive data, a useful technique is required. Cloud computing is such a useful technology for smart grid information management due to the following reasons:

- The requirements of information processing in smart grid fit well with the computing and storage mechanisms available for cloud applications.
- In a smart grid, information sharing is one of the most important issues. Information from different components, and the supply and demand state conditions can be shared with the help of cloud computing.
- Shared information is accessible to the micro-grids, end-users, and utilities, though they function in the *islanded* mode.
- Management of massive data is complex, costly, and may be beyond the capacity of existing data management systems in the smart grid.

Using a cloud-based information management system can help in encountering such drawbacks.

4.2 Information Management Using Cloud Applications

Several works are proposed to improve communication delays, thereby attempting to enable real-time communication through cloud data management in smart grid [53], [54], [55], [56], [57], [58]. Towards this goal of data management, Lv et al. [53] proposed a cloud data warehouse application in smart grid. Formally, the authors defined a cloud data warehouse model in terms of extract transform load (ETL), online analytical processing (OLAP), data mining (DM), and business intelligence (BI) report technologies.

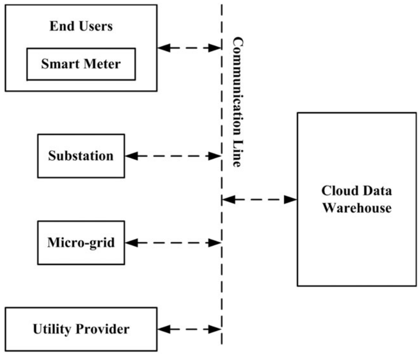


Fig. 5. A schematic view of smart grid communication with cloud data-warehouse.

This cloud data warehouse architecture provides different services for smart grid information management such as multi-dimensional data analysis, and data mining [53]. In multi-dimensional data analysis, the users have different rules for energy consumption. However, it is required to build a software platform using cloud data-warehouse for proving services to the customers as a whole. The mechanisms of coordination between a smart grid and cloud data-warehouse need to be addressed in the future.

Fig. 5 depicts the schematic view of the cloud data warehouse for smart grid, where the warehouse acts as data storage for all the components such as smart meters, micro-grids, utilities, and substations. A cost-optimization technique using cloud based architecture is presented by Fang et al. [54], in order to have simple and economical information management for smart grid. The work proposed different domains (such as smart grid, network, cloud, and broker) for cost effective information management. The broker domain acts as a programming module to support the optimization method as per the demand. However, in such a scenario, defining proper cloud-based data models for supporting the heterogeneous architecture is to be strengthened.

With the implementation of cost-optimized information sharing, electric vehicles such as the plug-in electric vehicles (PHEV) can be benefited. PHEV owners can access the real-time price, the real-state of the smart grid, and can accordingly charge and discharge their vehicles. In such a method, the utility is also able to know where most of the PHEVs are situated, and how much energy is required. The overall cost-optimization method in terms of computation and storage is studied for the smart grid architecture [54].

The cloud data center is used as communication and information optimization components to support cognitive radio-based AMI meters in a smart grid. The home area network (enabled with Zig-bee, and Bluetooth) is supported with the implementation of an optimization algorithm in the cloud data center. A net-AMI for micro-grid infrastructure is proposed using the cognitive radio network in the cloud data center [55]. PHEV can be supported using the net-AMI infrastructure, as it supports the cellular technology. The main advantage of this net-AMI technology is that it can be integrated with the existing BTS cellular service with the help of cloud computing [55]. In such an infrastructure, the net-AMI does not support the Ethernet protocols. So, defining a cloud-based proprietary protocol for cloud computing is needed to

TABLE 3
Comparison of Cloud Computing Applications for Information Management

Cloud Applications	Smart Grid Features			
	Cost Optimization	Data Storage	Dynamic Pricing	PaaS/ SaaS/ Iaas
Cloud data warehouse (such as in [53])	✗	✓	✗	SaaS, PaaS
Information management cloudward (such as in [54])	✓	✓	✓	IaaS, PaaS
Net-AMI infrastructure (such as in [55])	✓	✓	✓	PaaS, SaaS, IaaS
Smart meter data streams in cloud (such as in [56])	✗	✓	✓	IaaS
Smart grid data cloud (such as in [57])	✓	✓	✓	PaaS
Dynamic data center operations (such as in [60], [61])	✓	✓	✓	PaaS

support such protocols, while ensuring that they can work in the presence of radio-waves in the smart grid environments.

A smart meter is a key component in the smart grid architecture, and it supports two-way communication. For large-scale development, millions of smart meters are deployed in the distribution side. To successfully retrieve massive data from smart meters, the cloud technology is useful [56]. Lohrman and Kao [56] used cloud as *Infrastructure as a Service* for the processing of smart meter data streams. The *Nephele Execution Engine* framework is used for processing the smart meter data given in [56]. In such software platforms, communication latency and processing rates can be improved in order to have a real-time monitoring system in the smart grid.

Real-time distributed data management and parallel processing of information can be utilized using smart grid data cloud application, as discussed in [57]. In such smart grid data cloud scenario, cloud computing is used as *Platform as a Service*. In the smart grid data cloud infrastructure, cost and data management are shared. Due to the flexibility of cloud computing, information is retrieved from the data cloud more conveniently [57]. In the existing smart grid system, a dynamic pricing model is used depending on the load on micro-grids [59]. A dynamic pricing model can be established according to the load on cloud data services. In such a scenario, during peak-hour, load on data-cloud is high, and, thus, real-time price will be more, and vice-versa.

Cloud computing services are used as a dynamic data centers to store the real-time information from the smart meters [60]. In such a scenario, the cloud-based data centers are served as Internet data centers (IDC) which are available to the customers through the Internet. The real-time pricing policy is also presented as a non-linear function depending on the load on the data center.

Table 3 presents a list showing comparisons of cloud-based information management in the smart grid architecture. Different applications support different cloud services such as *IaaS, PaaS, and SaaS*, as shown in the Table.

In Table 4, we summarize different cloud-based applications for smart grid information management, while giving a few research directions [53], [54], [55], [56], [57].

4.3 Future Research Directions with Some Research Challenges

The heterogeneous architecture of a smart grid allows huge amount of data that are generated form smart meters, and, thus, cloud computing applications are useful for managing these data. However, there are some research challenges in smart grid, while incorporating the cloud computing applications as follows.

1) Integration of public cloud with the private cloud infrastructure for cost-effective communication in smart grid. Public cloud can be integrated with the private cloud for large-scale development in smart grid in a cost-effective manner. However, security and privacy are two of the important issues, while allowing information exchange between private and public cloud.
2) Similar to the energy scheduling, data traffic scheduling can also be the important one to maintain adequate data traffic rate in the smart grid and cloud environment. Consequently, with the help of data traffic scheduling technique, cyber-physical system will also be established in order to maintain the privacy of the users.
3) Use of multi-mobile agent combined with cloud computing for profitable smart grid operation. Due to heterogeneous communication architecture [11] of smart grid, multi-mobile agent can be used to communicate with different layers. Therefore, defining an adequate mobile strategy for the agent is required for cost-effective information management in the smart grid. Otherwise, it will be cost-expensive rather than the cost-effective one.
4) Interactive cooperation using cloud services to support not only multiple customers, but also multiple energy sources for large-scale development of smart grid for energy management, as discussed in Section 3.
5) Development of a cloud network, in which smart elements can improve their delay by changing their chosen path. On the other hand, it is also mentioned in [62] that smart elements cannot improve

TABLE 4
Summary of Cloud Computing Applications for Smart Grid Information Management

Application	Cloud Computing Applications	Future Research Directions
Cloud data warehouse (as in [53])	Multidimensional data analysis in smart grid.	• Define proper access control mechanism for cloud data warehouse to support smart grid architecture. • Establish co-ordination between smart grid and cloud data warehouse. • Build a software platform which support unified data management for smart grid environment.
Information management cloudward (as in [54])	Different domains for cost effective information management cloudward.	• Define a cloud-based model which support all domains simultaneously.
Net-AMI infrastructure (as in [55])	Cloud computing infrastructure for communication and information optimization.	• Define a proprietary protocol for cloud computing to support Ethernet for net-AMI architecture in smart grid. • Implement secure and privacy communication mechanism using cloud based net-AMI infrastructure in presence of radio waves.
Smart meter data streams in cloud (as in [56])	Cloud acts as *Infrastructure as a Service* for processing smart meter data.	• Guaranteed work-flow latency and processing rates with the help of cloud data optimization.
Smart grid data cloud (as in [57])	Real-time distributed data management and parallel processing of information using data cloud.	• Dynamic pricing model in smart grid architecture according to load on cloud data services.
Dynamic data center operations (as in [60], [61])	Storing the real-time data on cloud, and served the data as Internet data centers (IDC) to users.	• Implementation of secure data storage mechanism to preserve the privacy of the users. • Proposing adequate data transfer framework from users to cloud and vice-versa.

their delays by changing their chosen path. Therefore, it is also a challenging task to improve the delay incurred by the smart meters using cloud computing applications.

6) The key concept of smart grid is decentralized power delivery with the existing centralized infrastructure [63]. Development of cloud computing protocol architecture will support distributed nature of the smart grid. Therefore, enhancement of active participation by customers using cloud services, so that the customers get reliable, and cost-effective services such as billing.
7) Cloud computing can be used to recover network failures. Due to failures in one of the protocol suites used for communication, the entire system is affected in the smart grid technologies, as discussed by Wang and Khanna [64].
8) Using cloud data warehouse, as in [53], for optimization, control, and secure communication for the virtual power plant (VPP) technology.

5 Cloud Applications for Security in Smart Grid

A smart grid can be conceptualized as a cyber-physical system that connects physical electricity systems and cyber-infrastructure, with the integration of the Internet. This service can communicate with the consumer appliances and also provide the backbone for service providers to absorb contents and control operations. With the presence of online connectivity, it is a big challenge to prevent cyber-attacks in the smart grid that can potentially disrupt the power supply [65]. One of the important issues is power theft by consumers. This can be done by hacking a smart meter or modifying the real-time information through accessing communication channel to change the reported electricity usage. Additionally, data manipulation is also one of the most security concerns in the smart grid. To overcome these issues we need to implement proper security for secure and reliable smart grid architecture. Security can be implemented on the consumer side, transmission side, and generation side. The main security aspects of smart grid are as follows:

- With the increase of the grid system complexity and their integration, it is difficult to track interactions among business systems securely.
- The smart grid architecture is more complex than the one for the traditional power grid. The implementation of a smart sensor network, wireless communication, and smart meters increases the complexity in the protection of the information security system.
- With the implementation of millions of smart meters, the network is distributed to the end-user systems. So, the capacity of the protection at the end-users needs further enhancement.
- The denial-of-service (DoS) attack to affect the stability of the applications for the smart grid.
- Utility and third-party can access the user data as well as private information, thereby affecting the privacy of the users.

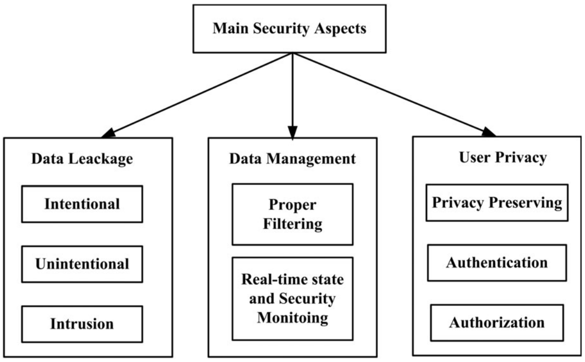


Fig. 6. Main security aspects in smart grid architecture.

In Fig. 6, we show the main security issues in the smart grid architecture. Data outage prevention, data management, and users' privacy are important issues. Additionally, Fig. 7 shows the interactions between different components of smart grid and cloud computing. Only authorized smart grid components can access different cloud services for providing adequate security to the end-users.

1. *Data leakage*. Data outage can be introduced intentionally or unintentionally. In the presence of cyber-physical attack, unintentional data leakage can be performed by third-party. Even data outage can take place with the help of user for her facility, and is known as intentional data leakage.
2. *Data management*. The choice between data to be discarded and the one to be stored is a major concern. Proper data management mechanism is needed for real-time state monitoring. With the integration of proper filtering method, data can be managed properly.
3. *Privacy*. Privacy preserving is one of the most important issues in smart grid infrastructure. Due to the lack of privacy policies, users' personal data can be disclosed to the utility and also to third party vendors. A proper authentication, and authorization process needs to be implemented for securing users' privacy.

5.1 Different Security Technologies in Smart Grid Using Cloud Applications

The existing information protection systems for electric power are deficient in handling the ever changing and growing nature of security threats [66]. To address these issues in the smart grid development, researchers proposed several security technologies in terms of cloud computing applications [66], [67], [68], [69], [70].

An electric power information security and protection system, based on cloud security, is presented by Yanliang et al. [66]. The authors classified cloud security into two parts: *server* and *client*. The clients mainly collect data and take action according to the server responses. On the contrary, the server uses the cloud computing platform to implement the distributed storage, thereby acting as an intelligent decision maker. Then the results are transmitted to the clients through the Internet.

Simmhan et al. [67] analyzed different security and privacy issues in smart grid software architecture operating on different cloud environments. Private cloud platforms are suitable for scaling out and processing millions of data from users. Using the cloud computing platform, the electrical utilities can quickly and effectively deal with malicious software, thereby reducing the overall network damage control costs and improving the overall safety level.

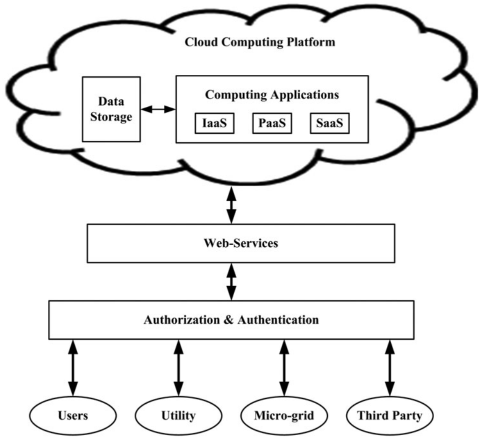


Fig. 7. Interactions between smart grid and cloud computing.

The distributed verification protocol (DVP) proposed by Ugale et al. [68] is focused on guaranteeing data storage security in cloud computing. The authors introduced the merits of the application field of cloud computing to reduce users' cost in the smart grid architecture. Ugale et al. [68] also proposed that the implementation of the DVP protocol is suitable to support data storage and power management mechanisms for smart grid.

With the construction of power cloud technology for smart grid development, many security issues are addressed in [69]. Cloud computing expands the trust boundary, and makes more stakeholders to join the adoption of the traditional security techniques. Several cloud computing security risks are discussed. For instance, (a) administrator being able to access personal sensitive data, and (b) the location of the cloud required to ensure that information is transmitted and kept securely.

Maheswari et al. [70] focused on the development of a cloud-based software platform for state estimation in a smart grid environment. With the implementation of the public key infrastructure (PKI), issues related to fault-tolerance and intrusion detection are addressed. This state estimation method utilizes maximum bandwidth that is available in the cloud, so as to achieve reliable, secure, and fault-tolerant smart grid architecture. This software platform also maximizes the use of cores.

Wen et al. [71] propose a privacy preserving smart metering scheme in the smart grid. In the proposed scheme, each individual smart meter stores the real-time information in encrypted form on the cloud platform. Therefore, only the authorized entities are permissible to access the stored data. In such a scenario, users can generate data query upto a possible range. Further, the query is transferred into two query tokens which are used to find the required data, while maintaining the users' privacy.

In Table 5, the comparison of different security aspects in smart grid using cloud applications is shown. The different smart security features—cyber-physical, data security and privacy, and threat detection are compared.

TABLE 5
Comparison of Cloud Computing Applications for Smart Grid Security

Cloud Applications	Smart Grid Security Features		
	Cyber-Security	Data Security and Privacy	Threat Detection
Software platform for server and client's security (as in [66])	✓	✗	✓
Software architecture for security and privacy (as in [67])	✓	✓	✓
Distributed verification protocol (as in [68])	✓	✗	✗
Power cloud computing (as in [69])	✗	✓	✓
State estimation method (as in [70])	✗	✓	✓
Privacy Preservation (as in [71])	✗	✓	✓

In Table 7, we synthesize the different security technologies adopted in the smart grid architecture using cloud applications, as proposed by the authors in [66], [67], [68], [69], [70], with some future extensions. Yangling et al. [66] proposed the server-client mechanism for securing smart grid, as discussed earlier. In such a mechanism, cloud can be used as *SaaS* for ensuring data privacy issues to motivate customers to be part of the smart grid.

Simmhan et al. also proposed a cloud-based software platform to deal with security and privacy issues to prevent malicious software attacks [67]. However, in such a software platform, public cloud computing is used. So, strong privacy policies need to be formulated while allowing the use of public cloud applications.

The distributed verification protocol is proposed for data storage security in cloud applications for smart grid [68]. The DVP mechanism can be used for preventing intentional or unintentional data-leakage.

Yang et al. [69] discussed some technical security issues in power-cloud computing. With the technical security issues, the non-technical issues such as the improvement service of quality can also be addressed.

The real-time state estimation method is proposed by Maheshwari et al. [70] using cloud applications. This cloud-based state estimation method can be used for target-oriented security technologies to track the location of electricity theft for smart grid development.

A cloud-based range query information access mechanism is proposed by Wen et al. [71]. The proposed method is useful to maintain the privacy of the users, while using a common platform (cloud) as a storage device. Therefore, the proposed cloud-based is useful to handle the issues of supporting multiple entities in a common platform, while maintaining the security and privacy of the users as well.

In Table 6, we present a summary of the existing cloud-based smart grid security technologies with some future research directions.

TABLE 6
Summary of Cloud Computing Applications for Smart Grid Security

Application	Cloud Computing Applications	Future Research Directions
Security and protection system for electric power information (as in [66])	Server acts as cloud and takes decision according to clients' data.	• Develop cloud as '*software as a service*' for data privacy issues in large scale deployment of smart grid.
Privacy and issues in smart grid software architecture (as in [67])	Quickly and effectively deal with malicious software with the implementation of cloud computing applications.	• Define security mechanism for smart grid while using public cloud computing applications. • Effective and efficient security and privacy policies to support increasing data from smart meters.
Distributed verification protocol (as in [68])	Data storage security in cloud computing.	• Use distributed verification protocol to prevent information leakage in smart grid.
Security technologies for power cloud computing (as in [69])	Trust boundary is expanded using cloud applications.	• Expand power cloud applications for non-technical issues in smart grid, such as improve quality of service mechanism.
Real-time state estimation for smart grid (as in [70])	Cloud based state estimation technique.	• State estimation method for mission-oriented security technologies for smart grid development.
Privacy preserving range-query (as in [71])	Cloud-based information privacy preserving scheme.	• Implementation of ranked range query, while preserving the privacy of the users.

TABLE 7
Existing Literature: Comparison- with and without Cloud in the Smart Grid

Technology	Smart Grid Features	Existing Literature	
		Without Cloud	With Cloud
Energy Management	• Demand-side Management	[73]–[80]	[31]–[33], [43]–[45]
	• Micro-grid Management	[81]–[85]	[41], [45]
	• Load Shifting	[73], [86]	[31], [32], [41], [43], [44]
	• Dynamic Pricing	[87]–[92]	[31], [32]
Information Management	• Cost Optimization	[93], [94]	[54], [55], [57]
	• Data Storage and Processing	[21], [95], [96]	[53]–[57]
	• Dynamic Pricing	[87]–[92], [97]	[54]–[57]
Security	• Cyber Security	[12], [98], [99]	[66]–[68]
	• Data Security and Privacy	[12], [100]–[103]	[67], [69], [70]
	• Threat Detection	[12], [65], [100], [104], [105]	[66], [67], [69], [70]

5.2 Future Research Directions with Some Research Challenges

Beyond the previously discussed cloud applications in order to provide security in the smart grid, various future opportunities for cloud-based security are also provided with some research challenges.

1) In smart grid, third parties are also allowed to participate in the real-time monitoring systems. Cloud computing applications are expected to provide adequate security to maintain the privacy of the users data. However, it is still not clear from the existing technologies that how this security can be provided, while allowing third parties to take part into the systems. Therefore, providing cloud security to prevent outage (third party vendors) to interact with the customers equipment to control and monitor [72], while allowing different vendors.
2) Implementing coordinated fault protection mechanism with the help of cloud-based infrastructure in smart grid. In this infrastructure, different equipment are able to perform together efficiently.
3) Using cloud-based state estimation method [70] for proactive and adaptive management for micro-grid. Therefore, adequate strategy can be taken by service providers in order to provide reliable energy services to the end-users.
4) Cloud computing applications are expected to detect intentional data leakage in smart grid. However, data leakage may take place unintentionally as well. Therefore, preventing unintentional data leakage is a research challenge, while incorporating cloud computing applications in the smart grid.
5) Privacy preserving data collection for different tasks such as billing, and real-time monitoring.

6 Overall Comparison

We synthesize the studies presented in some of the existing pieces of literature which address the issues related to smart grid development, in the context of cloud-based, and non-cloud-based (conventional) optimization mechanisms. The different smart grid features—demand side management, micro-grid management, load shifting, dynamic pricing, cost-optimization, data storage, cyber-security, data security, and threat detection—are discussed below.

a) Demand-side management. Allowing the customers to take real-time decisions for modeling their energy consumption is one of the key aspects of demand-side management. In the presence of a demand-side management system, peak-hour load is reduced and shifted to the non-peak hour. Logenthiran et al. [73] presented a demand-side management model based on a load shifting mechanism using a heuristic-based evolutionary algorithm (EA). Dynamic games model is proposed for distributed demand-side management in [74]. In such a scenario, a two-layer architecture is considered—*lower layer* (one household as one player), and *upper layer* (to store the interaction mechanism among different players). A sensor network is used as an emerging tool for smart grid real-time monitoring systems [75]. The authors use Sensor Web-services for demand-side energy management for large-scale development of smart grid. Due to the characteristics of huge storage and computation mechanisms, cloud-based applications are proposed as useful solutions for demand-side management efficiently, as discussed in [31], [32], [33], [43], [44], [45].

b) Micro-grid management. A micro-grid is envisioned as capable of distributing electricity to the end-users with distributed generation facility, as discussed in Section 2. The co-operative control strategy and energy management is discussed in [81]. Jeon et al. [82] proposed a real-time digital simulator-based test system for micro-grid energy management. However, the autonomous activities of micro-grids often lead to information islanding [6], and as a consequence of which it is difficult to exchange the energy information with the other micro-grids [6]. These issues can be undertaken using cloud applications, as discussed in [54], [55], [57], so that a micro-grid is able to exchange energy information in the islanding mode as well.

c) Load shifting. During peak hours, the load on the micro-grids is more than that in the non-peak hours. Different load shifting mechanisms are proposed in [73], [86], [106] for the conventional smart grid environment (without cloud). Logenthiran et al. [73] proposed that the shift-able devices such as washing machines, and refrigerator can be used in the non-peak hours to relieve the load on the grid during peak hours. A phase-based optimal service policy according to periodically incoming jobs from end-users is proposed in [86]. However, when there is an urgent requirement of energy during the peak hours, then the customer is required to pay high prices. This problem is addressed by the authors in [31], [32], [41], [43], [44] with the implementation of cloud energy services.

d) Cost-optimization. Due to the complex architecture of smart grid, resource (energy and data) optimization mechanisms is a challenging task. Several cost-optimization methods are proposed by the authors in [54], [55], [57], [93], [94]. Georgievski et al. [93] propose different cost-optimization methods in the smart grid architecture. Georgievski et al. [93] proposed a cost-optimization scheduling algorithm for use in an office environment and coupled it with the smart grid architecture. However, automatic metering infrastructure (AMI), smart meters, and micro-grids technologies make a complex architecture for large-scale development of smart grid. Integrating these systems into cloud application is useful, as discussed in Section 2.

e) Data storage. In Section 2, we discuss the need for proper management of incoming real-time information from smart meters. Wang et al. [95] proposed a hierarchical extended storage mechanism for massive dynamic data (HES) storage and monitoring of data in different areas according to different data types. An agent-based micro-storage facility is studied by Vytelingum et al. [21]. However, these approaches are cost-prohibitive. The requirements of information processing from smart meters fit well with the cloud applications [54]. In the absence of adopting cloud applications in smart grid, the computing devices are implemented within the end-users' energy management devices. As an example, during the peak hours, utility demands more computing and storage devices, and, thus, information management and computation is a difficult task to handle within the internal computing devices, as it has less memory and data storage capacity [67]. So, cloud applications are addressed as an useful mechanism for large-scale development of smart grid, as the authors suggested in [53], [54], [55], [56], [57].

f) Dynamic pricing. Real-time pricing mechanisms are proposed by the authors in [54], [55], [56], [57], [87], [88], [89], [90], [91], [92]. Dynamic price is based on dynamic demand from customers and total available power supply. However, in the existing dynamic pricing method, dynamic-pricing mechanism is modeled according to the load on the micro-grids. For this reason, a proper pricing policy may not always be maintained. So, using a cloud-based platform, dynamic pricing can be modeled according to the load on the cloud data center.

g) Cyber-security. Cyber-security is one of the important considerations in a smart grid architecture [12]. Different technologies are proposed to establish a secure smart grid environment [12], [66], [67], [68], [98], [99]. McKinnon et al. [98] proposed the digital-ants framework to identify a cyber-attack in the smart grid. The cyber-security issues are undertaken with the implementation of a human-automation interaction (HAI) method in [99]. However, cloud-based security technologies are useful for cost-effective mechanism, as cyber-security issues for a smart grid can be handled using the existing cloud security mechanisms [66], [67], [68].

h) Data security and privacy. In the smart grid architecture, third-parties are allowed to participate in smart grid energy and information management mechanisms. To address customers' security and privacy issues, researchers proposed various security and privacy schemes to motivate the customers [12], [67], [69], [70], [100], [101], [102], [103], [107].

i) Theft and threat detection. In the traditional power grid systems, no automatic methods exist for theft and threat detection. In the smart grid environment, automatic theft and threat detection mechanisms are proposed for reliable power supply to the end-users [12], [65], [66], [67], [69], [70], [100], [104], [105]. A distributed fault-tolerant, and theft detection mechanism is proposed using linear system of equations (LSE) in [100]. In such a mechanism, the status of the customers is modeled as unity when they are honest. On the other hand, when the status is greater than unity, the customers are treated as dishonest, and, thus, theft detection mechanism works to have secure smart grid architecture. Some cloud-based security applications are proposed in [67], [69], [70] for cost-effective security mechanisms in the smart grid.

7 Conclusion

In this survey, we provided an overview of existing works integrating cloud computing in the existing smart grid architecture, in order to have reliable, efficient and secure energy distribution. Different aspects of smart grid—*energy management*, *information management*, and *security*—are discussed. We identified some important technical issues and proposed several future research directions on cloud-based smart grid.

From this surveyed work, we can see that the use of cloud computing applications in smart grid is one of the useful techniques to overcome issues related to traditional power grid management, despite the existence of some technical challenges inherent of cloud computing [108], [109].

In this paper, we provided several directions for future research. We discussed the implementation of cloud energy storage devices, and cloud data storage mechanisms for the smart grid architecture. Using cloud computing applications, energy management techniques in smart grid can be evaluated within the cloud, instead of between the end-user's devices. This architecture gives more memory and storage to evaluate computing mechanism for energy management, and cost-optimization. On the issue of communication and information management in smart grid, cloud computing is used in different scenarios. Cloud data-ward can be used to process massive data from millions of smart meters. Further, cloud computing even gives better security capability than the conventional, pure IP-based security mechanisms.

Thus, the integration of cloud computing in smart grid is envisioned to be useful for evolving the smart grid architecture further in terms of considerations such as monitoring cost, computing, data management, power management, and security.

ACKNOWLEDGMENTS

This work has been supported by a project funded by Department of Electronics and Information Technology (DeitY), grant number 13(16)/2011-CC and BT. This work also has been supported by *Instituto de Telecomunicações*, Next Generation Networks and Applications Group (NetGNA), Covilhã Delegation, by National Funding from the FCT—*Fundação para a Ciência e Tecnologia* through the Pest-OE/EEI/LA0008/2013 Project.

REFERENCES

[1] J. Popeanga, "Cloud computing and smart grids," *Database Syst. J.*, vol. 3, no. 3, pp. 57–66, 2012.
[2] A. Lakhani, (2011, Feb). The Definition of Cloud Computing. [Online]. Available: http://www.cloudcentrics.com
[3] P. Mell and T. Grance, (2011). *The NIST Definition of Cloud Comput.*, US National Institute of Science and Techonology Std., 2011. [Online]. Available: http://csrc.nist.gov/publications/nistpubs/800-145/SP800-145.pdf
[4] Y. Guo, M. Pan, and Y. Fang, "Optimal power management of residential customers in the smart grid," *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 9, pp. 1593–1606, Sep. 2012.
[5] Y. Nozaki, T. Tominaga, N. Iwasaki, and A. Takeuchi, "A technical approach to achieve smart grid advantages using energy management systems," in *Proc. IEEE Int. Conf. Wireless Commun. Signal Process.*, 2011, pp. 1–5.
[6] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid—the new and improved power grid: A survey," *IEEE Commun. Surv. Tuts.*, vol. 14, no. 4, pp. 944–980, Fourth Quarter, 2012.
[7] M. Hashmi, S. Hanninen, and K. Maki, "Survey of smart grid concepts, architectures, and technological demonstrations worldwide," in *Proc. IEEE PES Conf. Innovative Smart Grid Technol.*, 2011, pp. 1–7.
[8] N. Lu, P. Du, P. Paulson, F. Greitzer, X. Guo, and M. Hadley, "A multi-layer, hierarchical information management system for the smart grid," in *Proc. IEEE Conf. Power Energy Soc. General Meet.*, 2011, pp. 1–8.
[9] J. Zhou, R. Q. Hu, and Y. Qian, "Scalable distributed communication architectures to support advanced metering infrastructure in smart grid," *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 9, p. 1632-1642, Sep. 2012.
[10] Y. Zhang, L. Wang, W. Sun, R. Green, and M. Alam, "Distributed intrusion detection system in a multi-layer network architecture of smart grids," *IEEE Trans. Smart Grid*, vol. 2, no. 4, pp. 796–808, Dec. 2011.
[11] A. Zaballos, A. Vallejo, and J. Selga, "Heterogeneous communication architecture for the smart grid," *IEEE Netw.*, vol. 25, no. 5, pp. 30–37, Sep. 2011.
[12] A. Metke and R. Ekl, "Smart grid security technology," in *Proc. IEEE Conf. Innovative Smart Grid Technol.*, 2010, pp. 1–7.
[13] R. Lu, X. Liang, X. Li, X. Lin, and X. Shen, "EPPA: An efficient and privacy-preserving aggregation scheme for secure smart grid communications," *IEEE Trans. Parallel Distrib. Syst.*, vol. 23, no. 9, pp. 1621–1631, Sep. 2012.
[14] H. Khurana, M. Hadley, N. Lu, and D. Frincke, "Smart-grid security issues," *IEEE Secur. Privacy*, vol. 8, no. 1, pp. 81–85, Jan.-Feb. 2010.
[15] A. H. Mohsenian-Rad and A. Leon-Garcia, "Coordination of cloud computing and smart power grids," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, 2010, pp. 368–372.
[16] T. Rajeev and S. Ashok, "Operational flexibility in smart grid through cloud computing," in *Proc. IEEE Int. Symp. Cloud Serv. Comput.*, 2012, pp. 21–24.
[17] F. Moghaddam, M. Cheriet, and K. K. Nguyen, "Low carbon virtual private clouds," in *Proc. IEEE Int. Conf. Cloud Comput.*, Jul. 2011, pp. 259–266.
[18] F. Li, W. Qiao, H. Sun, H. Wan, J. Wang, Y. Xia, Z. Xu, and P. Zhang, "Smart transmission grid: Vision and framework," *IEEE Trans. Smart Grid*, vol. 1, no. 2, pp. 168–177, Aug. 2010.
[19] Z. Minghan and M. Yun, "Summary of smart grid technology and research on smart grid security mechanism," in *Proc. IEEE 7th Int. Conf. Wireless Commun., Netw. Mobile Comput*, 2011, pp. 1–4.
[20] S. Misra, P. Krishna, V. Saritha, and M. S. Obaidat, "Learning automata as a utility for power management in smart grids," *IEEE Comm. Mag.*, vol. 51, no. 1, pp. 98–104, 2013.
[21] P. Vytelingum, T. D. Voice, S. D. Ramchurn, A. Rogers, and N. R. Jennings, "Agent-based micro-storage management for the smart grid," in *Proc. 9th Int. Conf. Auton. Agents Multiagent*, 2010, pp. 39–46.
[22] D. Hart, "Using AMI to realize the smart grid," in *Proc. IEEE Conf. Power Energy Soc. General Meet .*, 2008, pp. 1–2.
[23] I. Atzeni, L. G. Ordonez, G. Scutari, D. P. Palomar, and J. R. Fonollosa, "Demand-side management via distributed energy generation and storage optimization," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 866–876, Jun. 2012.
[24] V. Bakker, M. Bosman, A. Molderink, J. Hurink, and G. Smit, "Demand side load management using a three step optimization methodology," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, 2010, pp. 431–436.
[25] L. M. Vaquero, L. Rodero-Merino, J. Caceres, and M. Lindner, "A break in the clouds: Towards a cloud definition," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 39, no. 1, pp. 50–55, Jan. 2009.
[26] P. V. Krishna, S. Misra, D. Joshi, and M. S. Obaidat, "Learning automata based sentiment analysis for recommender system on cloud," in *Proc. IEEE Int. Conf. Comput, Inform Telecommun Syst.*, May 2013, pp. 1–5.
[27] E. Qaisar, "Introduction to cloud computing for developers: Key concepts, the players and their offerings," in *Proc. IEEE TCF Inform. Technol. Prof. Conf.*, 2012, pp. 1–6.
[28] F. Luo, Z. Y. Dong, Y. Chen, Y. Xu, K. Meng, and K. P. Wong, "Hybrid cloud computing platform: The next generation IT backbone for smart grid," in *Proc. IEEE Conf. Power Energy Soc. Gen. Meet.*, 2012, pp. 1–7.
[29] R. Prodan and S. Ostermann, "A survey and taxonomy of infrastructure as a service and web hosting cloud providers," in *Proc. Int. Conf. Grid Comput.*, 2009, pp. 1–10.
[30] S. Misra, P. Krishna, K. Kalaiselvan, V. Saritha, and M. S. Obaidat, "Learning automata-based QoS framework for cloud IaaS," *IEEE Trans. Netw. Serv. Manage.*, vol. 11, no. 1, pp. 15–24, Mar. 2014.
[31] H. Kim, Y. J. Kim, K. Yang, and M. Thottan, "Cloud-based demand response for smart grid-architecture and distributed algorithms," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, 2011, pp. 398–403.
[32] X. Li and J.-C. Lo, "Pricing and peak aware scheduling algorithm for cloud computing," in *Proc. IEEE Conf. Innovative Smart Grid Technol.*, 2012, pp. 1–7.
[33] C.-T. Yang, W.-S. Chen, K.-L. Huang, J.-C. Liu, W.-H. Hsu, and C.-H. Hsu, "Implementation of smart power management and service system on cloud computing," in *Proc. IEEE 9th Int. Conf. Ubiquitous Intell. Comput., 9th Int. Conf. Autonomic Trusted Comput.*, 2012, pp. 924–929.
[34] S. Misra, S. Das, M. Khatua, and S. M. Obaidat, "QoS-guaranteed bandwidth shifting and redistribution in mobile cloud environment," *IEEE Trans. Cloud Comput.*, 2013, DOI: 10.1109/TCC.2013.19
[35] B. C. Tak, B. Urgaonkar, and A. Sivasubramaniam, "Cloudy with a chance of cost savings," *IEEE Trans. Parallel Distrib. Syst.*, vol. 24, no. 6, pp. 1223–1233, Jun. 2013.
[36] A. Narayan, S. Rao, G. Ranjan, and K. Dheenadayalan, "Smart metering of cloud services," in *Proc. IEEE Int. Syst. Conf.*, 2012, pp. 1–7.
[37] R. C. Green II, L. Wang, and M. Alam, "Applications and trends of high performance computing for electric power systems-focusing on smart grid," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 922–931, Jun. 2013.
[38] U. D. of Energy, *Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them*, Report to the United States Congress, Feb. 2006.
[39] M. Erol-Kantarci and H. Mouftah, "TOU-aware energy management and wireless sensor networks for reducing peak load in smart grids," in *Proc. IEEE 72nd Conf. Veh. Technol. Conf. Fall*, 2010, pp. 1–5.
[40] P. Nezamabadi and G. Gharehpetian, "Electrical energy management of virtual power plants in distribution networks with renewable energy resources and energy storage systems," in *Proc. Elect. Power Distrib. Netw.*, Apr. 2011, pp. 1–5.
[41] T. Rajeev and S. Ashok, "A cloud computing approach for power management of microgrids," in *Proc. IEEE Conf. Innovative Smart Grid Technol.*, 2011, p. 49-52.

[42] N. L. Soultanis, S. A. Papathanasiou, and N. d. Hatziargyriou, "A stability algorithm for the dynamic analysis of inverter dominated unbalanced LV microgrids," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 294–304, Feb. 2007.

[43] L. Ji, W. Lifang, and Y. Li, "Cloud service based intelligent power monitoring and early-warning system," in *Proc. IEEE Conf. Innovative Smart Grid Technol.*, 2012, pp. 1–4.

[44] L. Tang, J. Li, and R. Wu, "Synergistic model of power system cloud computing based on mobile-agent," in *Proc. IEEE Int. Conf. Netw. Infrastructure Dig. Content*, 2012, pp. 222–226.

[45] V. Prasanna, S. Aman, A. Kumbhare, R. Liu, S. Stevens, and Q. Zhao, "Cloud-based software platform for big data analytics in smart grids," *IEEE J. Comput. Sci. Eng.*, vol. 14, no. 4, pp. 38–47, Aug. 2013.

[46] A.-H. Mohsenian-Rad, V. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid," *IEEE Trans. Smart Grid*, vol. 1, no. 3, pp. 320–331, Dec. 2010.

[47] J. Hu, J. Zhu, and G. Platt, "Smart grid—the next generation electricity grid with power flow optimization and high power quality," in *Proc. IEEE Int. Conf. Elect. Mach. Syst.*, 2011, pp. 1–6.

[48] W. Tushar, W. Saad, H. Poor, and D. Smith, "Economics of electric vehicle charging: A game theoretic approach," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1767–1778, Dec. 2012.

[49] C. Xu, F. Zhao, J. Guan, H. Zhang, and G.-M. Muntean, "QoE-driven user-centric VoD services in urban multi-homed p2p-based vehicular networks," *IEEE Trans. Veh. Tech.*, vol. 62, no. 5, pp. 2273–2289, Jun. 2013.

[50] X. Fang, S. Misra, G. Xue, and D. Yang, "Managing smart grid information in the cloud: Opportunities, model, and applications," *IEEE Netw.*, vol. 26, no. 4, pp. 32–38, Jul/Aug. 2012.

[51] K. Bilal, M. Manzano, S. U. Khan, E. Calle, K. Li, and A. Y. Zomaya, "On the characterization of the structural robustness of data center networks," *IEEE Trans. Cloud Comput.*, vol. 1, no. 1, pp. 64–77, Sep. 2013.

[52] H. Ma and Y. Qiu, "The cloud computing applications in information resource dynamic allocation," in *Proc. 15th Int. Conf. Netw.-Based Inform. Syst.*, Sep. 2012, pp. 14–17.

[53] H. Lv, F. Wang, A. Yan, and Y. Cheng, "Design of cloud data warehouse and its application in smart grid," in *Proc. IEEE Int. Conf. Automat. Control Artif. Intell.*, 2012, pp. 849–852.

[54] X. Fang, D. Yang, and G. Xue, "Evolving smart grid information management cloudward: A cloud optimization perspective," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 111–119, Mar. 2013.

[55] K. Nagothu, B. Kelley, M. Jamshidi, and A. Rajaee, "Persistent NET-AMI for microgrid infrastructure using cognitive radio on cloud data centers," *IEEE Syst. J.*, vol. 6, no. 1, pp. 4–15, Mar. 2012.

[56] B. Lohrmann and O. Kao, "Processing smart meter data streams in the cloud," in *Proc. 2nd IEEE PES Int. Conf. Exhib. Innovative Smart Grid Technol.*, 2011, pp. 1–8.

[57] S. Rusitschka, K. Eger, and C. Gerdes, "Smart grid data cloud: A model for utilizing cloud computing in the smart grid domain," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, 2010, pp. 483–488.

[58] S. Misra, S. Bera, A. Mondal, R. Tirkey, H.-C. Chao, and S. Chattopadhyay, "Optimal gateway selection in sensorcloud framework for health monitoring," *IET Wireless Sens. Syst.*, vol. 3, no. 4, p. 8, Dec. 2013.

[59] H. Goudarzi, S. Hatami, and M. Pedram, "Demand-side load scheduling incentivized by dynamic energy prices," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, 2011, pp. 351–356.

[60] P. Wang, L. Rao, X. Liu, and Y. Qi, "D-Pro: Dynamic data center operations with demand-responsive electricity prices in smart grid," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1743–1754, Dec. 2012.

[61] M. Ghamkhari and H. Mohsenian-Rad, "Energy and performance management of green data centers: A profit maximization approach," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 1017–1025, Jun. 2013.

[62] W. Saad, Z. Han, and H. V. Poor, "A game theoretic approach for multi-hop power line communications," in *Proc. Int. Conf. Game-Nets*, Apr. 2011, pp. 546–561.

[63] B. Panajotovic, M. Jankovic, and B. Odadzic, "ICT and smart grid," in *Proc. IEEE 10th Int. Conf. Telecommun. Modern Satellite Cable Broadcast. Serv.*, 2011, pp. 118–121.

[64] W. Wang and Y. X. M. Khanna, "A survey on the communication architectures in smart grid," *Comput. Netw.*, vol. 55, pp. 3604–3629, 2011.

[65] J. Liu, Y. Xiao, S. Li, W. Liang, and C. L. P. Chen, "Cyber security and privacy issues in smart grids," *IEEE Comm. Surv. Tut.*, vol. 14, no. 4, pp. 981–997, 2012.

[66] W. Yanliang, D. Song, L. Wei-Min, Z. Tao, and Y. Yong, "Research of electric power information security protection on cloud security," in *Proc. Int. Conf. IEEE Power Syst. Technol.*, 2010, pp. 1–6.

[67] Y. Simmhan, A. Kumbhare, B. Cao, and V. Prasanna, "An analysis of security and privacy issues in smart grid software architectures on clouds," in *Proc. IEEE Int. Conf. Cloud Comput.*, 2011, pp. 582–589.

[68] B. Ugale, P. Soni, T. Pema, and A. Patil, "Role of cloud computing for smart grid of India and its cyber security," in *Proc. IEEE Nirma Univ. Int. Conf. Eng.*, 2011, pp. 1–5.

[69] Y. Yang, L. Wu, and W. Hu, "Security architecture and key technologies for power cloud computing," in *Proc. IEEE Int. Conf. Transp., Mech., Electr. Eng.*, 2011, pp. 1717–1720.

[70] K. Maheshwari, M. Lim, L. Wang, K. Birman, and R. van Renesse, "Toward a reliable, secure and fault tolerant smart grid state estimation in the cloud," in *Proc. IEEE PES Innovative Smart Grid Technol.*, 2013, pp. 1–6.

[71] M. Wen, R. Lu, K. Zhang, J. Lei, X. Liang, and X. Shen, "PaRQ: A privacy-preserving range query scheme over encrypted metering data for smart grid," *IEEE Trans. Emerging Topics Comput.*, vol. 1, no. 1, pp. 178–191, Jun. 2013.

[72] S. Subashini and V. Kavitha, "A survey on security issues in service delivery models of cloud computing," *J. Netw. Comput. Appl.*, vol. 34, no. 1, pp. 1–11, 2011.

[73] T. Logenthiran and D.Srinivasan, T. Z. Shun, "Demand side management in smart grid using heuristic optimization," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1244–1252, Sep. 2012.

[74] Q. Zhu, Z. Han, and T. Basar, "A differential game approach to distributed demand side management in smart grid," in *Proc. IEEE Int. Conf. Commun.*, 2012, pp. 3345–3350.

[75] O. Asad, M. Erol-Kantarci, and H. Mouftah, "Sensor network web services for demand-side energy management applications in the smart grid," in *Proc. IEEE Consum. Commun. Netw. Conf.*, 2011, pp. 1176–1180.

[76] Z. Zhu, J. Tang, S. Lambotharan, W. Chin, and Z. Fan, "An integer linear programming and game theory based optimization for demand-side management in smart grid," in *Proc. IEEE Global Telecommun. Conf. Workshops*, 2011, pp. 1205–1210.

[77] I. Klavsuts, D. Klavsuts, and S. Levinzon, "Integration innovative method of demand side management in smart grid," in *Proc. IEEE 47th Int. Univ. Power Eng. Conf.*, 2012, pp. 1–4.

[78] P. Samadi, H. Mohsenian-Rad, R. Schober, and V. Wong, "Advanced demand side management for the future smart grid using mechanism design," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1170–1180, Sep. 2012.

[79] S. Misra, A. Mondal, S. Banik, M. Khatua, S. Bera, and M. S. Obaidat, "Residential energy management in smart grid: A Markov decision process-based approach," in *Proc. IEEE Conf. GreenCom/iThings/CPSCom*, Aug. 2013, pp. 1152–1157.

[80] S. Misra, S. Bera, and M. S. Obaidat, "Economics of customer's decisions in smart grid," *IET Netw.*, vol. 3, no. 1, p. 7, Mar. 2014.

[81] N. Zhi, H. Zhang, and J. Liu, "Overview of microgrid management and control," in *Proc. IEEE Int. Conf. Elect. Control Eng.*, 2011, pp. 4598–4601.

[82] J.-H. Jeon, J.-Y. Kim, S.-K. Kim, C.-H. Cho, K.-Y. Nam, and J.-M. Kim, "Real time digital simulator based test system for microgrid management system," in *Proc. IEEE Conf. Trans. Distrib. Expo.*, 2009, pp. 1–4.

[83] A. Bagherian and S. M. M. Tafreshi, "A developed energy management system for a microgrid in the competitive electricity market," in *Proc. IEEE Conf. Bucharest PowerTech*, 2009, pp. 1–6.

[84] R. Enrich, P. Skovron, M. Tolos, and M. Torrent-Moreno, "Microgrid management based on economic and technical criteria," in *Proc. IEEE Int. Energy Conf. Exhib.*, 2012, pp. 551–556.

[85] A. Parisio and L. Glielmo, "Energy efficient microgrid management using model predictive control," in *Proc. 50th IEEE Conf. Decision Control Eur. Control Conf.*, 2011, pp. 5449–5454.

[86] G. Koutitas and L. Tassiulas, "A delay based optimization scheme for peak load reduction in the smart grid," in *Proc. IEEE Int. Conf. Future Energy Syst.*, 2012, pp. 1–4.

[87] M. Roozbehani, M. Dahleh, and S. Mitter, "Dynamic pricing and stabilization of supply and demand in modern electric power grids," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, 2010, pp. 543–548.

[88] S. Bu, F. R. Yu, and P. X. Liu, "Dynamic pricing for demand-side management in the smart grid," in *Proc. IEEE Conf. GreenCom*, 2011, pp. 47–51.

[89] Q. Wang, M. Liu, and R. Jain, "Dynamic pricing of power in smart-grid networks," in *Proc. IEEE 51st Annu. Conf. Decision Control*, 2012, pp. 1099–1104.

[90] X. Liang, X. Li, R. Lu, X. Lin, and X. Shen, "UDP: Usage-based dynamic pricing with privacy preservation for smart grid," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 141–150, Mar. 2013.

[91] M. Erol-Kantarci and H. Mouftah, "Prediction-based charging of PHEVs from the smart grid with dynamic pricing," in *Proc. IEEE 35th Conf. Local Comput. Netw.*, 2010, pp. 1032–1039.

[92] K. Kok, B. Roossien, P. MacDougall, O. van Pruissen, G. Venekamp, R. Kamphuis, J. Laarakkers, and C. Warmer, "Dynamic pricing by scalable energy management systems field experiences and simulation results using PowerMatcher," in *Proc. IEEE Power Energy Soc. Gen. Meet.*, 2012, pp. 1–8.

[93] I. Georgievski, V. Degeler, G. Pagani, T. A. Nguyen, A. Lazovik, and M. Aiello, "Optimizing energy costs for offices connected to the smart grid," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2273–2285, Dec. 2012.

[94] D. Niyato, P. Wang, Z. Han, and E. Hossain, "Impact of packet loss on power demand estimation and power supply cost in smart grid," in *Proc. IEEE Wireless Commun. Netw. Conf.*, 2011, pp. 2024–2029.

[95] Y. Wang, Q. Deng, W. Liu, and B. Song, "A data-centric storage approach for efficient query of large-scale smart grid," in *Proc. IEEE Conf. Web Inform. Syst. Appl.*, 2012, pp. 193–197.

[96] M. Arenas-Martinez, S. Herrero-Lopez, A. Sanchez, J. R. Williams, P. Roth, P. Hofmann, and A. Zeier, "A comparative study of data storage and processing architectures for the smart grid," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, 2010, pp. 285–290.

[97] S. Misra, S. Bera, and T. Ojha, "D2P: Distributed dynamic pricing policy in smart grid for PHEVs management," *IEEE Trans. Parallel Distrib. Syst.*, 2014, DOI: 10.1109/TPDS.2014.2315195

[98] A. McKinnon, S. R. Thompson, R. A. Doroshchuk, G. A. Fink, and E. W. Fulp, "Bio-inspired cyber security for smart grid deployments," in *Proc. IEEE PES Innovative Smart Grid Technol.*, 2013, pp. 1–6.

[99] F. Boroomand, A. Fereidunian, M. Zamani, M. Amozegar, H. Jamalabadi, H. Nasrollahi, M. Moghimi, H. Lesani, and C. Lucas, "Cyber security for smart grid: A human-automation interaction framework," in *Proc. IEEE PES Innovative Smart Grid Technol. Conf. Eur.*, 2010, pp. 1–6.

[100] S. Salinas, M. Li, and P. Li, "Privacy-preserving energy theft detection in smart grids," in *Proc. 9th Annu. IEEE Commun. Sensor, Mesh Ad Hoc Commun Netw.*, 2012, pp. 605–613.

[101] Z. Yang, S. Yu, W. Lou, and C. Liu, "Privacy-preserving communication and precise reward architecture for V2G networks in smart grid," *IEEE Trans. Smart Grid*, vol. 2, no. 4, pp. 697–706, Dec. 2011.

[102] C. Efthymiou and G. Kalogridis, "Smart grid privacy via anonymization of smart metering data," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, 2010, pp. 238–243.

[103] M. Salehie, L. Pasquale, I. Omoronyia, and B. Nuseibeh, "Adaptive security and privacy in smart grids: A software engineering vision," in *Proc. IEEE Int. Workshop Softw. Eng. Smart Grid*, 2012, pp. 46–49.

[104] D. Grochocki, J. H. Huh, R. Berthier, R. Bobba, W. H. Sanders, A. A. Cardenas, and J. G. Jetcheva, "AMI threats, intrusion detection requirements and deployment recommendations," in *Proc. IEEE Int. Conf. Smart Grid Commun.*, 2012, pp. 395–400.

[105] S. McLaughlin, B. Holbert, S. Zonouz, and R. Berthier, "AMIDS: A multi-sensor energy theft detection framework for advanced metering infrastructures," in *Proc. IEEE Int. Conf. Smar tGrid Commun.*, 2012, pp. 354–359.

[106] M. Giuntoli and D. Poli, "Optimized thermal and electrical scheduling of a large scale virtual power plant in the presence of energy storages," *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 942–955, Jun. 2013.

[107] M. Zhou, R. Zhang, W. Xie, W. Qian, and A. Zhou, "Security and privacy in cloud computing: A survey," in *Proc. Int. Conf. Semantics, Knowl. Grids*, 2010, pp. 105–112.

[108] C. Rong, S. T. Nguyen, and M. G. Jaatun, "Beyond lightning: A survey on security challenges in cloud computing," *Comput. Elect. Eng.*, vol. 39, pp. 47–54, 2013.

[109] A. Verma and S. Kaushal, "Cloud computing security issues and challenges: A survey," *Commun. Comput. Inform. Sci.*, vol. 193, pp. 445–454, 2011.

Samaresh Bera received the BTech degree in electronics and communication engineering from the West Bengal University of Technology, India, in 2011. He is currently working toward the MS degree from the School of Information Technology, Indian Institute of Technology Kharagpur, India. Besides, he is working as a junior project officer in Development of Feasibility Assessment Model for Adaption of Underground Coal Gasification Technology in North-Eastern Region of India funded by DeitY, Government of India. His current research interests include smart grid communications and networking, and cloud computing.

Dr Sudip Misra is an Associate Professor in the School of Information Technology at the Indian Institute of Technology Kharagpur. Prior to this he was associated with Cornell University (USA), Yale University (USA), Nortel Networks (Canada) and the Government of Ontario (Canada). He received his PhD degree in Computer Science from Carleton University, in Ottawa, Canada, and the masters and bachelors degrees respectively from the University of New Brunswick, Fredericton, Canada, and the Indian Institute of Technology, Kharagpur, India. He has several years of experience working in the academia, government, and the private sectors in research, teaching, consulting, project management, architecture, software design and product engineering roles. His current research interests include algorithm design for emerging communication networks. He is the author of over 180 scholarly research papers (including 90 journal papers). He has won eight research paper awards in different conferences. He was awarded the IEEE ComSoc Asia Pacific Outstanding Young Researcher Award at IEEE GLOBECOM 2012, Anaheim, California, USA. He was also the recipient of several academic awards and fellowships such as the Young Scientist Award (National Academy of Sciences, India), Young Systems Scientist Award (Systems Society of India), Young Engineers Award (Institution of Engineers, India), (Canadian) Governor Generals Academic Gold Medal at Carleton University, the University Outstanding Graduate Student Award in the Doctoral level at Carleton University and the National Academy of Sciences, India Swarna Jayanti Puraskar (Golden Jubilee Award). He was also awarded the Canadian Governments prestigious NSERC Post Doctoral Fellowship and the Humboldt Research Fellowship in Germany. He is the Editor-in-Chief of the International Journal of Communication Networks and Distributed Systems (IJCNDS), Inderscience, U.K. He has also been serving as the Associate Editor of the Telecommunication Systems Journal (Springer), Security and Communication Networks Journal (Wiley), International Journal of Communication Systems (Wiley), and the EURASIP Journal of Wireless Communications and Networking. He is also an Editor/Editorial Board Member/Editorial Review Board Member of the IET Communications Journal, IET Wireless Sensor Systems, and Computers and Electrical Engineering Journal (Elsevier). He has edited 6 books in the areas of wireless ad hoc networks, wireless sensor networks, wireless mesh networks, communication networks and distributed systems, network reliability and fault tolerance, and information and coding theory, published by reputed publishers such as Springer, Wiley, and World Scientific. He was invited to chair several international conference/workshop pro-2 grams and sessions. He served in the program committees of several international conferences. He was also invited to deliver keynote/invited lectures in over 20 international conferences in USA, Canada, Europe, Asia and Africa.

Joel J.P.C. Rodrigues [S01-M06-SM06] received a PhD degree in informatics engineering, an MSc degree from the University of Beira Interior, and a five-year BSc degree (licentiate) in informatics engineering from the University of Coimbra, Portugal. He is currently a Professor in the Department of Informatics of the University of Beira Interior, Covilh, Portugal, and a Researcher at the Instituto de Telecomunicaes, Portugal. His main research interests include sensor networks, e-health, e-learning, vehicular communications, mobile and ubiquitous computing, and cloud technologies. He is the leader of NetGNA Research Group (http://netgna.it.ubi.pt), the Chair of the IEEE ComSoc Technical Committee on eHealth, the Past-chair of the IEEE ComSoc Technical Committee on Communications Software, Member Representative of the IEEE Communications Society on the IEEE Biometrics Council, Steering Committee member of the IEEE Life Sciences Technical Community, and officer of the IEEE 1907.1 standard. He is the editor-in-chief of the International Journal on E-Health and Medical Communications, the editor-in-chief of the Recent Advances on Communications and Networking Technology, and editorial board member of several journals, including IEEE Communications Magazine, IEEE Communications Surveys and Tutorials, Elsevier Journal of Computer Networks and Applications, Elsevier Computer Networks, Elsevier Journal of Vehicular Communications, Wiley Transactions on Emerging Telecommunications Technologies, and Wiley International Journal of Communications Systems. He has served as a guest editor for a number of journals and has been General Chair and TPC Chair of many international conferences. He is a member of many international TPCs and participated in several international conferences organisation. He has authored or coauthored over 350 papers in refereed international journals and conferences, a book, and 2 patents. He had been awarded the Outstanding Leadership Award of IEEE GLOBECOM 2010 as CSSMA Symposium Co-Chair and several best papers awards. He is a licensed professional engineer (as senior member), member of the Internet Society, an IARIA fellow, and a senior member of ACM and IEEE.