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Smart Grids from a Global Perspective

Bridging Old and New Energy Systems

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How Energy Distribution Will Change: An ICT Perspective

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Abstract The accessibility of small scale renewable sources, the emergence of electric vehicles, and a need for sustainability are fueling a change in the way electricity is produced and consumed. This is happening together with the digitalization of the electric infrastructure, something that is providing for vast amount of data and control opportunities. We overview the current and promised change in the electricity distribution grid from the perspective of Information and Communication Technology, taking the points of the smart meter, the user, the utility, and the ICT service provider.

1 Prologue

Once upon a time there were black boxes hosting electromagnetic motors, installed everywhere. Homes, factories, office buildings had these boxes which would be in almost constant activity, rotating as current went through them, mechanically increasing a Watt counter. Rooted on a patent of 1889 of the Hungarian electrical engineer Ottó Bláthy, these devices have been as pervasive as electricity in homes, offices, and companies. Their design has basically survived a century and they are still widely used worldwide.

The views and opinions expressed in this chapter are those of the authors and do not necessarily reflect the official policy or position of the respective affiliations.

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2 Introduction

Two more or less concurrent events changed the 100 year old way of doing electricity metering and billing. On the one hand, energy flows have become bi-directional. With the introduction of affordable small scale generators, such a PV, small wind turbine, μCHP, the meter had to also account for the energy fed back into the grid and not only coming from it. On the other hand, the meter moved from being a mechanic-analog device—inspected visually monthly or even yearly—to being an electronic meter with the ability to expose via wired or wireless communication channels its state.

Orthogonally, this has meant also the possibility of using the meter differently: not just reading it once a year by physically accessing it and looking at the numbers reported on the meter, Fig. 1. The electric meter gave the possibility of reading remotely the value as frequently as one desires. If some countries, like the Netherlands, pose a legal limitation on the sampling rate (six times a year), in other jurisdictions, these readings can be as frequent as just few a minute. This changes the role of the meter and transforms it into a device that can help predict the energy consumption quite precisely and deliver a real-time view of the consuming/producing situation of any node on the distribution grid.

The evolution underway is depicted in Fig. 2. On top the traditional way of doing analog metering with calendar based visual inspections. In the middle layer, the two trends: on the left, one remarks that current now flows bidirectionally due to the introduction of small scale renewables behind the meters; on the right, the transformation into a digital meter that can stream bits of information via telecommunication channels. On the bottom, the two trends coming together in what can be considered modern infrastructures.

The depicted evolution, today entails much more than just more precise and frequent billing of energy for the end users, this is actually contributing to a revolution in the way energy is produced and distributed. Advanced digital metering infrastructures generate large amounts of data that can be used for gaining insight in the energy use; they can help utilities manage their assets and plan their infrastructure based on the actual usage and not on the peak estimation; a digital meter that is able to react to signals in combination with intelligent equipment at home can open new business opportunities for the utilities and even for new players.

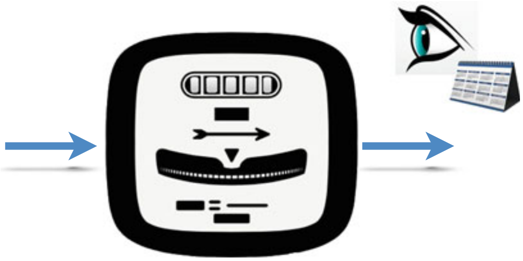


Fig. 1 Traditional analog meter

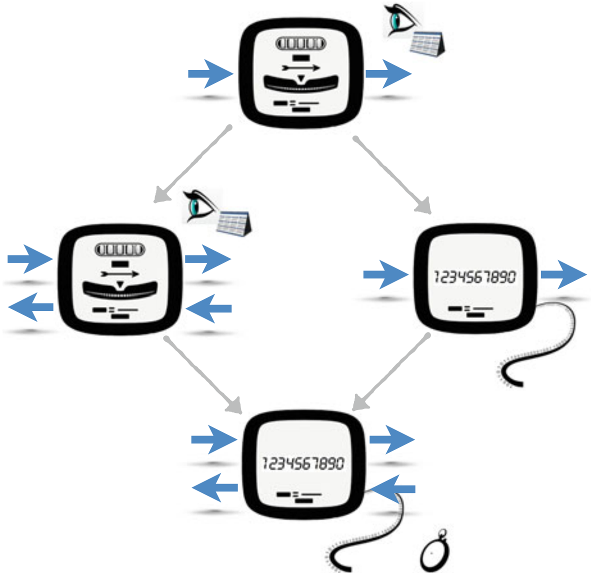


Fig. 2 Evolution of energy metering

Furthermore, it can help users understand how they use energy in order to change their behavior or, at least, account precisely for which action entails which consumption. In this chapter, we look at the current state of affairs in energy distribution from the various views relating to Information and Communication Technology (ICT), our lenses for this will be those of Information and Communication Technology. We leave economic, social, and regulatory perspectives to the other relevant chapters in the book.

3 The Smart Meter View

In some countries, smart meters have been rolled out to all users. Italy was one of the first countries undergoing this massive installation effort and is currently starting the roll out of the second generation of digital meters (Botte et al. 2005). In other countries, due to technical and political reasons, the roll out of the smart meters is partial. For instance, in the Netherlands, a user can refuse to have a meter installed at home on the basis of privacy concerns. Furthermore, the current legislation guarantees that the meter cannot be remotely read more than once every two months.

Smart meters are substituting the traditional analog ones, the pace might vary from country to country, though it appears to be inevitable. From the first million of installations at the beginning of the century, projections currently predict the surpassing of the 1 billion value by 2022 (Navigant Research 2013). Such a shift does not come in isolation. It is just not a matter of substituting one device for another one, it is a matter of putting in place an entire ICT infrastructure.

Smart meters need to communicate their readings with a back-end system on a regular basis. This requires a telecommunication infrastructure and an information system to manage the data. With a reading per month for billing purposes, this can be easily achieved. Though things become interesting when moving to more frequent readings. In fact, to make accurate predictions of energy consumption per unit, it is useful to have historical readings of a meter with the granularity of minutes, if not even smaller time intervals. Such readings may even allow to make accurate recognition of which appliances are running at any given moment (Laughman et al. 2003). In addition, one can make correlations with weather and calendar information so that the load of a customer can be estimated with a fair precision.

From a technical point of view, there are issues of amount of data, speed at which it is generated and has to be transfered, and of its usefulness. Issues that often go together under the heading of *Big Data.* Let's consider each of these individually.

Volume. In Aiello and Pagani (2014), we have estimated what the amount of data that could result from a fully smart energy system for a country like the Netherlands. Considering the number of households, the connected smart energy devices, the generation facilities and the grid itself, one could easily arrive to petabyte (PB) of grid data per year. Table 1 shows the case of a scenario possible in few decades from now where smart meters give a reading every five minutes. Meaning the move from the current bimonthly readings for few gigabyte (GB) of data for the whole country, to PB of information just for the Netherlands alone. Such an estimate is in line with those for other countries. The utility EDF has estimated in its French network 35 millions smart meters and a sampling frequency of 10 min to have a total amount of data of about 120 terabytes/year (dos Santos et al. 2012).

Velocity. The large amount of data is generated in a distributed and independent fashion. This entails the need for its transmission and, in turn, the existence of a

Table 1 Scenario of data generation related to the smart grid for the Netherlands. *Source* Aiello (2014)

Metering	
Metered customers	9,000,000
Installed smart meters	9,000,000
Smart meter sampling period (min)	5
Smart devices	
Electric vehicles	3,950,000
Battery packs	135,000
Intelligent appliances per household	20
Grid infrastructure	
Nodes HV (380/220 kV)	60
Nodes MV/LV	178,221

communication infrastructure. Power line communication is a possibility to go from the smart meter to the first substation and then using other higher bandwidth means to further aggregate the data (Botte et al. 2005). Alternatively, one can use wireless communication directly form the smart meter (Parikh et al. 2010) and then rely on fiber optics for the backbones (Holcomb 2012). Many studies agree that an existing infrastructure such the Internet would not be sufficient to satisfy the bandwidth and, especially, the response time needs an infrastructure based on high frequency sampling of smart meters, while filtering and aggregation and optimization of packet flows might be required based on the telecommunication infrastructure available in each specific case (Kansal and Bose 2012).

Value. Having large amounts of data brings no specific benefit, per se. It is not about the bits of data, but it is about the amount of information that reside in the data and that can give additional value and open new possibilities (Shannon 1964). It is about the use one can make of the information in the data that provides for the added value. As mentioned, precise billing is just the satisfaction of an elementary requirement, the real value has to be searched in the identification of correlations among events that allows one to make reliable predictive models of infrastructure usage and projected energy needs. Being able to predict and, possibly, shift the demand and production of energy can provide for major economic savings and, in some cases, also reduced environmental impact. The reason for this is that energy costs do not grow linearly with the amounts provided and different sources have different environmental impacts (Sims et al. 2003).

Typically, utilities provide a certain amount of energy that is scheduled to cover the base load at a more or less fixed cost. This base load is a function of the estimated load for a given time window and is met by the base-load generating infrastructure (e.g., nuclear and coal-fired plants). The additional demand that is not covered by the base load requires additional energy sources that come at increasing costs. E.g., serving an unpredicted peak much above the common average can cost several orders of magnitude more than the base load energy production. In the traditional energy paradigm, the need to influence the load by a differentiation of the tariff has been already implemented since long time. The solution in place is not dynamic, but simply it makes a broad classification of two time periods: the day-night/weekday-weekend (i.e., peak/off-peak) tariffs. This is done to achieve a better use of the base-load power plants by reducing the load in times of high use, and, in turn, to decrease the use of expensive generating resources and costs of congestion. There is also a technical reason to stimulate the use of base load plants: base load plants are characterized by precise dynamics rules in the variation of their input-output which are rather slow. It is therefore not admissible to shut a coal plant just for few hours since the dynamics of the plant do not allow fast ramp ups and downs of the plant (hours to days for complete shutdown). In plants powered by renewable sources such as sun and wind, the situation is different. The renewable-based plants have still their own dynamics, but they are definitely more difficult to control by human intervention. Sun, wind, waves, and tides obey the rules of physics and their availability to produce energy comes from the interaction with systems where the human influence is very limited and whose dynamics are also difficult to forecast. In a smart meter world, where energy can be metered at high frequency, it is not far fetched to envision real-time pricing of energy on the basis of the actual energy supply. The goal is to transition from a demand-driven (or demand-following) energy system to a system where users adapt their consumption to the amount of energy available, therefore becoming supply-driven (or supply-following). In this context, real-time energy pricing and precise real-time measurement through a smart meter are the fundamental ingredients.

4 The End User View

The digitalization of the electric infrastructure is also shifting the user perspective. If in the past, the user had very limited means of knowing how energy was used, today, users can finally *understand* their energy footprint, resort to automation, and make conscious decisions based on real-time information. If in the past, one would see a monthly or bi-monthly energy bill, now it is easy to display real-time data about energy consumption of individual devices. Products such as Plugwise devices allow the reading of high frequency energy data. These plugs can be placed between any appliance and an electric socket and relay information via a mesh zig-bee network. One can then easily see the consumption of individual devices and also spot possible emerging spikes in energy consumption, or anomalies in the energy needs of devices. Similarly, a product like the Nest thermostat records precisely the temperatures that are set by the user, the actual room temperature, and it provides feedbacks correlating these temperatures with the weather conditions and users' decisions. In other terms, the digitalization of the infrastructure now allows the energy relevant information to abundantly flow towards the energy user.

4.1 Information Flow

There are three ways in which such information flow can hit the user. **First**, the information is returned to the user via a graph in an mobile app, a personal web-page, an email notification, a screen in his living room, or similar means. In this way, the user becomes aware of how energy is used. Such information can help change behavior by gathering insight and knowledge, Chapter 4. The information can be presented as raw (e.g., kW samples), aggregated (a graph of kWh over hourly intervals in a day), or metaphoric (number of trees necessary to compensate for the CO_2 emissions of the consumed energy). It is important to realize that having real-time information has much higher impact than simply knowing the characteristics of a device. If the energy labels help to make informed decisions when purchasing an appliance, they don't tell the full story. It is the way in which these machines are used that really determines the energy footprint.

Second, the information is collected for the user and decisions are made on his/her behalf autonomously by his automation equipment. The Nest thermostat is a nice example of this category. The thermostat gathers information by monitoring how the user sets the temperature in a room. After enough samples are collected, it learns the likely patterns of use and then starts controlling the environment on the user's behalf. This form of automation is very important, because it works without necessarily requiring conscious user involvement. One of the driving principle for Nest was that about 95 % of owners of programmable thermostats never program them. Another way of looking at this is that energy information is rich and complex and must be reduced before direct "consumption" by the end user.

Third, the flow of information is reversed. The user gathers awareness and makes direct control decisions. Instead of delegating the decision to an automation system, having the possibility to directly control appliances, possibly remotely, it makes informed decisions. This is the case of programming a dishwasher to run when owned solar panels are at peak production, or scheduling for an off-peak tariff hour. More and more appliances are on-line and can be remotely monitored and operated, think of the Philips Hue lights, the Samsung WW9000 washing machine series, and so on. Devices have a programmable interface that allows users to interact with them remotely via mobile app, to define behaviors based on contextual information, and be always on-line.

4.2 Information with Value

Home energy management systems will also be able to optimize the energy consumption of the user. Like the Nest example above, the home energy management system might be able to learn the energy patterns of the users and buy energy for the user at a discounted price. Another solution could be for the user to specify a goal (e.g., run appliances at the lowest possible cost, maximize the use of on-premise renewables) and some constraints on the comfort (e.g., the dishwasher has to be ready before 19.00 every day) and let the home energy management system identify the solution and manage the turning on and off of the equipment. We have conducted a similar experiment by creating a simple energy management system of the future connected to a realistic simulator of the smart grid to manage the electrical equipment of an office space (Georgievski et al. 2012; Pagani and Aiello 2015). In our solution, we managed to achieve a reduction in the cost of running a common set of appliances available in a modern office by 20 % without modifying the well-being perception of the users.

Incidentally, all the information that is useful for the user, is also useful for the network. The user energy data can help make accurate predictive models of energy usage within a household and, in aggregated form, help the network operator to manage the grid and its assets. In addition, new data an insights on the energy use can open the door to cheap and personalized energy consultancy therefore enabling new business opportunities and enabling further energy savings. The aspects of privacy and ownership of metering data are an important concern here, for this we refer to the Chapters 12 and 14.

5 The DSO View

The Distribution system operator (DSO) is responsible for operating the grid, ensuring the safety and availability of energy to its customers. The operator is responsible for infrastructure and equipment maintenance, if necessary, for developing the distribution system (medium and low voltage) in a given geographical area, where applicable, for managing its interconnections with other systems, and for ensuring the long term ability of the system to meet reasonable demands for the distribution of electricity (E.U.: European directive 2007). To meet its responsibilities, the DSO has to have a good model of what are the energy needs of the users over time, what are the maximum peaks that one can expect, and how should the infrastructure evolve to meet future needs, both geographically and quantitatively.

Before the wide adoption of smart meters, a Dutch DSO would estimate an average of 1 kW per household and, taking a very conservative approach, by over-estimating the growth in electricity use in the following years. Such information was then used for the dimensioning of the infrastructure. The reason for this opulent approach is that the biggest part of the costs for realizing an underground distribution infrastructure such as the one present in the Netherlands is the labor cost of excavation and laying of cables. Such an estimate was based on experience and has worked in practice for many years, though clearly one can do better. By precisely measuring, instead of estimating, one can dimension the system to the actual needs. Under-utilized and saturated lines will emerge and new more precise planning of the evolution of the grid can be made. The old way here was to put an analog sensor in the transformation station and have it inspected regularly (e.g., monthly) by a human operator visiting the facility. Currently, we are transitioning to ICT monitored and operated facilities.

The creation of precise models of utilization is especially needed now. In fact, the evolution of the grid is not just about the growth of population and urban areas; the evolution has to do with new ways of utilizing energy. The introduction of distributed micro-generation, the appearance of home-level storage facilities, and the increasing popularity of electric vehicles are changing the game. The distribution grid, which traditionally has been, unidirectional in the energy flows is turning into a multidirectional system where micro-generating sources are intermittent and there is a high mobility of load and the increasing appearance of storage.

5.1 Topology Adaptation

The distribution grid, given its *passive* role, has been engineered in the form of a radial, tree-like network. Such a topological design is correct and the most efficient when there are few large producers of energy at remote locations. In the new paradigm, energy is produced also locally and the energy production and consumption take place at neighborhood level. In this situation, if one wants to create a grid that is suited to the local energy production and distribution, designs other than the radial/tree-like should be investigated. A future with plenty of prosumers that produce small quantities of energy and sell or share it at the level of neighborhoods will affect the shape and working of the distribution grid. The change from a passive-only grid to a smart grid will require to rethink the role of the medium and low voltage grids (Brown 2008). In particular, the distribution grid has to be robust and the distribution cost has to be kept low not to put an additional burden to the stimulus for new small-scale renewable energy installations. In our study (Pagani and Aiello 2013; Pagani and Aiello 2014), we resort to Complex Network Analysis (Newman et al. 2006) not only to analyze the existing infrastructure, but also to drive the design of the next generation grid. *Complex Network Analysis* (*CNA*) is a branch of Graph Theory taking its root in the early studies of Erdős and Rényi (Erdös and Rényi 1959) on random graphs and considering statistical structural properties of evolving very large graphs having the goal of looking at the properties of large networks with a complex systems behavior. After analyzing real samples of the distribution grid of the Northern of the Netherlands (Pagani and Aiello 2011) and looking at the topological properties that influence the price, we noticed that there are network samples more prone, from a topological perspective, to accommodate local energy interactions. An increase in the average connectivity of the distribution network and topological designs that are less close to the tree-like structures (cf. Fig. 3a) such a small-world network (cf. Fig. 3b) can provide a reduction in the parameters affecting the costs of distributing electricity while improving robustness and resilience to failure. However, it is not realistic to think of rebuilding completely the distribution grid already on the ground to change its topology to make the local energy interaction more efficient. It is necessary to study how to make the current network more efficient without impacting significantly on the cost of the infrastructure. In Pagani (2014), we have considered several strategies to evolve the networks taking into account the cost burden of realizing more connections too. The strategy that provides a good balance between the performance and the cost in upgrading the infrastructure is connecting the nodes of the network (not yet connected) that have a small distance to each other. An example following this strategy for a real network sample is shown in Fig. 4.

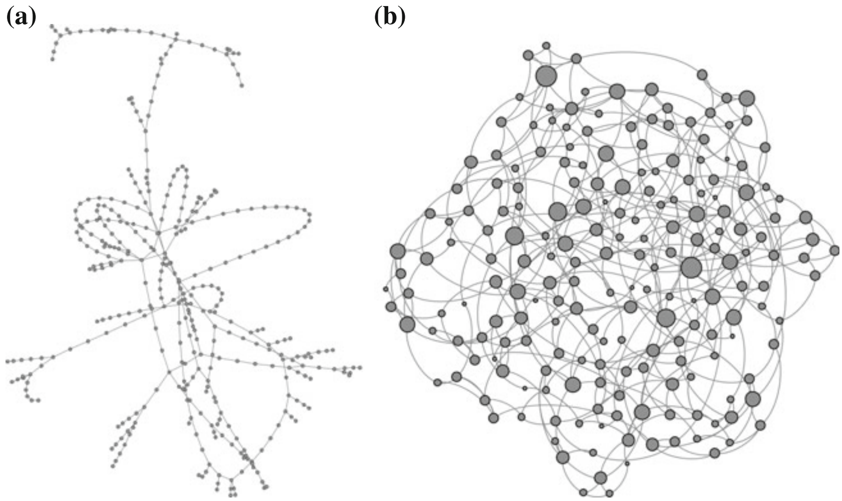
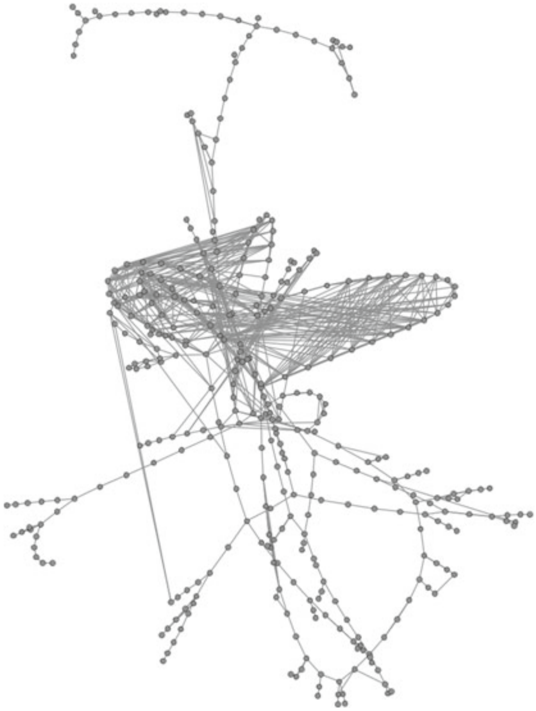


Fig. 3 Network topologies of a real (**a**) and a synthetic network (**b**). **a** A traditional radial distribution network. **b** A small world network (200 nodes, 399 edges). *Source* Pagani (2014)

Fig. 4 Evolution of a distribution network. *Source* Pagani (2014)



5.2 The Value of Analytics

DSOs are embracing the smart grid vision and widely deploying smart metering in order to improve their operations. The improvement comes from the embracing of analytics-based techniques to better analyze in real-time the actual condition of operation of the network. Traditionally, real-time telemetry services were confined to mission critical assets that needed to be continuously monitored or to the equipment used in the high voltage networks. With more and more cheap sensors and cheap data transmission, it is now possible to add sensors to almost any piece of equipment. The benefits to improve the operations of the utilities are enormous. The consulting firm Accenture estimates that smart grid analytics have a value ranging from 40$ to 70$ per electric meter per year where 40 % of this value is for the utilities and 60 % belongs to the customers (Azagury 2014). Concerning the utilities the most important areas of value are asset management, power quality, and revenue protection and billing. One can see the value of the benefits when the metering points are millions and millions. The above cited are just estimations since the roll-out of smart metering and sensing equipment are underway and utilities are developing analytics-based operations; the final answer on the benefits will be available in the near future.

5.3 A Parallel Between Telecoms and DSO

The major shift the DSOs are currently in, has some analogies to the revolution that happened in the telecommunication sector in the ’90s, which claimed many important players as victims. Let’s consider what happened back then.

The telecom sector, which was over 100 years old, was considered a natural monopoly, just like energy utilities. The telecom providers, mostly government owned, managed the service, network, and equipment layers. All R&D was done internally and any innovation sprouted by so-called non-market drivers. Fransman identifies as causes of the major paradigm shift that hit the telecom sector the following ones: cross-country competition, political pressure and consumer pressure (Fransman 2003). For instance, in 1985 the European Community emanates the Liberalization Directives under Article 90 of the Treaty of Rome determining the deregulation of telecommunications market for the next decade. Furthermore, Fransman notes “by the end of 1995, […] the now incumbent network operators [were] making the decision to leave more and more of the R&D related to the network and its elements to the specialist equipment suppliers. At the same time the incumbents decided to open their procurement, agreeing to buy from new suppliers in addition to their traditional suppliers.” In other words, the suppliers were becoming innovators and ready to play on the telecom market in more than just one role. New players were appearing from unexpected areas. For instance, an electronics company like Olivetti together with Mannesmann in 1995 enters the Italian market creating Infostrada, the first competitor of Telecom Italia. In the same period the Internet and the Web were emerging as infrastructures for all and people started requesting access to them. This was in contrast with the general worry of the telecoms of having enough bandwidth.

We claim that the electricity sector today is in a similar situation to the telecom one two decades ago (Aiello 2012). It is rooted in a tradition of natural monopoly, it is getting exposed to cross-country competition, political pressure is pushing for the unbundling (e.g., the EU directive 2009/72/EC), and there is consumer pressure for having free or deregulated access to the infrastructure. As we include renewables at all scales in our power grids and as consumers demand freedom to supply and to sell, low voltage capillary interconnectivity will be necessary so that neighbors can engage in energy trading and implicitly transform neighborhoods into energy neutral areas.

6 The ICT Provider View

ICT providers are going to play an important role in the future smart grid. Smart meters, home energy management systems, sensors, and ubiquitous computing technologies are the core expertise of ICT providers. The parties that have played a role in the expansion of an ICT-based society are going to be present in the digitalization of the grid together with domain specific providers that are forerunners in understanding the potentiality of the new energy grid and are responsible for its development.

ICT companies have the possibility to play novel roles to provide new added value services in the energy domain. In an information-driven grid, the data-driven companies offering services can increasingly have easy access to the data, perform appropriate computations and perform intervention on the smart grid equipment. For example, an ICT provider can plug its application into the energy management system of a home or an office and provide optimization for the use of equipment, give insight into the energy consumption of the appliances, understand the anomalies in energy usage, and foresee problems in the lifespan of the appliances. In addition, it is not difficult to imagine an ICT provider that takes the responsibility on behalf of the user for optimizing the energy use by utilizing local renewables and accessing the cheapest providers on an open retail energy market, thus acting as a virtual energy provider. Naturally, the automatic decisions must guarantee the comfort and economic provisions to the user. In such a dynamic and varied landscape, such as the smart grid characterized by several operators interacting in the different levels, a technology that enables interoperation and flexibility is required. The technological-software approach that is emerging and likely to stay for the implementation of the smart grid is the Service-Oriented Architecture one (SOA) (Pagani and Aiello 2012). Such a paradigm allows parties of the smart grid to interact on the service level (usually realized resorting to Web services standards) independently from the back-end system already in place. SOAs are also a powerful paradigm to easily allow the addition and removal of services on the fly, allowing a seamless interaction in an energy management system and the possibility for a true competition.

With the spread of electrical mobility, the increase in pervasive computing technologies, the ubiquity of devices connected with each other and the Internet, energy is going to become another product available and manageable through the Internet where specialized apps are going to emerge as widely popular. Examples of companies that are exploring this new ground are Opower in the energy awareness, billing services, demand response, and user engagement. A global player is AutoGrid which spans from the energy-related data from the grid operations, building energy optimization, and end-user equipment. Energy is transitioning towards being an exciting sector where the intertwining between Power Engineering and ICT is going to provide a vast amount of new services and solutions coming from various backgrounds to achieve a more efficient electricity infrastructure and sustainable energy footprint.

7 Concluding Remarks

The changes that are rapidly occurring in the electricity sector are empowered, if not driven, by ICT. Advanced metering infrastructures and smart devices which are energy aware are taking over a 100 year old infrastructure which used to be analog in its basic operation.

The intrusion of ICT in the power system field is neither straightforward nor risk free. As we have described in the chapter, there are important challenges of data management and it is still unclear how to extract value from data. Furthermore, ICT is generally less reliable than modern power systems. In the Netherlands, for instance, in 2014 the average downtime per year per customer is of just 20.0 min (Netbeheer Nederland 2015), that is, an availability of about 99.996198 %. This is two orders of magnitude better than the availability of a mobile network.

On the other hand, an infrastructure that has to accommodate for distributed and intermittent generation, for mobility of load and storage as electric vehicles do, of increasing user involvement, needs the power of ICT to manage the infrastructure and to accommodate for dynamic, adaptive and flexible solutions.

ICT and power system will have to go hand in hand and learn from each other. ICT research and development is challenged by dealing with a material infrastructure highly constrained by physical laws, while power systems research and development is challenged by having to decentralize decisions and rely on novel control mechanisms that give an increasing freedom to the end users.

Points for Discussion

- How much does the advent and success of Smart Grids depend on the full roll out of Smart Meters?
- Knowing how the Internet developed and changed our daily lives, can we draw a parallel with smart grids and predict their evolution in the future? Will energy sector manage to evolve from a commody to a vibrant ICT-based product for the consumer?
- The authors discuss energy distribution developments from an ICT perspective, consciously leaving social, economic, regulatory and political perspectives untouched. They conclude that the power system will have to deal with decentralized decision and new control mechanisms. How do you evaluate their conclusions in light of the non-ICT factors?

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