Applied Internet of Things Architecture to Unlock the Value of Smart Microgrids

Rosa Morales González, *Student Member, IEEE*, Frits D. Wattjes, *Student Member, IEEE*, Madeleine Gibescu, *Member, IEEE*, Wouter Vermeiden, J. G. Slootweg, *Member, IEEE*, and Wil L. Kling, *Senior Member, IEEE*

***Abstract*—This paper presents an applied Internet of Things (IoT) architecture for smart microgrids. Smart microgrids use IoT-enabling technologies conjointly with power system equipment to deliver additional services on top of the basic supply of electricity to local networks that operate in parallel with the regional grid or autonomously. Such ancillary services offered by the microgrid—e.g., local balancing, internal congestion management, and aggregation to support market or grid operator activities—can create value for its end-users and other stakeholders. A systems engineering design approach is used to apply two reference architectures from different domains (power systems and IoT) to create a novel, high-level framework for the design of information and communication technologies systems for smart microgrids. The framework covers the device layer, connectivity system, data processing and storage layers, and business applications. The IoT architecture for smart microgrids is applied to a case study of a pilot project in an industrial and commercial area in The Netherlands.**

***Index Terms*—Cyber-physical systems, information architecture, Internet of Things (IoT), microgrids, smart grid communications.**

Manuscript received August 24, 2015; revised June 3, 2016; accepted August 22, 2018. Date of publication September 10, 2018; date of current version January 16, 2019. This work was supported in part by Alliander NV and the Intelligent Networks Innovation Program (Innovatieprogramma Intelligente Netten) of The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland) (Project No. IPINS11011), and in part by ENGIE and EIT KIC InnoEnergy under the Smart Energy Buildings and Cities Postgraduate Program of the 3TU.School for Technological Design, Stan Ackermans Institute. *(Corresponding author: Rosa Morales González.)*

R. Morales González and J. G. Slootweg are with the Electrical Energy Systems Group, Department of Electrical Engineering, Eindhoven University of Technology, 5612AP Eindhoven, The Netherlands (e-mail: r.m.d.g.morales.gonzalez@tue.nl).

F. D. Wattjes was with the Electrical Energy Systems Group, Department of Electrical Engineering, Eindhoven University of Technology, 5612AP Eindhoven, The Netherlands, and also with the Business Development and Innovation Smart Grids Department, ENGIE, 3981AJ Bunnik, The Netherlands. He is now with the Network Development Department, Movares BV, 3511SX Utrecht, The Netherlands (e-mail: frits.wattjes@movares.nl).

M. Gibescu was with the Electrical Energy Systems Group, Department of Electrical Engineering, Eindhoven University of Technology, 5612AP Eindhoven, The Netherlands. She is now with the Energy and Resources Group, Copernicus Institute for Sustainable Development, Utrecht University, 3584CB Utrecht, The Netherlands.

W. Vermeiden is with Zown, a Division of Alliander NV, 6812AH Arnhem, The Netherlands.

W. L. Kling, deceased, was with the Electrical Energy Systems Group, Department of Electrical Engineering, Eindhoven University of Technology, 5612AP Eindhoven, The Netherlands.

Digital Object Identifier 10.1109/JIOT.2018.2869389

NOMENCLATURE

AMI	Advanced metering infrastructure.
DER	Distributed energy resources.
DG	Decentralized energy generation.
DG-RES	DG from renewable energy sources.
DNO	Distribution network operator.
DR	Demand response.
ESP	Energy service provider.
EV	Electric vehicle.
ICTs	Information and communication technologies.
SE	Systems engineering.
SGAM	Smart grid architecture model.

I. INTRODUCTION

SUSTAINABILITY targets, concerns over the security and affordability of fossil-fuel-dependent energy supply, and aging infrastructure have triggered the need for the electrical power system to evolve from centralized generation and top-down distribution toward a more complex system with enhanced functionalities in which DG is prevalent and customers play a more active role: the smart grid [1], [2]. However, the stochastic nature of DG-RES could negatively impact power availability and energy affordability in the energy transition [3]–[5]. Because renewable energy systems have generation patterns that generally do not follow the load, maintaining the power system in balance becomes more complex as penetration of DG-RES increases. Improving local balancing to create demand patterns that follow electricity supply requires changes in the infrastructure and operation mode of traditional power systems and their markets.

Fang *et al.* [6] mentioned two philosophical approaches to tackle the challenges of large-scale deployment of smart grids: 1) bottom-up and 2) top-down. The bottom-up approach, such as the one in [7], attempts to piece together subsystems of individual customer premises to give rise to greater systems. The problem with this approach is twofold.

1) It only takes into account the needs of a single stakeholder, which can cause interconnection problems with the other subsystems.
2) The individual subsystems, if not aggregated properly, could become too small and unmanageable [6].

By contrast, top-down approaches, such as those found in [8]–[10] require the intervention of a powerful, single authority that dictates a high-level framework, which then has to be implemented by different actors. The problem with such an approach is either: 1) as in the bottom-up approach, the methodology runs the risk of only considering the needs of one single stakeholder, thus missing out on win-win situations for the rest of the stakeholders, as may be the case in [9] or 2) if the framework does consider the entire power system value chain, such as in [8] and [10], this may result in a high degree of complexity in terms of the practical implementation on a large scale.

A compromise between the bottom-up and top-down approaches would be to focus on the microgrid domain as the standard building block toward larger smart grid projects. Microgrids are small-scale local networks that can operate in parallel with the regional distribution grid or autonomously in an islanded mode [11], [12]. They have independent controls that coordinate and optimize DER such that a considerable portion of the local energy demands is met by local generation, and can present themselves to the regional distribution grid as a single entity [13].

Microgrids have historically been proposed as a solution to overcome issues relating to the dispatch, control and interconnection of small generation close to customer loads in islanded situations (e.g., for emergency/backup power). In recent times, they have been proposed as the building blocks for implementing smart grid functions in the distribution system [1], [13]–[15]. This way, multiple stakeholder points of view are taken into account within a manageably sized entity that can grow/replicate organically into a sort of IoE. Not only does this concept require a (micro)grid topology that can efficiently connect available local production and storage resources with consumers and interconnect them with the larger, regional distribution grid, but also a more pervasive use of sensing and more sophisticated information-processing methods in order to monitor, schedule, and control DER—DG-RES, storage devices, and (flexible) customer loads—as well as to optimize grid assets [16].

The IoT communications paradigm is increasingly seen as the means for the power system's operational and information aspects to converge into the synergetic cyber-physical system that is the smart grid [17]–[20]. The IoT concept can be thought of as an integrated, interconnected sensing, actuating and information transfer platform upon which many applications and services can run [18], [21], [22]. Especially in the built environment and on industrial sites, developments in automation and ICT that can facilitate new paradigms and services for the operation of the electrical power system and markets are occurring [22]–[24].

Smart microgrids, therefore, use IoT technologies on top of the power system components to enhance the traditional functionalities and increase the operation efficiency of microgrids. The additional services of smart microgrids enabled by IoT can help reduce the costs of energy supply, manage energy price volatility for the end-users connected to it, and open the electricity markets for the participation of individual end-users through aggregation services. They can also improve the overall power system performance, for instance, by integrating DG-RES and managing its intermittency at a local level, and optimizing the interface with the external grid to flatten out peaks in consumption.

With more than 60% of final electricity consumption occurring in the industrial and commercial sectors in Europe [25] and DER emerging at these locations, such types of areas are a logical starting point for implementing the smart microgrid concept. However, individual commercial and industrial customers have diverse energy needs and opportunities, which calls for highly customized, heterogeneous ICT platforms. For these reasons, the replicability of smart microgrid projects is currently limited, implementations are unsystematic and restricted in scope, and the lessons learned in previous projects are rarely documented or considered [20], [23].

Drawing parallels with the work of Zanella *et al.* [20], the smart grids vision, much like that of IoT, encompasses an overwhelming variety of devices, technologies, stakeholders and services, and its realization entails an extremely complex task. Therefore, the starting point of the design of smart grids and the IoT platforms servicing them needs to be moved to a smaller domain (i.e., microgrids) and to a more conceptual level to create a shared vision of the opportunities smart grids create for all stakeholders involved [1], [26].

This paper proposes an applied IoT architecture for smart microgrids that can create added value for end-users and stakeholders, prepare the ground for standardization, and facilitate the large-scale implementation of smart grid solutions. We look into the applied architecture of one microgrid with the idea that it can be interconnected with other microgrids in the future to realize the overall smart grids vision.

The rest of this paper is organized as follows. Section II elaborates on existing IoT and smart grid architectures. Section III introduces the goals of the IoT architecture for smart microgrids. Section IV discusses the approach breakdown of the IoT platform into subsystems. Section V elaborates on each of the layers of the architecture, and shows how they connect with each other. Section VI illustrates how the applied architecture works, via a case study of a microgrid pilot project for an industrial and commercial site in The Netherlands. Finally, the conclusions and recommendations for further work are given in Section VII.

II. Existing Smart Grid and IoT Architectures

This section discusses existing reference frameworks in the literature for both smart grids and IoT.

A. Smart Grid Architectures

An extensive list of existing smart grid standardization roadmaps and studies worldwide is given in [6]. Among these is the SGAM [8], stemming from the European Commission's M/490 mandate on smart grid standards. SGAM is, in turn, a European implementation of the National Institute of Standards and Technology Interoperability Standards Roadmap [10].

SGAM describes the main actors of a smart grid and their interactions in terms of three dimensions.

1) The physical smart grid domains, which refers to power system components and their management requirements.
2) The partitioning zones, which represent information management hierarchies.

3) The interoperability layers, which represent the smart grid business objectives, processes, information exchanges, data models, communication protocols, devices, and interfaces to power system components.

In Europe, the SGAM framework has been used to map smart grid use cases [27] and adapted extensively to model different domains, such as smart cities [28] and electrified transport [27], [29]. In [30], the SGAM framework is used to map microgrid use cases and specifications. Because of its versatility and widespread acceptance, the SGAM is used as a basis in this paper as well.

In the U.S., (smart) microgrid projects have been more prolific than in Europe in recent years thanks to the sponsorship of the Microgrids Exchange group of the U.S. Department of Energy, driven by the need to improve reliability and deal with grid operators' aging infrastructure. However, because each project has different objectives and stakeholders, especially in the industrial/commercial sectors, no standard way of deploying smart (micro)grids has been developed, and most of the pilot work is based on *ad hoc* solutions [15].

B. IoT Architectures

Microgrids have been functioning for decades with hard-wired, automatic controls for regulating key performance indicators such as voltage and frequency, and providing the basic electricity services of generating capacity, energy supply, and power delivery [31] without the need for IoT. However, supplementary and emerging functionalities of the smart microgrid—e.g., improved network controls to enable the interconnectedness of microgrids with the larger distribution system, and open consumer participation in the energy- and ancillary service markets—are not possible without an IoT platform [2]. It is therefore necessary to intersect the power systems domain with that of ICT in order to enable the aforementioned added services of the smart (micro)grid.

IoT aims to pervasively use devices such as sensors, actuators, robots, mobile phones, tablets, and personal computers to bi-directionally and interoperably exchange information among users, devices, and software applications. This interaction would enable the achievement of common business goals, such as expanding the range of end-user services and generating new value for stakeholders [32], [33].

The IoT concept is independent of any particular networking, information or communications technology, so this framework can be used across a large variety of business sectors, communication networks, and devices. Many applied IoT architectures for different domains can be found in the literature; most prominently, for smart cities [20], [21] and vehicular information networks [19], [34].

Although smart grids are often mentioned as a prime example of an application of IoT [18], [19], only few sources explicitly talk about the intersection between the smart grids and IoT domains [7], [9], [17]. Even in these cases, they either only speak of the "greater" smart grids vision within IoT, which once again complicates the practical implementation, as is the case in [17]; or presents an IoT architecture applied on the smart grid from a single point of view, thus not taking into account the many stakeholders involved, as in [7] and [9].

TABLE I
DESIGN SCOPE OF THE IOT PLATFORM FOR SMART MICROGRIDS

What the IoT platform is	What the IoT platform is not
Process by which to arrive to a high-level design concept for a smart microgrid.	Detailed design of a smart microgrid.
Generic, iterative, and repeatable process to guide choices on concepts and —in later stages of the design—technologies for smart microgrid projects.	Concepts and technologies specific to a particular site.
Technically and economically feasible recommendations on concepts and commercially available technologies for the microgrid's ICT subsystems.	Catalog of specific components, communications protocols, security policies, and algorithms.
Concept for the microgrid IoT platform, limited to customer premises, DG, storage, and the point of connection with the public distribution network.	Concept for the ICT systems of the public grid administered by the Distribution Network Operator (DNO).
Guidelines for producing a replicable concept that can enable a wide range of basic and ancillary functionalities in a smart microgrid through use of IoT.	Algorithms for the different business and ancillary applications required for a specific microgrid implementation.

III. DESIGN GOALS

The main goal of this paper is to apply IoT-enabling technologies to the microgrid domain to go beyond basic electricity services with the purpose of: 1) escalating local DG-RES penetration (i.e., use locally produced renewable energy increasingly and more efficiently); 2) creating value for stakeholders in exchange for the use of their flexible resources [1]; and 3) contributing to the realization of the large-scale smart grid. The applied architecture will serve as a versatile, common blueprint for future smart microgrid projects.

The IoT platform of a smart microgrid should meet the high level requirements highlighted in [18], [19], and [30], e.g., be a flexible, scalable, reliable, and secure platform that ensures the integration and interoperability with the other microgrid subsystems, whilst safekeeping the privacy of the data collected. In addition, the applied IoT architecture for microgrids should provide a unified point of view not only for stakeholders in the power system or ICT domains, but also for nontechnical stakeholders, like policy makers and end-users. The scope of the IoT platform design specification is presented in Table I.

IV. APPROACH

Due to the innovative nature of smart microgrids, applying conventional information and control solutions is insufficient, since smart microgrids call for a paradigm shift on how future electricity networks should operate. Furthermore, microgrids are complex systems of systems that encompass diverse disciplines, stakeholders, and modes of interaction. Because both enabling technologies and operation paradigm of the smart grid need to be simultaneously and innovatively designed, a traditional sequential design approach cannot be used in this case. Instead, a more conceptual design approach is necessary.

Therefore, in order to ensure the replicability of our concept, it is necessary to apply a widely accepted reference architecture to our problem domain. Höller *et al.* [35] defined reference architectures as "generalized models that contain the richest set of elements and relations that are relevant to the domain." In our case, the domain is smart microgrids, and the reference architectures taken are the SGAM and the generic IoT. In this paper, we reuse modified versions of both reference architectures to merge the ICT and electrical engineering perspectives and create an applied IoT architecture specific for smart microgrids.

The proposed architecture focuses primarily on facilitating high-level concept development, but it can also be used to guide the development and management of smart microgrid projects from concept to roll-out when paired with a design methodology applicable to construction and/or ICT projects (e.g., Agile/SCRUM, waterfall, V-model, and SE). The next section will gloss over SE as a design-guidance method before discussing the approach for the applied architecture.

A. SE Design-Guidance Method

SE is the methodology chosen to guide the design, and it combines methodologies for information management, design, and quality with the purpose of understanding users' needs in terms of functionalities instead of technical solutions. A comprehensive description of the methodology and a comparison of SE with other design methodologies is given in [36].

SE treats the design problem from both a technical and socio-economical perspective, and translates stakeholders' environments, interactions, wishes, demands, expectations, and priorities into a complete view of the playing field. Documenting the design process using SE results in an all-purpose blueprint for future smart microgrid implementations, suitable for different types of sites at any development stage.

SE aids in the breakdown of the main question into sub-questions, for an incremental, iterative design cycle. This not only enables the development of innovative yet technologically and economically feasible solutions in the framework of a comprehensive, structured, and transparent method, but also aligns all stakeholders into a common, interdisciplinary vision of the end result. The proposed SE design method starts at a conceptual level and follows the eight steps depicted in Fig. 1. Economic constraints of the project are taken into account in the requirements analysis phase (step 3 of the design wheel) and the feasibility of the multiple possible design solutions are determined in step 4 through a cost and benefit assessment before arriving to the final design in step 5.

Cost efficiency is defined in the requirements analysis phase of the design wheel and supported through cost and benefit assessment of the various design choices in the tradeoffs section of the design wheel before arriving to the final design choice.

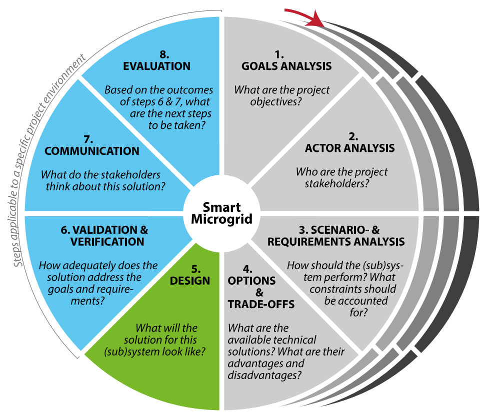

Fig. 1. Design wheel for smart microgrids (adapted from [36] to show the sequence of steps and iterations).

B. Intersection of the SGAM and IoT Domains

Fig. 2, adapted from [8] for this paper, shows the playing field for smart microgrids within the SGAM framework. The local electricity grid is shown as a dotted maroon and yellow line. The point of connection (POC) with the regional distribution network is shown as a red dot, and the geographical limits of the smart microgrid are outlined in a blue dashed line, comprising DER and end-user premises. In our opinion, the SGAM domains do not reflect the microgrid situation satisfactorily, which is why our proposed architecture breaks down the distribution physical domain into two separate but interconnected domains: the regional grid and the smart microgrid local distribution network.

Additionally, it is our contention that ICT should be considered as a domain with physical components, stakeholders and management requirements of its own. Therefore, our proposed architecture should make a more explicit connection between the power systems and ICT domains. By intersecting the smart grids and IoT domains from a multiple-stakeholder point of view, we can improve on some of the previous unsatisfactory examples mentioned in Section II.

Using SE, the IoT platform for smart microgrids is broken down into subsystems, which are the control system, the connectivity system, the data infrastructure, the software architecture, and the business applications. The IoT system components are mapped in Fig. 3 in relation to physical domains and information hierarchy zones that are analogous to SGAM. Fig. 3 also depicts the hierarchical and cross-cutting relationships between the subsystems of the IoT architecture.

The description of each subsystem and the design choices for a microgrid pilot project focused on the commercial and industrial customer segments in The Netherlands are discussed in more detail in Sections V and VI, respectively.

V. Applied IoT Framework for Smart Microgrids

This section describes the subsystems of the IoT platform for smart microgrids depicted in Fig. 3 and how they interact with each other. A more detailed version of this architecture is shown in Fig. 4 at the end of this section.

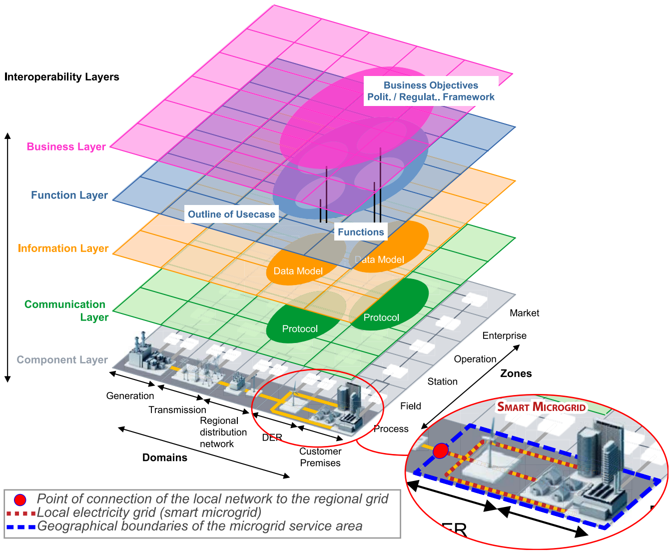

Fig. 2. SGAM framework adapted from [8] to show the smart microgrid domain.

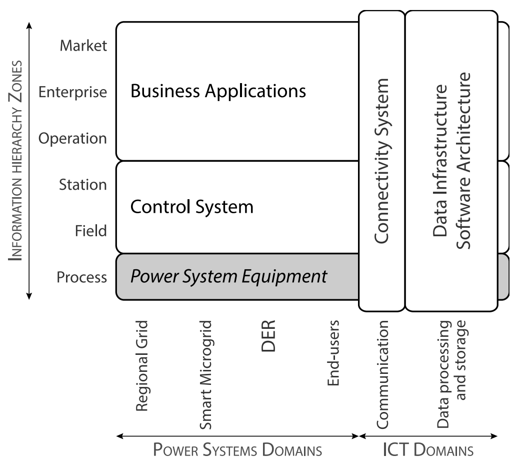

Fig. 3. Subsystems of the proposed simplified IoT architecture for smart microgrid applications, showing the relationships between the subsystems, and the intersection of the ICT domain with that of power systems.

A. Control System

The control system of the IoT platform comprises all instrumentation operating at the station and field zones in each power system domain in the smart microgrid and is denoted by the letter A in Fig. 4. Control system devices in the field zone include industrial and building automation systems, battery bank or EV charging station controls, and DG-RES controls at customer premises, as well as microgrid primary controls for voltage and frequency regulation at the POC with the regional grid. Outputs of field devices are aggregated at the station level through bi-directional metering equipment (e.g., smart meters and industrial telemetry equipment) that collects the energy consumption data and other metrics from each domain (i.e., end-users, DER, and the regional grid) that make up the smart microgrid's AMI.

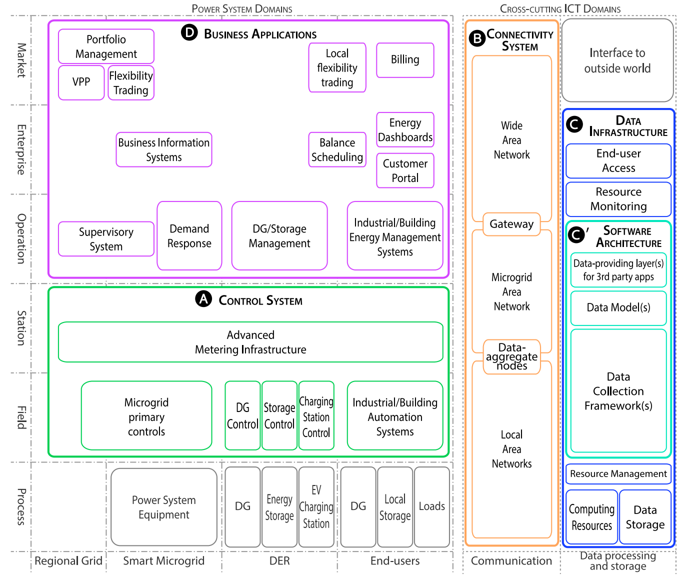

Fig. 4. Developed overall design of the IoT architecture for smart microgrids.

The field devices at each customer's premises form wired or wireless local networks that are used for local automation. Additionally, they make data available for microgrid-level coordination efforts.

B. Connectivity System

The Connectivity System refers to all connection nodes, data links, and communication networks that interconnect the smart microgrid field devices mentioned in Section V-A internally and to the outside world. All data transfers need to be reliable and secure, following the customers' quality of service (QoS) criteria and in compliance with standards and regulations.

As can be seen in Fig. 4 denoted by B, the connectivity system is broken down into three layers that describe the networking functions of the customer premises, the microgrid, and the outside world. These layers cross-cut through all partitioning zones and domains, and are: local area networks, the microgrid area network, and the wide area network.

1) Local Area Networks: Local area networks are formed by the interconnected field devices at each of the customer premises. Data collected at this level is sent to data-aggregate nodes, but can also be used to run end users' local processes. Usually, within the premises of a single customer, one can expect to have either: a homogeneous group of devices that form a single network (e.g., Ethernet-based industrial/building automation networks or ZigBee home area networks for small-scale commercial applications); or a heterogeneous group of field devices that form a single local area network through the use of media converters (e.g., serial-to-Ethernet or serial-to-WiFi for industrial/building automation systems).

2) Microgrid Area Network: The microgrid area network is made up of data-aggregate nodes that collect and preprocess data from every end-user, and transmit the data to a gateway for further aggregation. Because device communication protocols are probably standardized within individual customer premises but not among all the users of the microgrid, gateways are needed to convert the local (proprietary) communication protocols to a uniform format for the entire microgrid (e.g., ZigBee to Ethernet or WiFi).

3) Wide Area Network: The data signals of every customer connected to the microgrid are aggregated by a gateway that collects measurements from the data-aggregate nodes and sends them to the software architecture hosted in the data infrastructure via the wide area network. The software architecture then processes the data into information for microgrid coordination efforts, such as (centralized) DR mechanisms to perform demand-side management. Possible physical media over which connections can occur are: power line, copper twisted-pair, coaxial, and wireless (WiFi or cellular) communication networks.

C. Data Infrastructure and Software Architecture

1) Data Infrastructure: The data infrastructure is the collection of data storage, processing power and other computing resources that hosts the software architecture, denoted C and C', respectively, in Fig. 4. The software architecture is the middleware layer that enables the storage and processing of the data harvested in the microgrid network. The software architecture also facilitates the communication and input/output operations of the business applications and the control system assets, cross-cutting all partitioning zones and power system domains. Some of the business applications, such as the coordination programs for balancing supply and demand and the local optimization of energy use, will require increasing amounts of computational power and storage as data keeps growing with the passage of time.

It is necessary to have a data infrastructure that is flexible and scalable to address growing user requirements and increasing data volumes. It should be reliable and widely available, yet secure, to guarantee the continuity and stability of the business decisions derived from the data analysis. Some possibilities for organizing the data infrastructure are: 1) having each microgrid participant use their own storage and computing resources; or 2) have microgrid participants share storage and computing resources. Pooling resources could be achieved with grid or cloud computing. In grid computing, disparate computers are networked to form one large infrastructure that divides and farms out pieces of a program as one large system image to many computers [37]. Cloud computing offers data storage and processing services in a pay-as-you-use business model, similar to a utility service.

2) Software Architecture: The software architecture provides a standardized data model to unify raw data, and a manner of automatically acquiring from or sending data to the field devices of the control system. It enables third-party application developers to use the data models to design and implement the business applications that will manage the automation aspects within the microgrid.

There are several possibilities of managing the relationship between the field device data and the business applications: 1) one-to-one relations, where every end-user application has to communicate with all necessary field devices to acquire/send data or 2) many-1-many relations, in which a single party is responsible for centralizing all data for the end-user applications across the microgrid into a single repository.

TABLE II
EXAMPLES OF MICROGRID BUSINESS APPLICATIONS

Day-to-day operations	Customer services	Market participation
Islanding capability	Billing	Flexibility trading
Matching supply and demand	Energy dashboards	Portfolio management
Supervisory control	Energy service contracts	Virtual Power Plant (VPP) functionality
Internal congestion management through DR or generation-side/storage mgt.	Energy management systems	Ancillary services to the regional grid operator

D. Business Applications

The business applications are all the front-end applications that are required for day-to-day microgrid operations, as well as those needed for the creation of new, value-creating services for the microgrid stakeholders. They are enabled by the data models created by the software architecture, and are tied in with and validated by the business objectives, opportunities, and cases of the smart microgrid concept. In Fig. 4 they are denoted D, and are shown to cover the operation, enterprise, and market zones of the physical domains of the IoT smart microgrid architecture. The proposed IoT architecture is an application-oriented system, meaning that the types of applications needed for the smart microgrid should be derived from the requirements and specifications of each microgrid implementation. In general, they are meant to fulfill applications such as those listed in Table II. It is important to mention that critical day-to-day operations, such as voltage and frequency regulation and islanding capability are covered by hardwired controls that can respond to events in real time even when network communications are lost.

E. Complete IoT System Architecture

The overall design of the IoT platform for smart microgrids proposed in this paper is summarized in Fig. 4, which is an expanded version of Fig. 3. Sensors and actuators placed at end-user and DER facilities collect data regarding the electricity consumption and production that takes place. Individual generators and storage units have devices put in place behind the meter both for internal optimizations and for aggregated control functions controlled by the microgrid coordinator. End-user premises also have instrumentation behind the meter to control their internal processes and to bid their flexibility in demand for DR applications, for example. The end-users of the microgrid could also gain insight on their electricity consumption and/or production patterns via dashboard applications.

The data collected by the control system is relayed via the communications network to the software architecture hosted in the data infrastructure. Apart from providing storage space, the data infrastructure also supplies the computing power used by the software architecture to standardize the incoming signals

TABLE III
DESCRIPTION OF STAKEHOLDERS IN A SMART MICROGRID PILOT IN THE NETHERLANDS

Stakeholder	Description
DG producer	Operator of local power generators within the business site.
Consumer	Customers connected to the microgrid that consume electricity, some of which can offer flexibility in demand.
Prosumer	Customers connected to the microgrid that both produce and consume electricity, some of which can offer flexibility in supply and/or demand.
Storage provider	Provider of capacity for storing and delivering energy.
Microgrid Energy Service Provider (ESP)	Responsible of supporting service operations to the microgrid operator (e.g., reducing congestion, planning); collective contracting of energy supply in- and outside the microgrid; setting pricing policies inside the microgrid; and trading with the outside energy marketplaces. It also coordinates supply-side management with the demand-side management services offered by the aggregators.
Aggregator	Commercial manager of consumers/prosumers' flexibility. This flexibility is aggregated and optimized for the aggregator's own portfolio, offered to various parties both inside and outside the microgrid, with the aim to create as much value as possible. Within the microgrid, there could different aggregators present.
Retailer	Commercial entity that sells and buys electricity products (e.g., in the ancillary- and commodity markets).
Microgrid Operator	Responsible for overseeing hardwired microgrid primary controls (voltage and frequency regulation) and maintaining local network assets.
Distribution Network Operator (DNO)	Owner of the regional electricity distribution grid. Its main tasks are operating, maintaining and expanding the grid.

and create relations to process them into information and assets that can be used in the business applications for operation, coordination, and aggregation purposes.

VI. CASE STUDY

This section illustrates how the proposed framework can be applied to real-life scenarios through a case study of a microgrid pilot in an industrial and commercial site in The Netherlands.[1] The purpose of this case study is to define the actors in the system, describe their roles, and allocate the subsystems described in our framework to the different actors.

The pilot project in this case study is a greenfield in which the electricity distribution grid and its information systems must be flexible enough to grow as the industrial park evolves, so that the availability, accessibility, and affordability of electricity are guaranteed. The microgrid should synergize DG-RES, end-users, and storage systems, so that there is a balance between local electricity demand and supply. Furthermore, it should foster and facilitate cooperation among the microgrid stakeholders in order to create mutual economic benefits. The microgrid stakeholders and their roles for this case study are described in Table III.

[1] [Online]. Available: http://www.rvo.nl/subsidies-regelingen/projecten/modulair-intelligent-energienetwerk-voor-bedrijventerreinen-modienet

A. Example of Microgrid Business Application: Use Case for Local Matching of Demand and Supply

This section shows an example of how the proposed IoT framework for smart microgrids can be applied by giving a high-level use case description of the balancing of supply and demand. The objective of this use case is to accommodate the local power exchange between distributed generators, local consumers, and storage capabilities via a smart microgrid covering the area inside and around a business park. The use case diagram for balancing demand and supply is depicted in Fig. 5 and described in the next paragraph. It gives insight into the required applications and/or components from the IoT architecture (Fig. 4) for a specific service and which stakeholders are involved.

The microgrid ESP has to achieve this local balance for two main operating modes: grid-connected (to the regional distribution network) and islanded mode (autonomous operation). The simplest way of balancing will be with a permanent connection to the overlay grid, but even in this situation the ESP may try to keep an internal balance for efficiency and/or economic reasons (e.g., by providing ancillary services to the DNO). The microgrid ESP uses, for these balancing tasks: forecasting- and status information of grid devices, as well as devices on the demand, storage, and supply sides. This information will come from field devices. The microgrid ESP will control imbalances at different time scales by (semi)automated ancillary services; e.g., by changing supply and/or consumption profiles through offered services of the aggregators.

Although it is already possible to use conventional controls for the generation- and storage-side management functions for the overall local balancing of the smart microgrid, an IoT platform is crucial to unlock the devices behind the meter at consumer/prosumer premises. For this reason, the next section discusses how the proposed IoT platform enables demand-side management of the ESP through DR applications in the business park smart microgrid pilot.

B. IoT Platform for Smart Microgrid in Business Site

Table IV summarizes the steps of the SE design wheel (Fig. 1) for each subsystem of the IoT architecture in order to generate a common conceptual starting point. The last three steps of the design wheel are not worked out since they are feedback mechanisms applicable to a specific project environment. Fig. 6 depicts the result of applying the IoT architecture to the case study. The following paragraphs will elaborate on the design choices for each of the subsystems.

The microgrid end-users' industrial or building automation systems will send/receive signals to and from a central DR application via IP-based communications. Each end-user can customize the DR application based on the number and type of available controllable devices (e.g., process control units, charging controllers, pitch control for wind turbines, and active/reactive power controls for PV inverters). The end-users' process controls are run locally, while overall consumption/generation data are aggregated by smart meters. All smart meter data are collected via a gateway and sent to the

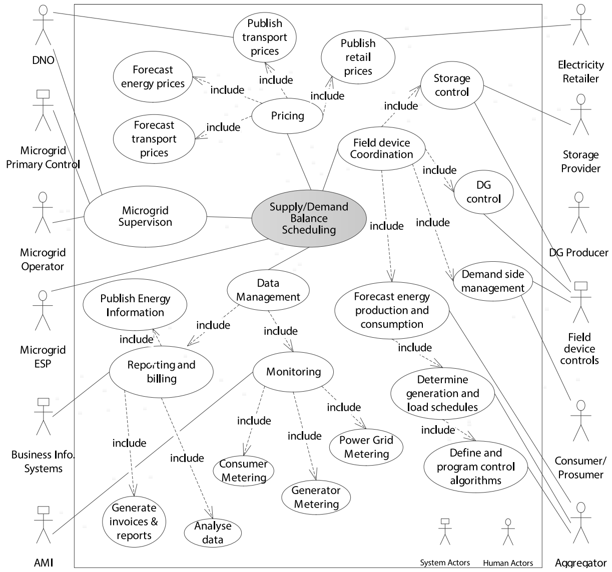

Fig. 5. Use case diagram: balancing supply and demand.

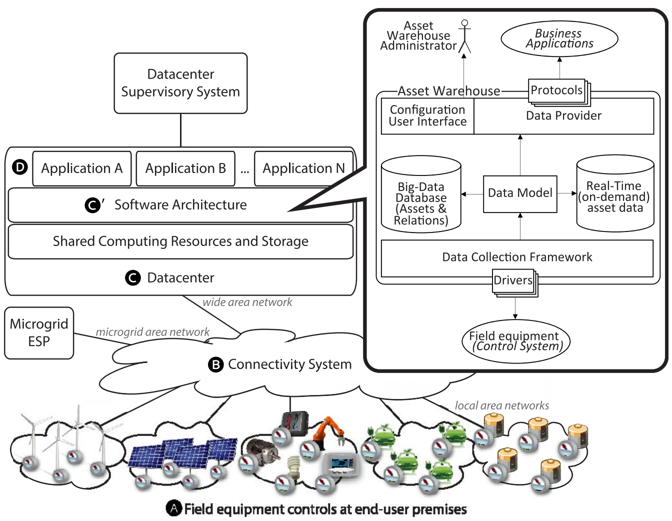

Fig. 6. IoT architecture for a smart microgrid pilot in The Netherlands.

TABLE IV
IoT Platform Design Choices for a Smart Microgrid Pilot in NL

Control System	*Goal:* Enable system users to gain insight on their energy behavior, and enable Demand Response (DR) services. *Stakeholders:* Customers; Connectivity-System providers; Software-Architecture developers; Microgrid Energy Services Provider (ESP). *Requirements:* Interoperable, accurate, scalable, affordable secure. *Variants:* Using centralized vs. decentralized logics. *Design choice:* Using decentralized logics for local processes and centralized logics for DR services.
Connectivity System	*Goal:* Provide accurate and reliable data communication. *Stakeholders:* Customers; network providers, Control-System and Data-Infrastructure providers; Software-Architecture developers; Microgrid ESP. *Requirements:* Secure, privacy-conscious data communications, sufficient bandwidth and latency, open protocols, scalable, reliable. *Variants:* Power line communications vs. optical fiber vs. wireless networks. *Design choice:* Wireless cellular networks.
Data Infrastructure	*Goal:* Platform for hosting flexible information services. *Stakeholders:* Customers; Connectivity System providers; Software Architecture and Business Application developers. *Requirements:* High processing power, fast computing times, scalable resources, secure access, high availability, backups. *Variants:* Own vs. shared resources; semi-private vs. public Cloud. *Design choice:* Semi-private cloud computing services.
Software Architecture	*Goal:* Effective management of the data collected in the microgrid; processing raw data into useful information and input for third-party applications. *Stakeholders:* Control System field devices; Connectivity System and Data Infrastructure providers; Business Application developers; Microgrid ESP. *Requirements:* Data transparency, consistency, security, privacy, and validation; universal data models; access control and authentication. *Variants:* Many-to-many vs. one-to-many architecture. *Design choice:* Centralized, one-to-many asset warehouse.
Business Applications	*Goal:* Create third party applications to enable business objectives (day-to-day operations, facilitate the creation of new services). *Stakeholders:* Customers, Software Architecture developers, Data Infrastructure providers, Microgrid ESP. *Requirements:* Plug-and-play, future-proof, scalable, flexible. *Variants:* Apps that obtain their data from multiple sources vs. apps connected to a central data input source. *Design choice:* Modular software packages connected to a central source.

software architecture, where the DR logics of the microgrid reside.

The chosen architecture for the data infrastructure consists of a system in which all microgrid end-users and the microgrid ESP share data storage, computing resources, and information services hosted in a semiprivate cloud in a data center. In this pay-as-you-use configuration, data redundancy is eliminated, and customers are guaranteed QoS and high system reliability. Apart from reducing costs, resource pooling also facilitates scaling up on data storage capacity and processing power.

The chosen software architecture consists of an asset warehouse that collects data from the control system devices into standardized data models that serve as input for the business applications' reading and writing operations. The asset warehouse technically enables an unlimited number of business applications and customer devices, since it is designed to expand dynamically. With one data administrator, business application developers need to invest less effort to implement the microgrid communication layer. Storing data in a single, centralized location simplifies the management of data integrity and solves the problems of data redundancy and inconsistency. It also allows for all kinds of information interpretation and analysis that can guide the business and technical decisions for balancing the smart microgrid. The availability and reliability of the data collected in the asset warehouse is protected against disconnection/failure by the warehouse's data-caching system and data center backup services.

The business applications for DR in the microgrid for this particular business site will include three programs implemented in different phases.

1) Load scheduling for a single customer, where the aggregator sends day-ahead price forecasts and the customer adjusts its loads.
2) ESP coordinating day-ahead scheduling of all microgrid customers for local balancing.

3) Enabling participation in the reserve market. All applications will be built on the same software platform.

C. Discussion

The driving choice in the design of most of the IoT platform's subsystems is to minimize initial investment and reduce operational and maintenance costs. This is achievable, in most cases, by partnering the microgrid ESP with its end-users and technology providers in order to share the financial risks associated with implementing the systems proposed. This also enables the ESP and end-users to shift the technical risks of implementing the solutions and focus on their own core business competences to extract the greatest possible economic value out of the microgrid. Technical risks have been addressed mainly by using commercially available technologies to build the system in a modular fashion. By preserving modularity, changes can be made over time without making major disruptions to the system and without incurring onerous costs. This trait can be observed in all subsystems of the microgrid.

ICT is starting to be more ubiquitous as technology prices go down. Technology is not the driver of having a centralized or decentralized system anymore. Rather, the drivers for the design choices made within specific implementations are the requirements of a specific site, budget constraints, customer preferences, etc. Stakeholders now have the power to think of several technological solutions to fit one function because the technology is already there and they can take their pick to use what is commercially available optimally. IT can further become more of a commodity/utility by using standard hardware and software products across multiple sites to bring down costs and strengthen the business case for smart microgrids.

As demonstration projects in which our proposed IoT architecture is applied start to roll-out, it is important to validate the proposed IoT architecture for smart microgrids with regard to its applicability in real-world projects. In order to do so, we propose identifying demonstration projects where the IoT architecture can be used as an accelerator in the design phase. After applying the IoT architecture, we can check with stakeholders to rate its success, and assess its "universal value."

In the future, with the roll-out of demonstration projects in which our proposed IoT architecture is used as an accelerator in the design phase, comes the need to validate its usefulness and universality. Related work in this topic should collect stakeholders' main learning experiences regarding the implementation of the IoT architecture by selecting key performance indicators and organizing them into an evaluation framework.

VII. Conclusion

The generic IoT platform for smart microgrids proposed in this paper intersects the electrical engineering and ICT domains, and contributes to the advancement of replicability in smart grid projects by the following.

1) Using microgrids as building blocks to advance the greater smart grid vision.
2) Providing a common viewpoint for project stakeholders and end-users to understand the functionality of the smart microgrid as a whole during the conceptual phase.
3) Providing a structured method by which to develop innovative, yet commercially feasible solutions to fulfill the IoT platform subsystem functions and requirements.
4) Showing how the framework can be applied to an existing smart microgrid pilot project for an industrial and commercial site in The Netherlands.

SE has proven to be an effective design methodology for smart microgrids because it captures the complexity of the problem and the stakeholders involved while simplifying the design tasks by iteratively breaking down the problem into subsystems. SE emphasizes the importance of documenting the design decisions, which makes the design process transparent, traceable and repeatable. Because applied information and communication technologies evolve more rapidly in comparison with power system hardware, the IoT framework for smart microgrids we propose allows for the possibility to revise the technical choices made for a particular subsystem as better, faster, or more suitable ICT solutions become available.

The proposed IoT platform applied to smart microgrids is a step forward toward standardization, which plays an important role in the replicability of smart microgrid projects and their up-scaling. However, there are still many challenges ahead, such as gaining experience on how this will work in practice and how future pilots can influence future standardization efforts, as well as cross-cutting issues such as data security, privacy, and market regulation. Obvious future steps include implementing the concept in practice by taking the architecture principles as a starting point for building a smart microgrid, and striving to employ standards.

Regarding the strengthening of business cases for smart microgrids (aside from falling costs for DG-RES and storage), there are a number of factors that could contribute to bringing down costs and making the bases more attractive.

1) The employment of standard communication protocols, not only within the smart microgrid but also across smart grid platforms.
2) Implementing solutions that can be used across multiple microgrids instead of having in-house IT solutions and silo applications.

This makes a strong case in favor of public and semipublic cloud computing, as well as a single, standardized and replicable multitenant microgrid platform that can be offered as a service.

Acknowledgment

The authors would like to thank Dr. R. Kamphuis for his feedback on an earlier version of this paper.

References

[1] *EUR 22040—European Technology Platform SmartGrids*. Eur. Commission, Brussels, Belgium, 2006.
[2] EU Commission Task Force for Smart Grids, "Expert group 1: Functionalities of smart grids and smart meters," Eur. Commission, Brussels, Belgium, Final Deliverable, Dec. 2010.
[3] "Energy 2020: A strategy for competitive, sustainable, and secure energy," Eur. Commission, Brussels, Belgium, Rep. COM(2010)639, 2011.
[4] "2011 technology map of the European strategic energy technology plan," Joint Res. Centre, Inst. Energy Transp., Eur. Commission, Brussels, Belgium, Rep. EUR 24979 EN, 2011.

[5] C. Hewicker, M. Hogan, and A. Mogren, "Power perspectives 2030: On the road to a decarbonised power sector," Project 2050, Eur. Climate Foundation, The Hague, The Netherlands, Rep. PP2030, 2012.
[6] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart Grid—The new and improved power grid: A survey," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 4, pp. 944–980, 4th Quart., 2012.
[7] W. Shu-Wen, "Research on the key technologies of IOT applied on smart grid," in *Proc. Int. Conf. Electron. Commun. Control (ICECC)*, Sep. 2011, pp. 2809–2812.
[8] "Smart grid reference architecture," CEN/CENELEC/ETSI Smart Grid Coordination Group, Brussels, Belgium, Final Rep., Nov. 2012.
[9] E. Kämpf, J. Ringelstein, and M. Braun, "Design of appropriate ICT infrastructures for smart grids," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, San Diego, CA, USA, Jul. 2012, pp. 1–6.
[10] "NIST framework and roadmap for smart grid interoperability standards, release 2.0," U.S. Dept. Commerce, Nat. Inst. Stand. Technol., Gaithersburg, MD, USA, Rep. 1108R2, 2012.
[11] N. Hatziargyriou, Ed., *Microgrids: Architectures and Control*. Piscataway, NJ, USA: Wiley, 2014.
[12] Navigant Consulting, "Microgrids research assessment—Phase 2," United States Dept. Energy, California Energy Commission, Sacramento, CA, USA, Final Rep., May 2006.
[13] B. Lasseter, "Microgrids [distributed power generation]," in *Proc. Power Eng. Soc. Win. Meeting*, vol. 1, Jan. 2001, pp. 146–149.
[14] R. H. Lasseter, "Smart distribution: Coupled microgrids," *Proc. IEEE*, vol. 99, no. 6, pp. 1074–1082, Jun. 2011.
[15] D. Ton and M. Smith, "The U.S. department of energy's microgrid initiative," *Electricity J.*, vol. 25, no. 8, pp. 84–94, Oct. 2012.
[16] J. A. Momoh, *Smart Grid: Fundamentals of Design and Analysis*. Piscataway, NJ, USA: Wiley, 2012.
[17] J. Höller *et al.*, "The smart grid," in *From Machine-to-Machine to the Internet of Things*. Cambridge, MA, USA: Elsevier, 2014, ch. 12, pp. 255–268.
[18] I. Stojmenovic, "Machine-to-machine communications with in-network data aggregation, processing, and actuation for large-scale cyber-physical systems," *IEEE Internet Things J.*, vol. 1, no. 2, pp. 122–128, Apr. 2014.
[19] G. Wu, S. Talwar, K. Johnsson, N. Himayat, and K. D. Johnson, "M2M: From mobile to embedded Internet," *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 36–43, Apr. 2011.
[20] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.
[21] J. Jin, J. Gubbi, S. Marusic, and M. Palaniswami, "An information framework for creating a smart city through Internet of Things," *IEEE Internet Things J.*, vol. 1, no. 2, pp. 112–121, Apr. 2014.
[22] J. A. Stankovic, "Research directions for the Internet of Things," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 3–9, Feb. 2014.
[23] T. Samad and S. Kiliccote, "Smart grid technologies and applications for the industrial sector," *Comput. Chem. Eng.*, vol. 47, pp. 76–84, Dec. 2012.
[24] *NewsRoom Features—August 2009 Energy Efficiencies in Buildings to Improve Under NETL-Directed ARRA Funding*, U.S. Dept. Energy, Washington, DC, USA, 2009. [Online]. Available: http://204.154.137.14/newsroom/features/08-2009.html
[25] European Energy Agency. *Final Energy Consumption by Sector and Fuel*. Accessed: Oct. 23, 2017. [Online]. Available: http://www.eea.europa.eu/data-and-maps/indicators/final-energy-consumption-by-sector-9/assessment
[26] J. Trefke, C. Danekas, S. Rohjans, and J. M. G. Vazquez, "Adaptive architecture development for smart grids based on integrated building blocks," in *Proc. 3rd IEEE PES Innov. Smart Grid Technol. Europe (ISGT Europe)*, Oct. 2012, pp. 1–8.
[27] J. Trefke *et al.*, "Smart grid architecture model use case management in a large European smart grid project," in *Proc. 4th IEEE/PES Innov. Smart Grid Technol. Europe (ISGT EUROPE)*, Oct. 2013, pp. 1–5.
[28] "DKE/DIN roadmap: Die deutsche normungs-roadmap smart city, version 1.0," Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE, Frankfurt, Germany, Rep., 2014.
[29] G. Schuh, J. Fluhr, M. Birkmeier, and M. Sund, "Information system architecture for the interaction of electric vehicles with the power grid," in *Proc. 10th IEEE Int. Conf. Netw. Sens. Control (ICNSC)*, Apr. 2013, pp. 821–825.
[30] K. Eger *et al.*, "Microgrid functional architecture description," FINSENY Consortium, Munich, Germany, Rep. FI.ICT-2011-285135, 2013.
[31] E. Hirst and B. Kirby, "Electric-power ancillary services," Oak Ridge Nat. Lab., U.S. Dept. Energy, Washington, DC, USA, Rep. ORNL/CON-426, Feb. 1996.
[32] D. Boswarthick, O. Elloumi, and O. Hersent, Eds., *M2M Communications: A Systems Approach*. Chichester, U.K.: Wiley, 2012.
[33] D. Giusto, A. Iera, G. Morabito, and L. Atzori, Eds., *The Internet of Things: 20th Tyrrhenian Workshop on Digital Communications*. Dordrecht, The Netherlands: Springer, 2010.
[34] Z. Yan, S. Zeadally, and Y.-J. Park, "A novel vehicular information network architecture based on named data networking (NDN)," *IEEE Internet Things J.*, vol. 1, no. 6, pp. 525–532, Dec. 2014.
[35] J. Höller *et al.*, "M2M to IoT—An architectural overview," in *From Machine-to-Machine to the Internet of Things*. Cambridge, MA, USA: Elsevier, 2014, pp. 61–77.
[36] F. Wattjes and H. Slootweg, "Design considerations for smart microgrids," in *Proc. 48th Int. Universities Power Eng. Conf. (UPEC)*, Sep. 2013, pp. 1–6.
[37] J. M. Myerson. (2009). *Cloud Computing Versus Grid Computing: Service Types, Similarities and Differences, and Things to Consider*. [Online]. Available: http://www.ibm.com/developerworks/library/wa-cloudgrid/

Rosa Morales González (S'12) received the B.Sc. degree in mechatronics engineering from Universidad Panamericana, Mexico City, Mexico, the M.Sc. degree in sustainable energy technology from the Eindhoven University of Technology, Eindhoven, The Netherlands, and the P.D.Eng. degree in smart energy buildings and cities from the 3TU.School for Technological Design, Stan Ackermans Institute, The Netherlands. She is currently pursuing the Ph.D. degree at the Electrical Energy Systems Group, Eindhoven University of Technology.

Her current research interests include demand response programs for commercial and industrial areas in order to support the integration of renewable energy sources into electricity distribution networks.

Frits D. Wattjes (S'13) received the B.Sc. degrees in electrical engineering and industrial engineering and management sciences from the Alkmaar University of Applied Sciences, Alkmaar, The Netherlands, in 1994 and 1995, respectively, the master's degree in business and energy systems from the Delft University of Technology, Delft, The Netherlands, in 2010, and the Ph.D. degree in electrical engineering from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 2018.

While with the Eindhoven University of Technology, he conducted applied research on system architectures for smart microgrids for industrial and commercial areas. He was with ENGIE NL (formerly, GDF SUEZ), Bunnik, The Netherlands, where he was involved with business development and innovation. He is currently a Senior Consultant with Movares BV, Utrecht, The Netherlands.

Madeleine Gibescu (M'05) received the diploma degree in power engineering from the Politehnica University of Bucharest, Bucharest, Romania, in 1993, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of Washington, Seattle, WA, USA, in 1995 and 2003, respectively.

She was a Research Engineer with Clear-Sight Systems, and a Power Systems Engineer with Alstom Grid, Seattle. Since 2007, she has been an Assistant Professor with the Electrical Sustainable Energy Department, Delft University of Technology, Delft, The Netherlands. Until 2018, she was an Associate Professor with the Electrical Energy Systems Department, Eindhoven University of Technology, Eindhoven, The Netherlands. She is currently a Professor and the Chair of Integration of Intermittent Renewable Energy Sources with Utrecht University, Utrecht, The Netherlands.

Wouter Vermeiden received the M.Sc. degree in business administration from the Rotterdam School of Management, Erasmus University, Rotterdam, The Netherlands, in 1996.

He is a Senior Consultant in the fields of information management, information and communication technologies, and the energy transition. He is currently an IT/OT Manager with Zown, a subsidiary of the Dutch distribution system operator Alliander NV, Arnhem, The Netherlands. Zown is focused on consulting and solutions for micro grids. He has 14 years of consulting, and (project) management experience in the areas of energy and information and communication technologies. Previous to Alliander, he was with Essent/RWE, Hertogenbosch, The Netherlands, Accenture, Dublin, Ireland, and Baan, Barneveld, The Netherlands.

J. G. (Han) Slootweg (M'00) received the M.Sc. degree (*cum laude*) in electrical power engineering from the Delft University of Technology, Delft, The Netherlands, in 1998, the M.Sc. degree in business administration from the Delft University of Technology, and the Ph.D. degree from the Delft University of Technology, in 2003.

He is currently the Manager of the Innovation Department, Enexis BV (Dutch distribution system operator), Hertogenbosch, The Netherlands. Its spearheads are energy transition (including distributed generation and smart grids), asset condition assessment and increasing workforce productivity through new technologies. He also holds a professorship in smart grids with the Electrical Energy Systems Group, Eindhoven University of Technology, Eindhoven, The Netherlands. He has co-authored over 100 papers covering a broad range of aspects of the electricity supply.

Wil L. Kling (M'95) was born in Heesch, The Netherlands, in 1950. He died on March 14, 2015, in Hangzhou, China. He received the M.Sc. degree in electrical engineering from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 1978.

From 1978 to 1983, he was with Kema, Arnhem, The Netherlands, and from 1983 to 1998 with Sep. Since then and until the end of 2008, he was with TenneT, Arnhem, the Dutch transmission system operator, as a Senior Engineer of Network Planning and Network Strategy. Since 1993, he had been a part-time Professor with the Delft University of Technology, Delft, The Netherlands, and since 2000, he had also been a part-time Professor with the Electric Power Systems Group, Eindhoven University of Technology. Since 2008 and until his death, he was a full-time Professor and the Chair of the Electrical Energy Systems Group, Eindhoven University of Technology. He led research programs on distributed generation, integration of wind power, network concepts, and reliability.

Mr. Kling was involved in scientific organizations such as Cigré and the IEEE. He was the Dutch Representative of the Cigré Study Committee C6 Distribution Systems and Dispersed Generation.