Enhancing Smart Grids via Advanced Metering Infrastructure and Fog Computing Fusion

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Abstract **—The smart grid is a new generation of the power grid that incorporates advanced features such as distributed energy resources, two-way communication and situation awareness. It is not just energy that is exchanged between consumers and producers but information. An efficient and robust smart grid requires efficient and robust communication and computation infrastructure to carry and process the associated data. We provide an overview of the possibilities that fog computing offer for smart grids. In our investigation, the pillars of fog computing, such as decentralization, resiliency, scalability and mobility, offer a perfect match for the decentralized smart grid. Fog computing nodes, capable of communication and coordination, incorporated in smart meters, will provide distributed control, communication and computation. Thus, enhancing reliability, resiliency and scalability of the smart grid as more and more distributed energy resources (DERs) are added to the grid.**

Keywords—smart grids, fog computing, AMI, Fusion

I. INTRODUCTION

In the smart grid concept, the legacy grid is upgraded with the incorporation of information and communication technologies along with advanced algorithms for control, monitoring and optimization. Furthermore, smart grid incorporates distributed energy resources through the integration of renewable energy such as solar and wind energy [1].

The two popular frameworks for the smart grid are the NIST framework and the EU framework. The latter is an improvement of the former in which the distributed energy resources is emphasized. However, to clearly emphasize the impact of our work, we will use the SGAM model [Figure 1]. Our work caters to the component and communication layer. These two layers deal with basic connectivity and network and syntactic interoperability.

In the smart grid model, the customer plays a vital role in generating the electricity and reducing the peak power. In the NIST model for the smart grid, the customer can be a residential area, business or industry settings. A smart meter is the enabler technology for the two-way communication between the utility and the customer. The smart meters are connected to the utility backhaul network through advanced metering infrastructure (AMI). The communication technologies used in the advanced metering infrastructure are not standardized. The commercially available smart-meters support more than one communication technologies. Furthermore, the meter should be able to communicate with various home appliances [2].

Besides being an enabler for AMI, we see an expanded role for smart-meters and AMI in the future smart-grid networks by merging them with fog computing. Fog computing is a distributed and close-to-the-end-user computing paradigm [3]. With the merger of AMI and fog computing, we can make AMI more reliable, scalable and robust. Besides that, we can also offer more control to the end-users, i.e. preserving privacy by storing sensitive user data locally, more control over their smart-meters and using the smart meter as a hub for their smart homes (hybrid smart-meters).

II. RELATED WORK

The literature on Fog and Smart Grid integration is limited. It can broadly be divided into two categories, architectures/models and solutions. Regarding Architecture, Rabindra et al. [4] and Feyza et al. [5] propose a 3-tier fog model where fog computing fulfils the need of a communication and data middleman between the smart grid infrastructure on the ground and the cloud. The scenarios where their models can be beneficial are different. Muzzakir et al. [6] discuss the opportunities and challenges presented when integrating fog and smart grid networks.

Regarding Solutions, Gaolei et al. [7], offer a Fog based demand-response scheme. Paola et al. [8] assess fog computing as a solution to the big data problem in smart grids. Lingjuan et al. [9] propose a privacy-preserving data aggregation scheme supported at both the cloud and fog layer. Load balancing of computation resources for smart grids is discussed in [10]–[12]. Conserving energy utilizing fog computing and microgrids is considered in [13].

Considering the previous discussion, our paper offers the following novel contributions:

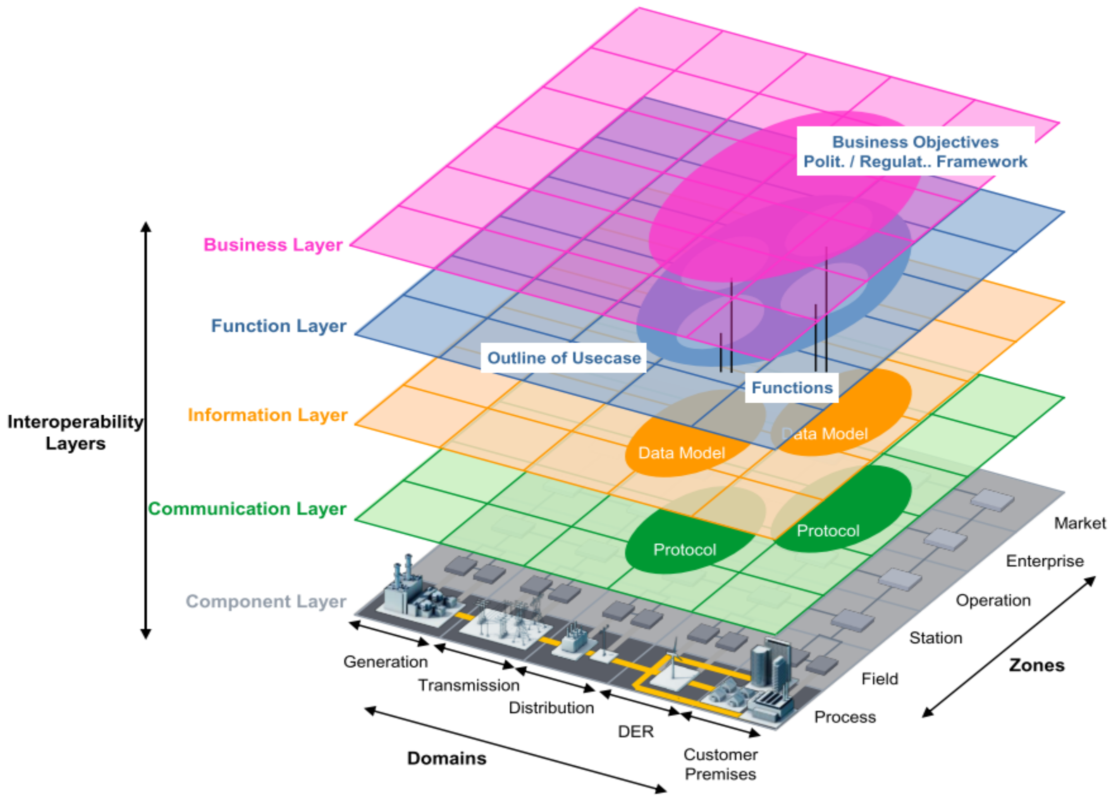

Figure 1 The SGAM Model [14]

1. We provide a comprehensive architecture evaluation towards the synergies of Fog Computing and Smart Grids.
2. We discuss AMI in detail and assess it as a pillar of the Fog-Cloud-Smart Grids integration.

The remaining paper is organized as follows. The next section gives a brief overview of AMI, its applications and current market solutions. Afterwards, we look at the OpenFog architecture and draw parallels between SG and fog computing. We further evaluate the benefits of utilizing fog computing in smart grid applications. The paper is concluded with a discussion on the missing features and future work.

III. ADVANCED METERING INFRASTRUCTURE

The ageing grid infrastructure, along with the increasing demands for reliable energy, and the need to reduce carbon dioxide are believed the main driving forces for the transition towards the smart grid. Renewable energy and distributed generation are the main pillars to match the demand-supply scheme. The migration from the legacy grid towards smart-grid calls for synergy among customers, distributors, service providers, bulk generation, transmission, operations, and markets. Communication technologies, along with smart-devices and sensors, are the cornerstones in the smart-grid. Smart-meter is the heart for the realization of the advanced metering infrastructure and further considered as the central revolutionary unit to optimize energy and to realize advanced smart grid services like demand-response, protection and dynamic pricing.

A. AMI Architecture

A typical architecture of a smart meter infrastructure for a microgrid consists of three primary subsystems. The first subsystem consists of smart meter sensors which monitor and measure the user's energy consumption in real time. These smart meters are installed in customers houses. They can interface with smart appliance found inside homes and act as their gateway. They measure energy consumption continuously and send this data to a central data collector for further processing. This data can then be analyzed and used for purposes such as billing and load control. The data collected by smart meters can also be directly accessible in real time by other applications. This allows new functions such as the ability of customers to monitor and control their energy consumption in real time. Smart-meters also can receive commands from upstream, thus providing the ability to regulate energy consumption accordingly.

The second subsystem consists of a data collector component that receives data from a collection of smart meters, stores it, and provides an interface to applications for various use cases. This collector component can be in the form of a database located either locally or in the cloud, easily reachable by all smart meters. In addition to the database, this subsystem also consists of the software stack that provides appropriate API for different smart meter applications.

TABLE I Smart Meters on the Market

No.	Companies/ Functions	**Corinex** [15]	**Elster** [16]	**Intron** [17]	**GE** [18]	**Sensus** [19]	**ABB** [20]	**Siemens** [21]	**Landis+Gyr** [22]
1	IP addressable	x	x	x	x	x	x	x	x
2	On demand	x	x	x	x	x	x	x	x
3	Remote reconnect/	x				x			
4	Time of Use	x		x	x	x			
5	Outage detection	x		x	x	x			x
6	Tampering/ Fraud detection	x	x	x	x	x	x	x	x
7	Load profiling		x	x	x		x		x
8	Load limiting/ management		x	x	x	x			
9	Prepayment			x	x			x	
10	Power quality monitoring			x		x			x
11	Outage restoration				x	x			
12	Demand side management				x	x		x	x
13	Critical peak pricing					x			x

The third subsystem is made up of all the different applications enabled by the smart metering infrastructure. These applications include functions such as remote meter reading, load control (which is a form of demand response) through commands signals sent to smart meters, distribution automation, billing and customer management, dynamic pricing, fraud detection, outage and restoration management and energy consumption forecasting. Each of these applications has different requirements depending on the functions they provide.

Many companies produce smart meter devices. These devices come with a variety of features and capabilities. Table 1 highlights current commercially available smart meters and their functions. AMI applications can be divided into the following functional categories:

Protection (No. 3,5,6,7,8,10), Control (No. 8,12,7,11), Monitoring (10, 12, 7), Metering/Billing (2, 4, 7, 9, 13), Reporting (7, 12, 9), IoT communication protocol. Below is a brief introduction of each:

Protection. This category consists of AMI applications that facilitate the protection of the power system from faults that can cause harm or stability issues. These applications enable the power system to detect, react and respond to electrical faults [23], [24]. Due to the sensitivity of this category, these applications tend to have stringent reliability requirements.

Control. This category consists of AMI applications that facilitate the energy management operation of a power system [25]. This entails the optimization of power generation and consumption. To enable this function, applications in this group rely on the availability of correct information from different nodes in a power system. The availability of this information enables the control and management of new and emerging distributed generation and storage resources. From the perspectives of service providers, this allows new applications such as demand response [1] and load scheduling [2] that ensure a more stable power system. From the consumers' perspective, this allows them to play a more active role by remotely controlling devices.

In the traditional power grid, voltage control was done only at the substation and transformers. Smart meters now allow this application to done at the end users level. This voltage data can be further aggregated and analyzed to provide a more accurate state of the grid for other applications.

Monitoring. This consists of AMI applications that collect and have constant access to selected parameters of the infrastructure [26]. These parameters are used to build an up to date picture of the status of the AMI. Applications that belong to this category are characterized by the requirement of a communication system with high reliability and availability. Information from every point of interest in the infrastructure always needs to be available. From the producer side, example applications include quality monitoring of the power signals. This relates to the overall health of the power system. The purpose is to ensure that all essential parameters such as voltage and current are at the required and safe levels. Any deviations should be quickly detected and corrected. From the consumer side, example applications include remote monitoring of consumption.

Metering/Billing. One of the primary functions of the AMI is monitoring power consumption for billing. This entails the reliable collection and storage of power consumption information of all consumers in the system. Addition, this information can also be used for other types of applications. Examples include dynamic pricing where the unit price if the power changes depending on the current power consumption in the system. Another example application relates to fraud detection, where power consumption values are used to detect power theft and other unusual behavior [27], [28].

TABLE II. Function and Service Highlights.

Function	Service	Cryptography requirements	Latency
Control	Integrated service Switch (Remote open/ close function by the utility)	Very high	Very low latency
	Demand response	High	Low
	Remote programming	High	Not important
	User feedback/awareness	High	Low latency
Metering/Billing	Time-based rates	Low	Very low
	Automatic or on-demand read	Very high	Very low
Monitoring	Tamper detection	Very high	Very low
	Power quality	High	Very low
	Commodities reads	High	Not important
	Outage notifications	Very high	Very low
Protection	State estimation	High	Very low
	Fault detection	High	Very low
	Fault tolerance	High	Very low
Reporting	Load profiling	Moderate	Not important

Reporting. This is a category of AMI applications that consists of services used for long-term analysis and prediction. These applications use data mining and aggregation techniques to discover interesting power usage patterns and trends [29], [30]. They depend on massive amounts of data, collected over an extended period to achieve this. As a result, there is less demand for high bandwidth and latency requirements in the communication protocols. There is more need for reliable and scalable data storage technologies. Examples of applications include profiling of power consumption patterns.

IoT communication. Contemporary smart-meters offer IoT communication capabilities. The IP-based communication protocols are insured using, for instance, ADSL, WiMAX, LTE, GPRS and 5G. The smart-meter should also have a rescue plan to handle the possible loss of communication. Applications in each of these categories have different functional and nonfunctional requirements that enable them to operate. Table II highlights these requirements.

IV. Fog Computing And Smart Grids

Fog computing is about utilizing the decentralized and distributed computing resources available in the network path, from the edge to the cloud. The OpenFog consortium defines Fog computing as "A horizontal, system-level architecture that distributes computing, storage, control and networking functions closer to the users along a cloud-to-thing continuum." [31] Fog computing (FC), initially envisioned as a solution to the massive amount of data generated by IoT devices has far outgrown this use-case [3]. FC is now seen as a solution to providing low-latency applications, such as augmented and virtual reality, eHealthcare, vehicular networks and smart cities [32]. FC by nature is distributed, not only fog nodes reside along the network path towards the cloud but also east-west in a peer-to-peer fashion. The second important natural property of fog computing is proximity to the target, whether it is a smartphone user and a smart home or a smart city control system. To support proximity and hierarchy, it must be heterogeneous in terms of computational resources. When you have such a large number of compute nodes, distributed along the network and geographical pathways, you need autonomy in operations.

As discussed earlier, the computational and storage elements (fog nodes) are distributed and connected. In the case of failure, a proximate fog node can resume the operational responsibilities of its neighbor. In overloaded situations, the computation can be transferred to the cloud end-point. This adds to the resiliency of the overall system. The hierarchy, however, is not rigid.

According to the OpenFog Consortium, there are eight fundamental pillars of Fog Computing. Scalability regarding resources creation and utilization. Openness towards its implementation and communication and interoperability. Autonomy in discovery and operations. Programmability in terms of both software and hardware flexibility and efficient utilization. RAS (Reliability, Availability and Serviceability) in operations via security and autonomy. Agility, flexibility towards addressing business and operational use-cases. Hierarchy, in terms of not only resource placement (fog nodes over the network path) but application partitioning and deployment accordingly. Security that enables trust, privacy and verification between its distributed computing nodes and the Cloud. Utilizing such a diverse architecture would offer many benefits to Smart Grids such as:

Decentralization: In the context of Fog Computing, there are no central servers. This decentralization is unlike Cloud Computing, where a large pool of resources is concentrated within a datacenter. This shift in the decentralization of computing resources aligns with the shift in distributed smart-grids. Instead of one or more large-scale energy producers, there are many, and the

TABLE III. AMI Application and Corresponding Fog/Cloud Residency

Function	Service	Latency	Fog / Cloud Layer
Control	Integrated service Switch (Remote open/ close function by the utility)	Very low latency	Fog (lower latency) & Cloud (greater control)
	Demand response	Low	Fog (hyper-local response), Cloud (global response)
	Remote programming	Not important	Cloud / Enterprise Servers
	User feedback/awareness	Low latency	Fog Layer (notifications and consumer communication)
Metering/Billing	Time-based rates	Very low	Cloud (billing), Fog (information decimation)
	Automatic or on-demand read	Very low	Cloud (instruction from Cloud/enterprise server)
Monitoring	Tamper detection	Very low	On the node (Fog)
	Power quality	Very low	Fog (real-time) & Cloud (for overall analytics)
	Commodities reads	Not important	Fog
	Outage notifications	Very low	Fog (local) & Cloud (wide-area)
Protection	State estimation	Very low	Fog
	Fault detection	Very low	Fog
	Fault tolerance	Very low	via Fog Resiliency
Reporting	Load profiling	Not important	Cloud

consumers themselves can now be producers. Similarly, in Fog Computing, the consumer's routers can be computing devices as well. The decentralized nature of fog computing nodes is a perfect fit for the decentralized smart-grid. Fog computing nodes can be spread around to offer on-demand computation to the distributed smart grid applications. We see the advanced smart meter as a bridge between the grid and fog.

Scalability: Increases in smart home deployments, on-premises renewable energy solutions, a vehicle to grid-enabled cars would create scalability challenges for SG/AMI applications. Fog computing has a north-south (things to the cloud), east-west (peer-to-peer) architecture that can help mitigate those challenges. The north-south/east-west architecture means that applications and services can either move to another node in the vicinity or move upwards in the fog towards the cloud. The most significant benefit is in terms of scalability.

Resiliency: Scalability and decentralization result in resiliency of deployments. An outage at a datacenter can take out all the applications and services running there; this is not the case with fog computing. Small fog nodes can offer cached services to local users whenever there is a cloud outage. A similar example would be a distributed set of storage batteries offering energy to critical local services in case of a grid outage.

Mobility: Decentralization allows services to exist anywhere between the end-node/things, all the way on the network path towards the cloud. Fog architecture allows services to be mobile. Vehicle-based fog computing is an active research area. This is in-line with vehicle-2-grid (V2G) technologies [33]. One element of V2G technologies is the communication with the grid provider or automation services that act as middlemen between the consumer and the grid. Cars are already being bundled with V2G capability. Adding a fog node to the car would enhance communication, security and identity verification in a highly dynamic environment.

V. DISCUSSION AND LIMITATIONS

Table III summarizes the AMI applications and servicers discussed in section III and their corresponding residency. In the absence of a central command and control server, the nodes themselves must identify and authenticate newer nodes or resources that enter the system. This complicates trust, authentication and confidentiality. Identifying a new distributed power resource, its capabilities, authenticating it and adding or utilizing it in times of need requires complex trust relationships. This can be improved via adapting solutions from wireless sensor networks or distributed ledgers.

Support for communication and network protocols is one step towards achieving interoperability. Semantic and data interoperability is another open research question. Solutions from web ontology language (OWL) and semantic search engines for the web can be adopted for semantic interoperability. An industry-wide effort is underway for higher-level data interoperability standards (IEC 61850, IEC 61970 and NIST standards).

VI. CONCLUSION

Fog computing is an approach to complement the traditional cloud and enterprise server architectures. By offering distributed computation and communication resources across a wide geographical area, fog computing is an excellent complement for the smart grid as well. Smart grids require robust IT infrastructure and scalability. For highly computationally demanding applications, cloud computing can scale to meet the needs. However, applications requiring exceptional latencies and resiliency can be catered to via fog computing. Albeit, trust and semantic interoperability are still open issues. Further integration of fog computing, blockchain and IoT can open avenues for distributed peer-to-peer energy markets. But closer cooperation between fog computing and smart grid researchers is required.

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