Smart Grids

Peter Palensky and Friederich Kupzog

Energy Department, Austrian Institute of Technology, Vienna 1210, Austria;
email: peter.palensky@ait.ac.at, friederich.kupzog@ait.ac.at

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Abstract

This review covers the current state of "smart" grid research and demonstration projects. At present, smart elements are making their way into traditional electricity grid systems at every level, from transmission down to distribution. The vast size of the power grid makes the extension of digitally enabled electric infrastructure a question of cost. Drivers for this development are the growing security requirements and sustainability of supply in the face of rising demand and aging infrastructure. Information technology (IT) is one of the key elements of smart grids because it enables cooperation of distributed energy resources, local control, and globalized energy markets. Smart grids are expected to make our power system more resilient, "green," and efficient; a challenge that the automotive industry could only manage by introducing digital controls in engines. We now witness the same development in electric energy systems. This article provides an introduction to the topic, a snapshot of current activities, and a general outlook on what still is needed.

Contents

ICT: information and communication technology

1. INTRODUCTION

The US Department of Energy issued "The Smart Grid: An Introduction" (1), one of the initial documents aimed at a broad audience. The paper opens with a famous comparison that, although Alexander Graham Bell would not recognize today's telecommunication system, Thomas Edison would be very familiar with today's energy grid. The article implies that it is high time to renew the energy system that has served us well for the past century. Developing a smart grid would allow us to flexibly manage capacities for growing demand, to accommodate new sources of energy with bidirectional and flexible grids, and to allow new players to participate in new energy markets. It is especially the renewable and distributed types of energy sources (wind, solar, small hydro) that require such flexibility in order to integrate them without putting the system into danger. Therefore, the smart grid is one key technology for reaching the climate goals in the western world, which heavily rely on increasing the share of renewable energy sources.

The difference between a nonsmart and a smart grid cannot be nailed down to one single aspect. First, it is about functionality. A smart grid can host the latest energy products and technologies. This flexibility is based on two design principles that need to be introduced:

- More distributed architecture, i.e., more physical players in the system, flexibly networked by
- More information and communication technology (ICT), which implements adaptive controls and other smart algorithms.

The topology of the existing grid was planned and implemented with large centralized power stations in mind. Recent developments in renewable distributed energy require change. Making grids capable of hosting distributed energy resources leads to the second design requirement. Distributed infrastructure needs more remote monitoring and control than centralized infrastructure. Additionally, new renewable energy generation resources (2) need a flexible and "active" grid, which can only be implemented by means of ICT. The above two principles are implemented via a large variety of technologies, leading to the notion of a "silver buckshot," in contrast to a silver bullet, that would lead to the smart grid.

However, it is important to understand that we need an entirely smart energy system, not just a smart grid. The grid, i.e., transport and distribution infrastructure, is certainly important and requires dramatic upgrades but so do the end points of the energy system: generation, storage, and demand. Technological upgrades like more efficient or low-emission technologies must be combined with systematic upgrades, for instance, coordinated demand and supply, automatic analytics, and other ICT-based functions. Demand response (DR) is an example of smart coordination of energy resources. Additionally, the smart grid idea spans different types of grids, such as gas and district heating networks. This article, however, is mainly focused on the electric grid.

The smart grid comes in gradual, evolutionary steps: Whenever a certain technology or application makes fiscal sense, it is implemented (3). Therefore, there is a phase of coexistence (4), when both the traditional and new parts form one system. The distribution grid, where new technologies and applications are to be located, will have the most significant changes because it is currently in a low-technology state, with little utilization of ICT (5).

The International Energy Agency has developed a technology road map for smart grids (6), providing a comprehensive outlook on the "smartening" path until the year 2050. It clearly states that developing a smart grid is an evolutionary process, not a one-time event. It also emphasizes that the smart grid combines technological, economical, regulatory, and societal aspects to make our energy system more secure and sustainable.

Compared to the existing energy system, the smart grid is expected to be flatter and more democratic with improved transparency. Currently, most energy customers are protected from volatile prices (7), making their lives easier but not necessarily optimal. The smart grid can open the door for more participants to enter these markets.

The European Technology Platform SmartGrids (8) defines six priorities for implementing the smart grid in Europe: operations, optimizing grid infrastructure, integration of intermittent generation, ICT, distribution networks, and new market places. Another document, "Strategic Research Agenda Update of the SmartGrids SRA 2007 for the Needs by the Year 2035" (9), identifies the need for research in the following areas: integrated systems, transmission and distribution systems, and the demand-side and socioeconomic phenomena. Ultimately, it is clear that the smart grid is about the integration and networking of electricity, information, and applications.

2. SMART ENERGY SYSTEMS

As mentioned above, there is no clear line between smart and "traditional" power systems, neither in functionality nor in time. The electrical energy system has always contained components that added a bit of "smartness": protection relays that interrupt power flow, energy meters, remotely operated substations, and cascades of power stations that implement ancillary services. Thus, the upcoming smart grid is not really the first attempt to make the power system smart.

However, the introduction of smart grids elevates system complexity to new levels through broader use of affordable information technology (IT) at the distribution level, bidirectional communication and energy flows, and interaction with other information systems, e.g., energy markets.

The US Energy Independence and Security Act of 2007 (EISA) (H.R.6) describes the smart grid under "Title XIII–Smart Grid," section 1301, as a "modernization of the Nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure. . . . " The EISA explicitly lists the properties of this envisioned smart grid as follows:

(1) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.
(2) Dynamic optimization of grid operations and resources, with full cyber-security.

Demand response (DR): the demand side reacts (increases or decreases its load) dynamically to asynchronous events in the energy system

Distribution network: provides regional distribution of medium-voltage electricity with low-voltage connections to the customers

Ancillary services: services, typically offered by power stations, that grid operators need to keep the infrastructure running, e.g., frequency control and voltage control

IT: information technology

Interoperability: the ability to make two or more components work together, typically realized using specific rules for electric connection or communication interfaces

Microgrid: a small grid with generation, consumption, and sometimes storage that can operate in a grid-connected and "isolated" mode

PV: photovoltaic

EV: electric vehicle

(3) Deployment and integration of distributed resources and generation, including renewable resources.

(4) Development and incorporation of DR, demand-side resources, and energy-efficiency resources.

(5) Deployment of smart technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation.

(6) Integration of "smart" appliances and consumer devices.

(7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning.

(8) Provision to consumers of timely information and control options.

(9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid.

(10) Identification and lowering of unreasonable or unnecessary barriers.

Achieving this requires innovation in several domains. We can distinguish between technological innovations (new storage technologies, renewable energy resources) and systematic innovations (standards, integration of formerly disconnected parts, on-line optimization). The ISO New England 2009 report (10) lists three categories of technologies: supply side (distributed generation, microgrids, and storage), demand side (efficiency, DR, metering, automated homes and buildings), and transmission and distribution (wide-area monitoring, transmission, and distribution control). This report (10) can also be viewed for the mapping of prominent US smart grid activities versus categories like policy and regulation, operating model, systems integration, and technologies.

Aside from the plethora of advantages, a smart grid usually has a single dominating purpose depending on the particular country or continent. If the points of interest are ambitious climate goals, the smart grid serves as an enabler for integrating more renewable and low-emission energy sources, i.e., wind (11) and photovoltaic (PV) (12). The intermittent nature of these sources requires flexibility from cooperative loads, storage, and an active grid that can deal with fluctuating generation. According to recent studies, a smart grid can decrease carbon emissions by 5–16% (13) if several measures are combined: consumer information, dynamic pricing, load shifting, and others. The smart grid is also the enabler for integrating all forms of energy, including gas, heat, and distributed combined heat and power (CHP) (14) into one energy system that is more flexible and more reliable (15), and more efficient than the simple sum of its parts. Consequently, we should not see the smart grid as an electric-only grid.

If capacity problems are on the political agenda, the smart grid is expected to improve grid reliability, security of supply, and utilization of existing generation, transport, and distribution capacities. A lack of grid investment and growing energy demand are often not the only causes of capacity problems: Renewable energy sources are becoming increasingly competitive (5) (i.e., they are commercially profitable and not just "green"), forcing the grid to incorporate them.

The use and success of smart grid and renewable technologies are largely influenced by national renewable energy policies. Some countries like Germany and Denmark show impressive figures, which is why they are sometimes even not shown in global charts in order to recognize and distinguish other countries' otherwise negligible curves (16).

Leading Asian industrial nations are evaluating the speed and extent to which renewable supply and smart grids can be implemented. Esteban et al. (17) estimate the storage requirements if fluctuating sources are used to supply 100% of Japan's electricity. Their conclusion is that, despite the predicted high levels of electric vehicles (EVs) in Japan, these will not be sufficient to meet storage needs; a combination of hydrogen, biomass, and pumped storage will be necessary. Korea has an action plan to implement smart technologies for its grid, transportation sector, and built environment (18). The Korean goals include reductions of blackout durations, transmission losses, and power consumption, as well as ramping up smart meter usage. The most prominent example of this action plan is the Jeju Island Smart Grid, which serves as a test bed for all kinds of smart grid technologies before their nation-wide unveiling. China's plan for its power systems revolves around growth (19): more power plants, more renewables, more transport capacity, and more storage (20), as well as enhancing all of these with IT. Balijepalli et al. (21) describe the unique example of India, where very fast growing demand meets poorly managed and maintained grids. Here again, IT is viewed as the vital solution toward a reliable and efficient grid in India.

Western industrial nations have released acts and resolutions to implement smart grids and renewable technologies to meet climate goals. Brunner et al. (22) give a mapping and a gap analysis of European smart grid projects, originally implemented for identifying synergies among European smart grid research projects. The largest gaps were identified with regard to integrated energy storage, market models, and overall framework questions. One country whose renewable generation stands out is Denmark with its sights set on wind power comprising 50% of the grid (23). Simoes et al. (24) compare progress of smart grid technologies in Europe and the United States, putting legislative measures, barriers, and technologies side by side. According to EPRI's comprehensive report on California's 2020 vision of the smart grid (25), California has a leading role in the smart grid demonstration projects in the United States. The report describes a policy-driven road map that leads to economical and technological innovation and is based on six areas of expertise: communications infrastructure, customer systems, grid operations, renewable energy, grid planning, and workforce effectiveness.

3. SMART GRID STYLES AND COMPONENTS

A variety of smart grid styles have evolved. Although the power grid originally managed without any ICTs because these did not exist when it was designed, more and more digital technologies found their way into the electrical power grid infrastructure. The factors driving this push were renewable integration, security of supply, and efficiency of infrastructure maintenance. The different voltage levels of the grid (**Figure 1**) show different levels of maturity with regard to smart grids.

3.1. Smart Transmission

The transmission grid was the first domain in which ICTs were broadly applied. At this level, electricity is transmitted over large distances using high voltages before being locally distributed. Owing to the comparably low number of "nodes" (e.g., substations) in the transmission grid, it is usually viable to fully automate grid assets at this network level. The prominent tasks are monitoring the system's state and the control of power flows. A precise estimation of the system's state can be obtained from phasor measurement units distributed over the network (26). The optimal layout of real-time monitoring and wide-area control infrastructures is a widely discussed topic (27). Current research and development topics include efficiency improvements from real-time control and real-time decision making (in contrast to state-of-the-art off-line studies) as well as improvements in state estimation, fault identification, and isolation (self-healing) capabilities (28).

Totally new research issues emerge from advances in high-voltage direct current (DC) technologies as researchers find their applications in offshore wind energy transmission (29) and potentially also in long-distance intercontinental backbone infrastructure (see the Supergrids and Large-Scale Energy Storage section below). When DC links are extended to multi-terminal (and not just point-to-point) networks,

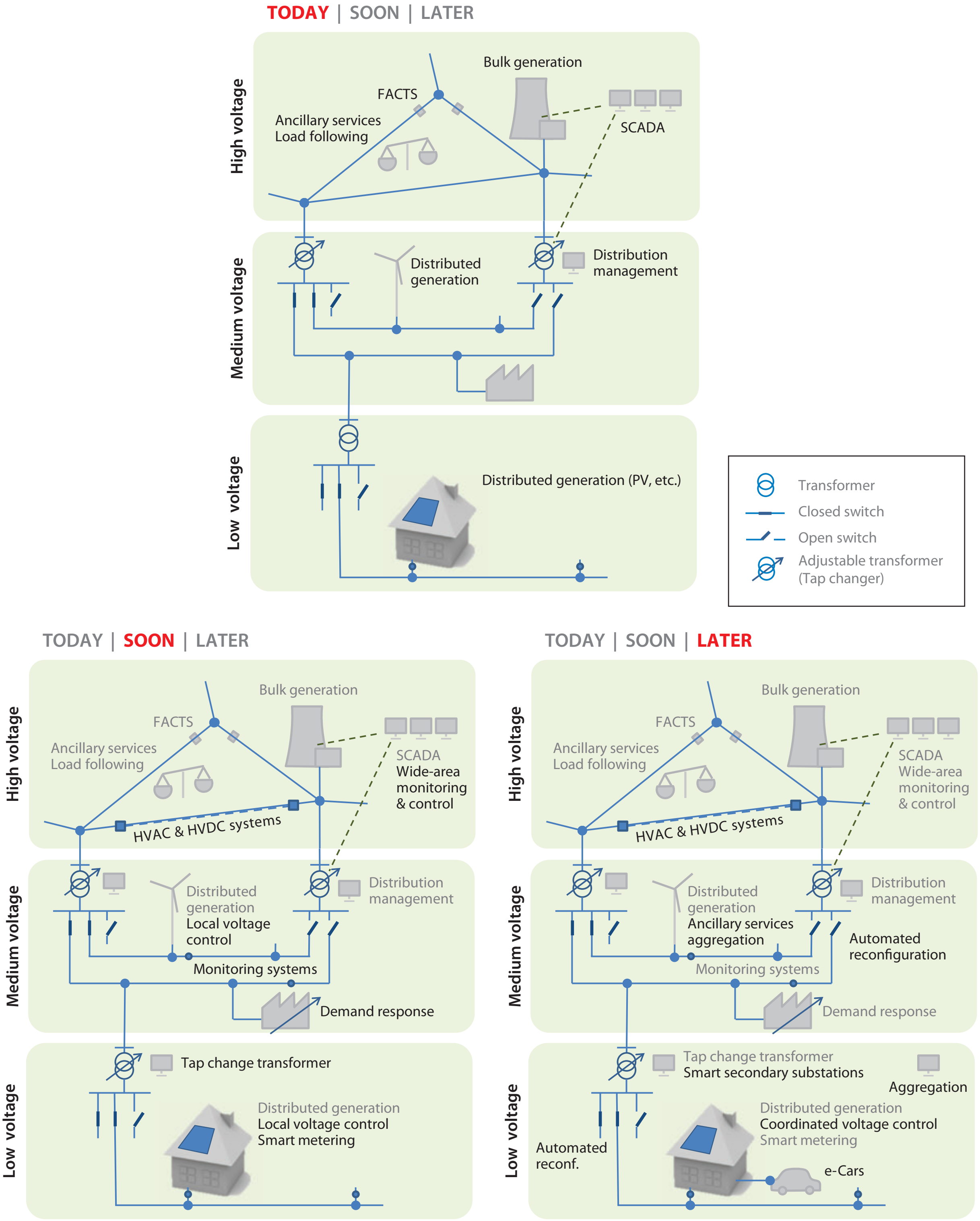
TODAY | SOON | LATER
High voltage
Bulk generation
FACTS
Ancillary services
Load following
SCADA
Medium voltage
Distributed generation
Distribution management
Low voltage
Distributed generation (PV, etc.)
Transformer
Closed switch
Open switch
Adjustable transformer (Tap changer)
TODAY | SOON | LATER
High voltage
Bulk generation
FACTS
Ancillary services
Load following
SCADA
Wide-area monitoring & control
HVAC & HVDC systems
Medium voltage
Distributed generation
Local voltage control
Distribution management
Monitoring systems
Demand response
Low voltage
Tap change transformer
Distributed generation
Local voltage control
Smart metering
TODAY | SOON | LATER
High voltage
Bulk generation
FACTS
Ancillary services
Load following
SCADA
Wide-area monitoring & control
HVAC & HVDC systems
Medium voltage
Distributed generation
Ancillary services aggregation
Distribution management
Automated reconfiguration
Monitoring systems
Demand response
Low voltage
Tap change transformer
Smart secondary substations
Aggregation
Automated reconf.
Distributed generation
Coordinated voltage control
Smart metering
e-Cars

Figure 1

Technical view of the three voltage levels of power grids with their standard, recent, and future features. Abbreviations: FACTS, flexible alternating current transmission systems; HVAC, high-voltage alternating current; HVDC, high-voltage direct current; PV, photovoltaic; SCADA, supervisory control and data acquisition.

traditional approaches for demand-supply balancing and protection (30) cannot be used. These topics are, however, only loosely coupled with the idea of smart grids for which research mainly focuses on the extension and better utilization of existing grid infrastructure via ICTs.

3.2. Smart Distribution

Except for large-scale installations, such as offshore wind farms and solar power plants, most renewables can be found at the distribution level, i.e., either at medium voltage, where the majority of wind, small water power plants, and PV arrays are connected, or at low voltage, where the majority of small PV and CHP units are connected. Distribution network operators around the world have to cope with the challenge of existing distribution infrastructure, which is not always able to host the expected amount of renewable generators. A prominent example is the PV integration issue in Germany (31). The integration is difficult for two reasons: First, today's distribution grids have been designed for demand only. It is merely by chance that distribution transformers can also work in the reverse direction and feed, for example, local PV generation back into the higher network levels. Still, generation in the distribution grid requires additional capacity reserves. The allowed voltage band can no longer be fully dedicated to voltage reductions caused by loads. Instead, it has to be split in a (now smaller) band for loads, with a reserve for voltage rise from distributed generation. Second, in contrast to the transmission level, the distribution level (especially the European low-voltage grid with its millions of nodes) is operated almost blindly. The lack of on-line measurement is the reason why utilities have to stick strictly to allocated capacities (32).

To avoid the large investments that would be necessary to build up additional capacity for distributed generation (33), promising smart grid approaches have been designed to cleverly manage available capacities and are currently undergoing testing. Especially in rural grids, where the ratio between local generation and demand can become very high, the maximum permitted line voltage variation is the major limiting factor for renewable integration (34, 35). In order to adjust the line voltage during operation and to keep it within limits, the feeding tap-changer transformer can be tapped up or down. If this is not sufficient, the reactive power of individual generators on that feeder can be managed before finally shedding the active power (32). Given an appropriate automation infrastructure enabling remote access to these variables, a distributed control system can be designed (36) that not only keeps voltage in its limits but also optimizes other aspects, such as maximum renewable power utilization (37) and/or minimal distribution losses (38).

The active network operation approach can similarly be applied at the medium- and low-voltage levels; however, the type of generation units and communication infrastructure differ significantly. Tap-changer transformers for low-voltage applications (39) are relatively new; they can be seen as one of the first products, apart from specially designed converters, being offered for distribution grids to specifically cope with distributed generation (40). To learn more about the actual conditions in low-voltage networks, monitoring systems that make use of existing communication infrastructure have been developed (41). Advances in PV converters have resulted in the first systems with interfaces to intentionally change the power factor or reduce the supplied power depending on the voltage at the connection point (42–44). Also, local battery storage in combination with PV inverters is often considered (45), but it is still very costly. There remain the questions of how to design a

Information security: protection of data against release to or manipulation by third parties; includes authenticity, integrity, confidentiality, availability, and nonrepudiation

distributed control system that can be deployed in thousands of low-voltage networks and how the system can be adapted with minimum effort for local conditions.

3.3. Smart Metering

The most well-known and prominently discussed smart grid application is probably smart metering. The main motivations for the introduction of smart metering are access to frequently automated meter readings as a base for time-varying energy tariffs and the expectation of further energy savings resulting from improved feedback about energy consumption to the consumer. A detailed discussion of the potential benefits for customers can be found in Darby's paper on smart metering (46). The smart meter is the direct contact point between the grid and consumers. Therefore, smart metering is often confused with smart grids, which is unfortunate because this significantly limits the notion of the smart grids. The first advanced metering infrastructures rolled out for businesses were developed to reduce energy theft and to disconnect bad-debt customers. A discussion of the effects on these so-called nontechnical losses by smart metering systems can be found in Reference 47. Today, further smart meter rollout is also pushed by national and/or international agendas (see, e.g., Reference 48).

Smart metering is predominantly an infrastructure topic when seen from a technical viewpoint. As with all smart grid applications, smart metering requires a dedicated communication infrastructure. To reduce installation costs when retrofitting millions of meters, wireless and power line communications are usually chosen for last-mile connections (49). European low-voltage grids usually have many (up to ∼200) customers connected to one low-voltage transformer station, making the distance from the transformer to the customers relatively large. Despite this, power line communication is chosen in Europe more often than in the United States, where only a few local customers are connected to a pole-mounted transformer, and therefore direct wireless connections are possible. In the American case, power line communication only makes sense if the signal is able to cross the transformers (50). A number of different power line communication standards have been developed and are still under development (overviews can be found in References 51 and 52). Dedicated smart metering protocols are usually narrowband and purpose specific. The convergence of smart metering infrastructures with other smart grid applications, such as active distribution grid operation or coordination of EV charging (see below), is an important issue for future research and development. It is unfortunate that many infrastructure rollouts for smart metering in the past have been made with a very narrow application focus.

Currently, the main concerns for advanced metering systems are security and privacy (see the section Information and Communication Technology for Smart Grids below). Although there is a constant research effort to obtain device identification from aggregated measurements (see Reference 53 for an overview) to obtain a breakdown of device-level energy consumption from meter readings, it is also important to find solutions that make transmitted meter data anonymous while maintaining essential information for billing purposes (54).

As a step toward the convergence of smart metering infrastructures with other smart grid applications, the concept of a smart grid gateway has emerged, mainly from a collection of German "e-energy" research projects. The smart grid gateway can be seen as the unified and universal interface between home area networks and existing last-mile communication, such as wired broadband access (55). Within the home area network, different smart grid–relevant appliances, such as metering, PV converters, heat pumps, or charging stations for electric cars, can be accessed. This smart grid gateway can be part of the smart meter itself or a dedicated device. In Europe, the standardization effort regarding the security of such a gateway is driven by the protection profile published by the German Federal Office for Information Security (BSI) (56).

3.4. Microgrids and the Security of Electricity Supply

Small power distribution systems, containing generators, loads, and usually some kind of energy storage, can be referred to as microgrids (57). Microgrids may have an optional connection to larger utility grids. Traditionally, microgrids can be found in isolated environments, such as islands and ships, or in remote areas not covered by public electricity infrastructure. With the advent of distributed generation from renewable sources, microgrids have also become a key concept for grid integration of renewables because locally consumed renewable power does not have to be propagated to higher network levels (58).

Power flows in microgrids are rather dynamic compared to the conditions in larger utility grids owing to the absence of statistical averaging effects. Thus, maintaining the stability of an isolated microgrid can be a challenging control task. For microgrids without a dedicated communication system for controls, individual controllers use frequency and line voltage as an indicator for the system state and typically implement droop-based controllers (59). However, for fine-grain power flow management and economic dispatch of generation units, dedicated communications ranging from power line to fiber communications are also used (57).

Of the numerous commercially or experimentally operated microgrids (see References 57 and 58 for overviews), most have rather specific purposes. In most cases, the aim is to manage the microgrid in such a way that it represents a single aggregated load (or generator) toward the supplying distribution grid, a strategy that is scalable and does not require configuration changes over many hierarchical levels when additional distributed generation units are connected (57). However, as long as these approaches are not reflected in the system's overall organization, they remain academic experiments. Microgrids can also provide special services to connected customers that utility grids do not support. These services include economic optimization, such as the maximization of self-supply (60), and the provision of an interruption-free electricity supply. The latter is often implemented in regions with lower availability of utility grid supply and also as a pilot strategy for electricity systems with a large share of volatile renewable generation. Examples include the Danish Cell Project (61, 62), where entire medium-voltage grids can disconnect and survive on local resources, and the Consortium for Electric Reliability Technology Solutions (CERTS) microgrid, where dedicated lines with different levels of supply security are provided in a low-voltage microgrid (58).

3.5. Supergrids and Large-Scale Energy Storage

It is a point of controversy whether supergrids count as a certain style of smart grids or as a competing concept. When connecting geographically distant regions (or even continents) by means of supergrid infrastructure, the resulting averaging effects make it easier to operate a system with volatile generation and loads. The required high-voltage transmission systems can be considered as physics-based technologies in contrast to a smart grid approach ("iron instead of bits") that focuses on innovative and efficient control and coordination (63). Although China plans to massively extend 1,000-kV AC and 800-kV DC transmission lines (63) to cover rising energy demand, the United States (64) is considering the supergrid approach for outage prevention, and the European Union (65) is considering it for wind integration. In Europe, the so-called Club of Rome has proposed a supergrid connecting northern Africa and Europe, potentially allowing the European Union to be supplied with renewable energy collected in African deserts (66). The likelihood of positive effects on the security of energy supplied in Africa is, however, strongly questionable (67).

The ultimate solution for the challenges that are currently driving the development of a wide variety of smart grid styles would be

DSM: demand-side management

DSO: distribution system operator

the availability of a cost-efficient option for large-scale energy storage. A recent study for storage-enabled large-scale wind integration for Ireland (68) has shown that, without considerable subsidies, even the most suitable storage technology—in this case compressed air (69, 70)—would be far from economically viable.

3.6. Electric Vehicles

The predicted increase in EV use leads to another new and powerful element in the energy systems: electric batteries. Whether the batteries are still in the car while attached to the charging pole, load only, feedback, or used during the "second life" phase, a large number of distributed batteries would provide a desirable degree of freedom in a smart grid.

There are numerous studies, simulations, pilots, and experiments to determine the potential of such batteries in a future smart grid. Unfortunately, every new generation of battery changes the game, and new calculations are necessary.

Vehicle-to-grid services can be categorized into those with an unchanged EV state (e.g., stays charging) or changing state (e.g., switches between charging and feeding into the grid) (71).

A crucial part of massive EV deployment is charging control. Callaway & Hiskens (72) show how to change the control of EV charging applications in the context of intelligent loads and demand-side management (DSM). Sundstrom & Binding (73) show an EV charging algorithm that satisfies grid constraints (voltage, power). Uncoordinated EV charging contributes massively to the morning and evening peaks, owing to the high statistical correlation of charging times with peak times. An EV aggregator, called charging system provider (CSP), charges each car individually and communicates with the distribution system operator (DSO) and the retailer. The CSP, in the simulated case (73), is capable of solving some of the grid problems occurring in the uncoordinated case as found in the first analysis, and further studies answering the following questions are necessary: How do multiple CSPs in a free market compete and/or cooperate with each other and the DSO? How do other grid participants pay for the benefits that the CSP's operations create?

Another example of an EV aggregator is given by Aabrandt et al. (74), presenting the well-known EDISON Project. The authors describe the mathematical background of predicting driving and charging behavior and an optimization method for minimizing charging costs.

Two barriers for plug-in EV participation in the smart grid are the costs of the charging post, especially in the feedback case, and interoperability of communication protocols. Morrow et al. (75) put the figure at US$2,000 per charger, depending on the type. The digital communications between the EV, charging post, grid operator, and utility need to meet certain standards (76) and to be secure. See "Information and Communication Technology for Smart Grids," below, for details concerning security issues.

An alternative to lifetime integration is second life usage: old EV batteries, connected to the grid and contributing to grid services. Cready et al. (77) identified four viable cases for the use of second life EV batteries: transmission support, light commercial load following, residential load following, and distributed node telecommunications backup power. There are, however, still unresolved issues, e.g., standardization, warranty, and the benefits for the original battery purchaser. Using current battery degradation rates and energy prices, Neubauer & Pesaran (78) show that second life use has low impact on (plug-in hybrid) EV investment costs. The number of such batteries—and the need to reuse them—will, however, certainly increase, so there is a need for research in battery lifetime management. It will be individual batteries, and not the entire pack, that will change its place from the EV to the second life use station in the cellar. It is, therefore, also necessary to determine the right time to pick the right battery. Interestingly enough, the dominating cost factor is often power electronics and not the batteries themselves.

4. THE DEMAND SIDE

Generation and network utilization (i.e., the relation between the installed capacity and its real usage) are sometimes below 50% (79) because the demand side does not permanently consume all of its theoretical load capacity. The supply side's answers to this demand/supply mismatch are its load-forecast-based unit commitment and economic dispatch, made a day in advance, and its more dynamic frequency control. Both can be complemented by the load side: For the demand/supply balance, reducing load has the same effect as increasing generation. Although peak generation capacity sometimes has a high share in total electric power provision (20% in the United States), its utilization is typically low [5% in the United States (24)], so the load side constitutes a competitive alternative.

Giving the load side an active role in energy systems has a number of advantages. Since loads are distributed, the demand side can sometimes react extremely fast (compared to some types of traditional power stations), so there is no need to install expensive and/or environmentally questionable equipment, like batteries or diesel aggregates, to dynamically back up particular branches of the power system (80).

It is, however, not that straightforward. Electric loads typically have a purpose based on some energy-consuming tasks (e.g., cooling a building, pumping water, welding a car) with timing constraints (e.g., predefined schedule, minimum output, incoming orders, reaction to environmental changes). For higher customer acceptance, load management is ideally nondisruptive, i.e., load interruption does not lead to a noticeable interruption or degradation of the customer's processes, such as maintaining indoor temperature or pump speeds (72).

DSM is the superset of all activities that one can do at the demand side to relieve the power system. This can range from energy-efficiency measures (replacing equipment with more efficient alternatives, adding insulation to the building shell) via time-dependent prices (predefined tariffs for peak and off-peak times) to DR, where the load side reacts to asynchronous events like dynamic price changes or emergency signals.

We distinguish between centralized, hierarchical, and fully distributed load control. A centralized topology has the advantage of clear decisions, but scales badly: It might be fine for a handful of industrial customers but will not work for hundreds of thousands of homes. This can be partly overcome using hierarchical load control, which is a cascade of centralized structures. One example of this is the so-called aggregator (72), which groups individual loads to one entity toward the DSO. Fully distributed control, by contrast, has the promise of self-organization but can also add another level of complexity that leads to unwanted stability problems.

4.1. Dollars versus Kilowatts

Influencing load side processes is not undertaken voluntarily. The loads have a job to do that is typically optimized toward performance or efficacy. Unless load reduction generates a value larger than the added value of the customer process itself, load management is not profitable.

Efficiency measures at the load side are the easiest to understand: The energy savings are input to a simple return of investment calculation. Time-of-use tariffs or dynamic pricing is slightly more complicated. The savings can be estimated only statistically.

This type of price response is, however, too slow for fast ancillary services (72) and other grid reliability programs. Direct load control is necessary, without humans or hesitating software agents in the loop. The grid operator (e.g., the DSO) offers a financial incentive for keeping a certain amount of shed capacity in reserve. Even if the sheds are not called upon, the reward is given. If the shed is called, it happens with a quick broadcast signal, and no negotiations are needed.

One of the first influential publications on intelligent energy resources and market-oriented operations is found in Reference 81. A market-oriented multiagent system for the private home (called Homebots) is presented. The agents use bids and auctions to find the optimum amount of energy consumption. In a simulation, the agents could optimize toward resources or prices.

Dynamic tariffs (7) try to forward fluctuating wholesale market prices to customers who are usually billed with a flat rate. Time of use is a soft variant of dynamic pricing and contains periods of low and high prices. Critical-peak pricing adds very high prices to certain events, typically known no more than 24 h in advance. Day-ahead pricing provides price changes in a periodic manner, using forecasts of weather, load, fuel price, and other items. The extreme case is real-time pricing, where wholesale market prices are simply forwarded on an hourly or subhourly basis. See Reference 82 for an overview of dynamic pricing prepared for the World Bank. With regard to introducing DSM programs to the above rates, Uhlaner et al. (83) add five additional levers: incentives, information, controls, education, and verification.

Demand elasticity is the ability of the consuming side to react to prices. Although easy in the automated case, humans in the loop typically create latency and availability problems with regard to the DSM potential. Sioshansi & Short (84) describe a study on wind power that is complemented by real-time pricing in the Electricity Reliability Council of Texas (ERCOT) system. Wind power periodically needs to be curtailed because of grid constraints. An elastic load side would react to low (wind) energy prices and consume that excess energy. Considering wind has no marginal generation cost, every used kilowatt-hour is valuable. The above study, however, is just a simulation. The elasticity of real customers can be much lower than assumed.

An additional factor that has to be taken into account when dynamic pricing is used for grid services is speculation. Consumers, system operators, and traders might end up in a "game theory" situation where one side tries to predict the moves of the other side. See Mohsenian-Rad & Leon-Garcia (85) for a study of online pricing where price prediction is used to schedule residential loads.

Rahimi & Ipakchi (86) discuss the industry drivers for smart grids, such as renewable resources, supply economics, and operational efficiency. Economic details on the DR programs are given. An example is the emergency DR program of the New York Independent System Operator, where US$500/MWh are provided for participating customers (typically commercial and industrial or aggregated residential customers).

There are complex macroeconomic implications if local automated control is added to loads. Stadler et al. (87) show that unimportant demand elements (cheap, flat) blend with important ones (expensive, steep) and result in a combined, aggregated economic demand curve that intersects the supply curve, which itself consists of cheap and expensive curve elements (i.e., power sources). Enabling both sides to economically dispatch their individual elements would lead to a self-stabilizing, classical market situation.

DSM is, however, just one part of a smart power system. Facts and figures on improving transmission or distribution network efficiency via DSM, reducing the generation margin, or enabling demand-supply matching via DSM are given in Reference 79. It is interesting that the value of DSM is determined by the rest of the generation in the system: Generation is categorized as low, medium, and high flexibility and assigned certain criteria and values. Strbac (79) describes the example of 26 GW wind power, which requires flexible generation to compensate for fluctuations in the wind power resource. The associated fuel costs are directly connected with the potential value of DSM in this system.

4.2. Automatic Load Management

As stated above, automatic load management is more reliable and quicker than the humans in the loop. Such automated systems typically leverage virtual storage characteristics: thermal inertia (heating or cooling processes), matter transport (conveyor belts, pumps, ventilation), and programmable loads (think of dish washers) (88). Heat pumps, especially in combination with phase-change material, provide perfect virtual energy storage behavior to balance fluctuating wind power (89). They can easily compete with traditional power stations that sometimes require several hours of response (synchronization) time.

A residential-sector pilot study in Norway (90) combined dynamic hourly energy prices, a time-of-use network tariff, automated water heaters, and a customer information system. The magnitude of the gained DR was on average 1 kWh per customer per hour. Equipping 50% of households with such infrastructure would lead to 4.3% coverage of the Norwegian peak load.

Cost factors for automated DSM are hardware, software, installation, communication, and maintenance of the system and its components. Choi et al. (91) describe a typical hardware/software combination to implement DSM and other energy management services in a smart home. The usual components are low-cost, communicating microcontrollers in a casing combined with high-power semiconductors. Depending on the system philosophy, the nodes are more or less distributed or centralized.

An interesting pilot project is described by Kiliccote et al. (92): Nonresidential customers (large retail stores, office buildings) were equipped with DR infrastructure to join the California ISO day-ahead nonspinning ancillary services market via bidding. Open automated demand response (OpenADR) (93) was used for communications, based on 4-s latency telemetry equipment. The system works without humans in the loop, which was the initial driver for developing OpenADR. On the load side, the telemetry equipment adjusts customer processes, e.g., a 4° Fahrenheit set point change of the air conditioning system.

Kok et al. (94) describe the PowerMatcher, initially a research project but now an established energy optimization product, used in the EcoGRID EU project (95). It is a multiagent-based system for distributed energy resource use optimization. It uses market-based algorithms for demand/supply matching and combines microeconomic principles and grid control aspects. The PowerMatcher allows for hierarchies in the power system, i.e., one node can represent the aggregated nodes "below" to the agent community. It works with a number of different agent categories that care for thermostat-controlled processes as well as for devices that shift and/or schedule electricity use or that store electricity.

Demand/supply matching: generation and consumption of power need to be equal at any given point in time

Kreutz et al. (96) discuss the impact of DSM to the residual load (feed in from green sources minus load) in Germany. Interestingly enough, this study investigates the use of heat pumps, EVs, and white goods as controllable loads, demonstrating one analysis of the residential sector. It presents two scenarios, one with nuclear withdrawal combined with investments into renewable energy sources, and another with even higher investments that would lead to frequent situations of 100% renewable energy in the grid. Customer satisfaction is achieved by first considering the invisible loads, such as heat pumps, before the adjustments in other loads.

One prominent player in automatic DSM is the Grid Friendly^{TM} Appliance Project (97): A small, embedded controller performs autonomous underfrequency load shedding. In a pilot, 200 residential thermal processes (cloth dryers, electric water heaters) in Washington and Oregon were equipped with this highly integrated chip in order to shed load when the frequency drops below 59.95 Hz. During the study, such events happened on average once a day and lasted from a few seconds up to 10 min. Only the heating elements of dryers were disconnected, leaving the dryer up and running during the shed. A complete disconnect would require an inconvenient reset and restart. As a result, the appliance owners did not notice the sheds. The controller had tolerance bands much narrower than those of the substation protection units that disconnect entire feeders in the event of underfrequency. As a result,

Supervisory control and data acquisition (SCADA): the traditional point-to-point communication infrastructure to monitor and control energy resources, e.g., substations

many situations were cleared by the soft controllers before the substation units noticed. An important detail is that the controller does not have two-way communication, which would help keep costs low.

DSM can also be implemented with demand-side generation technologies, such as microcombined heat and power systems (micro-CHPs) (98). The flexibility of micro-CHPs (which are easily controllable and usually combined with heat storage) makes them a perfect element in an intelligent energy system. A study by Houwing et al. (98) shows up to 14% savings with predictive model controls for micro-CHP-based DR. Molderink et al. (99) describe a case where a threefold combination of predictions (based on artificial neural networks), planning (implemented via dynamic programming), and real-time control manages micro-CHPs and batteries in home energy systems to automate the loads and respond to market information.

5. INFORMATION AND COMMUNICATION TECHNOLOGY FOR SMART GRIDS

As discussed above, ICT is crucial to smart grids. There are several very distinct flavors of ICT in an intelligent energy system, ranging from business processes (eBIX, trading) down to hard real-time control of distributed energy resources via supervisory control and data acquisition (SCADA), for example, IEC 61850. The dominating topic is interoperability because investors want to make sure that their equipment is still of use in some years in the future.

5.1. Traditional Information and Communication Technology Domains in Power Grids and Upcoming Hot Spots

In today's power grid operations, ICT systems are often still considered as secondary infrastructures, despite their technical advantages, such as allowing remote access to field devices and substations as well as metering data for billing purposes by businesses. Typical architectures start at operations centers, connecting the user interfaces of the SCADA systems via wide-area network connections, which are typically isolated from other ICT networks, such as a business local area network or the Internet with substations and associated field devices (sensors, switches, protection devices). A wide range of protocols are used within this architecture: Internet protocol (IP)-based automation protocols such as the IEC 60870-5 series within the wide-area network, Modbus, DNP3, IEC 61850 within substations, RS485, RS232, and field buses on the field level, as well as many others (100). There is, however, usually just a very simple paradigm on the application layer: Each data point is connected from its physical position like a virtual connection to the SCADA system.

Parallel to substation automation systems, dedicated infrastructure for remote metering (see Section 3.3. Smart Metering) and wide-area sensor networks, e.g., phasor measurement units (26), can exist. These systems are usually physically separated from each other for security and dependability reasons. Furthermore, at the control center level, many centralized IT systems exist for applications like billing and energy trading.

A number of ICT-related challenges have to be resolved in future smart grids, such as interoperability [see the common information model as an example (101)], security, and infrastructure costs. Most of these challenges are not caused by the centralized parts but happen at the interface between centralized and distributed control. First of all, the smart grid ICT system is far from being homogeneous. The IEEE Guide for Smart Grid Interoperability describes the smart grid as a system of systems (102). Many of the relevant subsystems already exist today. Others are currently emerging, driven by new smart grid uses (such as electric mobility operators or load aggregators). From the functionality point of view, there is a strong trend toward the interconnection of currently separated systems (e.g., metering infrastructure and grid operation networks) in order to use meters as field sensors. Also from an economic viewpoint, setting up dedicated infrastructures for different applications is not financially viable. Currently, the rollout of smart grid technologies is being held back by significant infrastructure costs. Multiple-use and modular extension capabilities are key factors to reduce investment costs and to avoid stranded costs. However, from a security and dependability viewpoint, this convergence of infrastructure is not always ideal; most discussions and contributions in the area of smart grids ICT are currently affected by the challenges of providing security and dependability.

5.2. Smart Grid Architectures Defining Smart Grid Domains and Their Interconnections

The first large-scale implementations of smart grid use are imminent today. The issues requiring attention are a common understanding of smart grid architecture, in general, and an understanding of ICT architecture, in particular. It is essential to know what particular interfaces a smart grid device, such as a novel controller, gateway, or smart meter, should have when designing the product. The "NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 2.0" (103) has been a major contribution of the National Institute of Standards and Technology (NIST). The report describes a conceptual framework for the smart grid, reviews existing and emerging standards, and, more importantly in this context, defines different smart grid domains, ranging from bulk generation via transmission and distribution to the customer domain, markets, service providers, and operations. Europe's standardization bodies CEN, CENELEC, and ETSI have—via the *M/490 EU Mandate* (104)—supplemented this by discussing distributed energy resources, which in the NIST model were only part of the customer domain, and arranged them in a three-dimensional model with the three axes: energy domains (generation, transmission, distribution, distributed energy resources, and customer premises), zones (from process and field levels up to operations and markets), and an interoperability dimensions (physical connections, protocols, functions, data models, and business layers).

5.3. Security, Privacy, and Reliability

Initial concerns about the cyber security of existing and future ICT infrastructure for power systems came up in the context of DR schemes in the United States. Substantial work has been performed by NIST with its Guidelines for Smart Grid Cyber Security (105), which analyzes the risks and provides a methodical framework that utility companies can use to develop strategies for effectively securing their ICT infrastructure. Subsequently, great effort is made to apply IT security techniques to power grid-specific ICT networks. Among others, Metke & Ekl (106) propose the use of key public infrastructure and trustworthy computing.

Giani et al. (107) show how trusted data from a small number of sensors can be used to tackle the issue of data integrity in grid monitoring and control. Wei et al. (108) analyze how to improve the state of the art in SCADA security by an integrated architecture, moving away from a security gateway toward a security service proxy solution. Chen et al. (109) show how protocol weaknesses can be used in attacks and how to analyze system connectivity by statistical means to estimate the potential damage that could be wreaked. Despite the large amount of research performed in the field, the smart grid security challenge is far from being resolved. Most work focuses on securing existing architectures because a fixed system model is required to perform a security analysis. For emerging smart grid architecture, building security into the design is imperative. There is no doubt that, even with advanced security architectures, there will always be a race between attackers and defenders, rendering smart grid security an ongoing process.

The introduction of smart metering systems has not only led to security issues but also to privacy concerns. Again, NIST has published one of the first conceptual works defining privacy issues for the smart grid domain and published the first recommendations (110). Four privacy dimensions are described: (*a*) privacy of personal information, (*b*) privacy of the individual, (*c*) behavioral privacy, and (*d*) personal communications privacy. Cavoukian et al. (111) argue that, as smart grid technology is currently in the development stage, now is the time to build in measures for ensuring privacy within the system. They propose a set of basic principles to achieve privacy by design in smart grids. Included are measures providing the proactive approach (prevent privacy invasion events before they happen) or end-to-end life cycle protection of private data (111). These or similar principles are now in the process of being applied to real-world metering systems. One example of this is the German "Protection Profile for the Gateway of a Smart Metering System" (56) (also see Section 3.3. Smart Metering). Best practices from conventional IT systems, known to ensure a high level of security and privacy, are transferred to power grid components in this and similar approaches. However, it has been found that this method will not automatically lead to a perfect solution. Still, a migration path from available and existing state-of-the-art components to a system with built-in privacy and security features has to be developed.

6. MODELING AND SIMULATION

Infrastructure topics, such as transport, water, or—in this case—energy, are usually associated with high costs. Wise decisions are, therefore, important, although the smart grid does not make them very easy. System complexity makes the consequences of certain subsidies, policies, planning, rules, or other guiding principles very hard to estimate. Modeling and simulation are the preferred tools to shed some light on this complicated matter.

Unfortunately, it is again system complexity that, in the case of smart grids, reaches a level where traditional modeling methods fail. If the system gets too large, existing modeling and simulation methods reach their limits. This is especially the case when the physical system is tightly interlinked with the digital world and associated markets (112).

The problems can be separated into two categories: multidomain problems and scalability problems. Analyzing modern power components requires submodels in several physical domains (e.g., thermal, mechanical, chemical, electromagnetic) (113) and also in completely orthogonal domains like discrete events (ICT), game theory (markets, agents), or stochastics (failures, weather). Combining these different domains is difficult as they have specialized problem-solving algorithms and languages that are not compatible with each other. See Faruque et al. (113) for a comprehensive overview of multidomain simulation possibilities. Although universal languages like Modelica (112) seem to approach the multidomain interoperability problem, the actual implementation, however, runs into the second problem category: scalability. This is because the energy systems can consist of a large number of individual, interacting components, and most multiphysics simulation engines are suited for simulating one single component. A potential solution to this dilemma is cosimulation, where specialized tools are combined to solve the problem.

Power hardware-in-the-loop testing is an extended version of power system simulation: Real components are part of the simulation run, fully interacting with the simulated parts (114). The advantage is that a component manufacturer can test their newly developed products in a variety of grid situations and topologies without expensive experimental installations. Such grid topologies can even be automatically generated, provided they meet certain criteria to make them plausible (115). The ICT part receives special attention for testing and verification, ranging from faults to attacks (116). In addition to electrical power and ICT (117), other domains can be integrated in hardware-in-the-loop environments. See Monti et al. (118) for an example where the hydraulic system from heat pumps was put into the simulation loop.

7. DEMONSTRATION PROJECTS

Numerous projects around the world are being carried out to demonstrate the feasibility of smart grid approaches with practical applications. Demonstration projects are often seen as key measures to bring smart grid technology into the field. They permit not only the evaluation of new technical concepts in real-life operations but also bring together scientists, industry, and utility companies. Potential innovative smart grid solutions for practical use can evolve from such cooperation. Wakefield (119) has studied the costs and benefits of smart grid demonstration projects and has proposed a method to achieve comparable results, which was later the basis for Giordano et al.'s report (120).

Demonstration projects usually aim to prove the feasibility of technical and sometimes nontechnical concepts in the field. These concepts typically include the following:

- Effects of large-scale renewable installations (see, e.g., References 12, 95, and 121)
- Smart grid techniques to handle grid integration of renewables (see, e.g., References 95 and 121–123)
- Achieving demand-side flexibility by technical or market-oriented means (see, e.g., References 93, 121, and 124–127)
- Improving security of supply, by cell or microgrid approaches, and of local storage (see, e.g., References 57, 62, and 121)
- EVs and their impact on mobility as well as distribution grids (see Section 3. Smart Grid Styles and Components)

Picking three smart grid demonstration clusters from around the world (without claiming full representation of them all by this selection), it can be shown that smart grids have indeed advanced beyond initial theoretical ideas.

The first example, which is no longer a demonstration activity, is the integration of DR measures into the daily grid operation in the United States. Mainly motivated by restricted generation, transmission, and distribution capacities, on the one hand, and strong demand peaks owing to ventilation and air conditioning, on the other, field tests conducted by Lawrence Berkeley National Laboratory (93, 127) and other institutions [see, e.g., Hammerstrom et al. (126)] have shown that DR is feasible even in an open-loop control fashion without direct feedback from the field resources. To utilize the >10% US peak load reduction potential, a growing DR industry has evolved (128).

The next examples are the early and also recent PV- and microgrid-related demonstrations in Japan. In cities, such as Ota City, Wakkanai, Tomamae, and in the Aichi prefecture, wind and PV installations combined with battery storage systems have been implemented in recent years by NEDO, the Japanese New Energy and Industrial Technology Development Organization (121). Prevention of unintentional islanding and voltage rise has been tested, as well as grid-connected and isolated microgrid operations (121). Noro et al. (123) present a recent battery approach to suppress short-time power variations at Wakkanai. The work of Shen et al. (125) shows that DR will also play a key role in Japan. These projects have demonstrated that large-scale PV integration is possible. However, given the current cost of batteries and the complexity of operation, the role of battery storage is still an open issue.

Third, European demonstrations aim for large-scale grid integration of renewables, with focuses on generator-side measures determined by new grid codes, active network control, and DSM. The Danish island Bornholm sets the scene for a local real-time energy market, EVs, and high wind penetration with the project EcoGrid EU (95). The market approach and clustering of distributed generators in virtual larger power plants are also used in many German e-energy projects as described by Hollinger & Erge (124). In addition, North Sea wind demonstration projects, projects coping with large-scale distributed hydropower (129), and PV (12) can be found. These efforts have shown that balancing renewable supply and demand by means of grid exchange is economically advantageous over a storage solution, but the necessary grid extension is a challenge in itself. Smart grid technologies can help here, especially at the distribution level.

8. COSTS, RISKS, AND LIMITATIONS

Smart grid technology is new and, as yet, expensive. There are, however, some cases where smart grid management has substituted conventional grid reinforcement (i.e., "investment into copper") with intelligent controls that exploit the existing infrastructure better. Growing distributed generation in Austria led to overvoltage events in some feeders, making grid investments necessary (129). A smart tap-change transformer, plus some smart, communicating inverters were much cheaper than upgrading an entire feeder, leading to a dramatic cost reduction (or capacity extension of about 30%) compared to the traditional solution (130).

A cost-benefit analysis and business models for EV management in a smart grid are given in Reference 131. Market models and billing concepts for private, semipublic, and public charging as well as for battery swapping and other options are analyzed and presented. The most promising model is private charging owing to its low investment costs. Urban settings, however, might not allow private charging posts for everyone. Public charging (where some authority offers the charging infrastructure) is connected to high investments but has the benefit of professional personnel. By contrast, semipublic charging (where anyone can offer a charging station) would enable competition among the charging providers, assuming charging interoperability. Costs are often dominated by the space necessary for the charging post. Authorities are therefore requested to offer that space for a fee that is transparent, stable, and low. The potential business models vary. The aggregator can certainly engage in the business via trading and hedging products and risks. Ancillary services also have a potential market, depending on the local regulatory framework. Vehicle-to-grid transfer, i.e., feeding energy back when the grid is low in generation, does not make business sense under current market and battery situations.

The magnitude of the costs for smart grid functions, and who has to bear these costs, as analyzed by Barth et al. (132), also depends heavily on regulatory issues. If renewable energy is not part of the conventional power market (e.g., Germany), the power balance costs are carried by the system operators (i.e., their customers). By contrast, if renewable generation participates in conventional power markets (e.g., United Kingdom), the energy producer has to make allowances for renewables.

Gellings (3) provides a comprehensive analysis and report on the costs associated with the introduction of smart grids in the United States. As an update of an earlier report for the same purpose, it exposes significantly higher costs, since as the expectations of the smart grid have evolved and increased, so did the costs. The report systematically analyzes the costs of transmission systems, substations, flexible alternating current transmission systems devices, cyber-security measures, distribution systems, controllers, inverters, EV charging infrastructure, electric storage, and many other elements that are necessary when implementing a smart grid. It also includes the expected benefits, such as avoided power station investments owing to improved energy efficiency and DR. The earlier report concluded similar annual investment costs as blackout and power quality–related costs (~US$150 billion per year) (133). The updated report talks of investing ~US$20 billion per year for the next 20 years, with a final benefit-to-cost ratio of 2.8 to 6.0. The benefits, therefore, outweigh the costs significantly. The majority (two-thirds) of these costs lies in the distribution part of the smart grid. The questions of the distribution and visibility of these costs are discussed in a variety of ways in different countries. During an initial period of 10 years, the energy bill of private and commercial customers would be 10% higher than now, whereas industrial customers would just face a 1% higher bill during that time (3).

The anticipated challenges can be categorized into procedural challenges (a broad set of stakeholders, cyber security, standards, smooth transition, etc.) and technical challenges (data management, various software applications, smart equipment, communication, etc.) (3). There are also regulatory challenges as the smart grid positions society in an entirely new setting, where highly competitive and flexible markets are possible, everyone can participate, and new generation technologies keep entering the stage.

9. CONCLUSION

Considering the amount of research in the area, and the number and size of successful demonstration projects worldwide, the term smart grid relates to far more than a short-term technological fad. Smart grids are the key innovation in the area of electric power systems that bring today's infrastructure in a position to cope with the challenges of dependable and efficient electricity supply using renewable energies. Globally, smart grids will not immediately come into existence. The transformation from traditional power systems to smart grids is a long process, which progresses at different rates in countries with different priorities, rendering large opportunities for a lively interplay between industry, research, and infrastructure operators. Already today, combined knowledge of power and information systems is a key competence for a new field of education and employment.

Technological development is always a balance between demand for technologies and new ideas. Consequently, the different styles of smart grids outlined in this article have reached different levels of maturity. Technical developments in the area of smart grids include certain interdisciplinary aspects and require collaboration between different fields of study, such as power engineering, IT, economics, law, and other social sciences. Despite this complication, the exchange between the different disciplines has worked very well so far. One of the reasons for this might be that people involved in smart grid research and development are motivated by the strong societal impacts of smart grids. Unfortunately, outside the technical community, there is still very little awareness of the implications of increasing energy use and the role smart grids can play in the sustainable transformation of energy systems. The question of who should pay for today's smart grid to offset substantially higher future societal costs has yet to be answered.

SUMMARY POINTS

1. Renewable energy sources require a smart and active grid to make maximum use of the existing grid infrastructure.
2. The demand side will become an active player in the energy system in order to be able to cope with fluctuating generation.
3. Cyber security plays a major role in smart grids; it requires not only encrypted communication channels but also life-cycle considerations.
4. Centralized and decentralized control and generation structures will coexist. Existing systems will not be replaced but enhanced.
5. There is no smart grid without some improvements for business. One of the primary business models for implementation involves the reduction of infrastructure costs.

6. Integration of previously separate functions is key to cost reduction.
7. Regulations and policies need to be specifically adjusted for optimal implementation conditions for the smart grid.
8. The transformation into the smart grid has already begun.

FUTURE ISSUES

1. How can we provide full cyber security for smart grids, which not only protects an insecure system but is based on an intrinsically designed secure architecture?
2. How can interoperability of ICT systems and components be assured? This is a particular challenge owing to the vast number of different systems that will potentially be interconnected in the future and the need for data privacy.
3. Markets with electronic, automatic participants might show unwanted behavior if they are not self-stabilizing. How can we design a fair, transparent, stable and optimizing energy market for energy producers and consumers?
4. Advanced control methods for grid operation will be based not only on local control loops but also on remote measurements and distributed control techniques. Therefore, stability analysis of smart grid applications will play a major role in upcoming smart grid research.
5. Energy systems that consist of many very different and autonomous components tend to get complex. How can we describe, analyze, and optimize such heterogeneous systems?
6. Development of smart grid components supporting active grid operation is underway. The testing of such networked ICT and power hardware components is still an issue. Therefore, topics such as power hardware in the loop and cosimulation of power grids and communication systems will be an important area of research.
7. How can regulatory incentives make renewable energy attractive? And how can the technical measures to enable grid integration of renewables be financed?
8. The social aspects of smart grids are yet to be analyzed. Although this has already started, there are many unanswered questions. Also, the public awareness of smart grids and their societal benefits has to be improved.

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