Decentralized Intelligence in Energy Efficient Power Systems

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Abstract Power systems are increasingly built from distributed generation units and *smart* consumers that are able to react to grid conditions. Managing this large number of decentralized electricity sources and flexible loads represent a very huge optimization problem. Both from the regulatory and the computational perspective, no one central coordinator can optimize this overall system. Decentralized control mechanisms can, however, distribute the optimization task through price signals or market-based mechanisms. This chapter presents the concepts that enable a decentralized control of demand and supply while enhancing overall efficiency of the electricity system. It highlights both technological and business challenges that result from the realization of these concepts, and presents the state-of-the-art in the respective domains.

Key words: smart grid, demand response, distributed generation, decentralized control, load shifting

1 Introduction

In an electricity system with increasing shares of fluctuating generation and of flexible loads, centralized power system optimization has limitations in terms of scalability, actuation speed, security and robustness to failures. Besides, there is no central entity that has information about all generation, load and grid components and who could take over the central coordinator role. Well-designed decentralized coordination mechanisms, in contrast, are less vulnerable to attacks or random failures at a central location and can react more quickly and reliably to local conditions. One

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of the major challenges facing future electricity transmission and distribution grids is the question of how to integrate the fluctuating renewable electricity generation, both from decentralized and from centralized supplies. This requires greater flexibility in voltage maintenance and efficient load flow control than in present electricity systems. On the other hand, with electric vehicles, a new type of load becomes part of the electricity landscape. By their characteristics as mobile electricity storage devices, they can contribute to stabilizing the grid, if they bring their charging patterns in line with the supply side, or even feed electricity back into the grid in critical peak situations.

Information and communication technologies form the basis for realizing an intelligent electronic network of all components of an electricity system. The higher connectivity enables generating units, network components, usage devices, and electricity system users to exchange information among each other and align and optimize their processes on their own. This forms the basis of a market-oriented, service-based, and decentralized integrated system providing potential for interactive optimization. Bi-directional communication flows can go down to the household level, where home energy management systems and smart meters optimize the energy usage of residential customers and commercial buildings, enabling them to reduce their energy consumption or to avoid using electricity during peak load times, thus preventing critical system situations.

The challenge in a smart grid as envisioned in this context partly lies in establishing the device connectivity within households and buildings, and the bi-directional communication infrastructure between the houses and the grid or the energy service company. Commonly agreed standards form the basis for a convenient integration of new appliances into the local energy management system that can interact with the smart grid. However, at least equally important are the applied control mechanisms that deliver value to all parties involved – i.e. the energy retailer or energy service provider, the grid operator, the metering company and the end-customer – and that respect the privacy and flexibility concerns that the customers have. The decision on which appliance operates at what time should be with the energy consumer as much as possible. It should, however, be guided through incentives to behave in a way that is beneficial for the overall energy system efficiency. Market-based mechanisms and price signals are promising ways to combine the two objectives of maximizing energy efficiency and user comfort at the same time. These are, therefore, reviewed in this chapter, along with other concerns that must be regarded when applying decentralized control mechanisms, e.g. privacy and security.

The remainder of this chapter is structured as follows: Section 2 sets the basis for the discussion in the subsequent sections by describing the changes that power systems are undergoing currently and in the near future. In Section 3, different possible options of decentralized control in power systems are presented. Sections 4 and 5 then discuss the technological and economic challenges, respectively, that arise with the development of today's power systems towards a smarter grid. Section 6 finally summarizes the findings and concludes.

2 Trends in Power Systems

Besides the developments stimulated by policy and regulation measures in different countries, three major trends can be observed that considerably change the framework of the electricity sector: the still ongoing restructuring or liberalization process that forces integrated utilities to unbundle their activities, thus disintegrating the energy value chain (Section 2.1), the new loads that have to be integrated into the electricity system, in which electric vehicles might play the most prominent role (Section 2.2), and the increasing share of renewable generation, especially from fluctuating sources such as wind power and photovoltaic plants (Section 2.3).

2.1 Restructuring and the Disintegration of the Value Chain

The traditional integrated planning of electricity generation and transmission has become obsolete as a result of liberalization and the unbundling of the electricity value chain.[1] From former vertically integrated regional monopolies, a separation of generation, transmission, distribution and retail supply has been mandated. The generation and retail supply parts of the electricity value chain are subject to competition. On the generation side, generating companies compete for selling power to the wholesale markets. On the retail supply side, energy service companies buy on the wholesale markets the electric power that they need to serve their retail customers. The power grids, i.e. the transmission and distribution systems, are regarded as natural monopolies. They are operated by transmission and distribution system operators, respectively, who are regulated and monitored by a responsible governmental authority. Where possible, competitive elements are introduced into this regulation.

The changed regulatory environment is placing greater demands on the energy system's data networks. Following the disintegration of the electricity value chain, different actors along the value-added chain must now communicate and interact using joint interfaces. Furthermore, new rules on standardization, metering, and consumer transparency generate large amounts of data, which require intelligent, automated processes.

Due to the fundamental changes in constraints, it is essential to maintain the functionality of the power grids. This will require, for example, that the transmission grids have a much higher degree of flexibility in the area of voltage maintenance and efficient load flow control than has been the case to date. The fact that the – partly contradictory – requirements are becoming increasingly and ever more complex means that we must strive for integrated, system-wide innovations to the power supply system.

[1] In Europe, electricity sector liberalization was introduced through the Directive 96/02/EG of the European Union [9].

A well-developed power grid plays a key role in a liberalized energy economy. Through increased power trading and the use of renewable energies, the requirements have already changed considerably today. Whereas these were formerly operated using interconnections spaced far apart, mainly to increase system stability, they now increasingly serve to transport loads across long distances. With a change in the electricity system topology, i.e. due to new generation locations in, e.g., offshore wind parks, this trend will continue to gather force. Major restructuring measures and new operating concepts will thus become indispensable.

New requirements are also emerging on the level of lower-voltage networks. Medium- and low-voltage networks, in which network automation has so far not been installed to a large extent, have more and more difficulties to cope with the requirements posed by the increased integration of decentralized generation facilities. In addition, the continual increase in the demand for power will push the well-developed distribution networks to the limit of their load capacity. Although the networks would be able to absorb additional loads in the medium term, peak loads that depend on the time of day are creating problems not only for the power generation companies. Optimizing the daily load flow can help to avoid expensive investments that are needed only for a few hours each day. Therefore, in the future mechanisms are needed that allow for shifting demand in accordance with economical grid operation criteria. In the future, efficient load management of the power grid will, thus, also have to take into account the requirements of the distribution networks and involve all market players, down to private customers.

2.2 Continued Electrification and Electric Mobility

Global electricity demand has always been rising in the past decades, and is projected to continue to do so in the future [13]. This pattern is observable not only at the global level, but also at all regional and most national levels. As, in many cases, electric appliances allow for a more efficient use of energy to provide the desired final energy service (such as heating by heat pumps, motion by electric motors, light from efficient LEDs etc.), a more sustainable energy system would require even higher shares of electricity in relation to other energy carriers such as liquid fuels or natural gas [18]. Electricity grids are thus facing the connection of new consumption devices in the future, constituting a considerable additional load.

While electric vehicles have been developed since decades, and have been hyped as the future mobility solution several times in the past, there is reason to believe that the current enthusiasm for the use of battery electric vehicles, and also of plug-in hybrid electric vehicles, is sustainable. Announcements of policy-makers and car manufacturers in Asia, Europe, America and elsewhere suggest that relevant stakeholders see a viable future for electric cars, and that these will gain a significant share of the overall car fleet within the next decade. Examples for current electric car promotion initiatives are the planned U.S. “Electric Vehicle Deployment Act of

2010" or the EU "Roadmap on regulations and standards for the electrification of cars", and further national support schemes.

If a significant number of plug-in (hybrid) electric cars are plugged to the grid simultaneously, this imposes a considerable additional stress to the power grid, especially at the distribution level. In order to avoid costly investments into the physical grid infrastructure, intelligent algorithms need to be developed that balance the load caused by car charging events. These algorithms would animate cars to charge preferably when renewable energy is available or when the overall load is low, thus avoiding massive car charging during peak demand. Through such algorithms, car batteries could be used as storage devices in the grid, which are able to serve as buffers for capturing renewable energy supplies and for optimizing the load profiles. They could even re-inject power into the grid in order to level out demand peaks, thus delivering *Vehicle-to-Grid* services [15].

2.3 Decentralization and Renewable Generation

Driven by the need to reduce the dependency on fossil fuels, political and economical pressure are fostering the use of renewable resources and increased efficiency in the generation of usable energy, most importantly electricity and heat. Technology is being pushed by large investments into research and engineering. The market for generation based on renewable resources is the fastest growing branch in the energy sector. The United States have adopted the Energy Independence and Security Act of 2007 [26], which does not demand detailed action about the generation of usable energy, but tries to foster increased efficiency in the consumption of energy. Instead, progress in the generation based on renewable resources shall be honored, and grants for innovation projects are given. The European Commission has issued guidelines for achieving and measuring energy efficiency on the national level in its Directive 2006/32/EC as of April 5, 2006 [10].

Renewable generation is a key element in achieving a truly sustainable energy supply. Wind and solar power are the most important of these technologies, outperforming geothermal energy, tidal power generation and other technologies.

Renewable resources are inherently volatile. Their total power output might be sufficient to provide for demand, but sufficient availability is limited to certain times. Therefore, renewable power generation must be complemented by storage capabilities as well as backup systems and demand side management. Storage of electrical power is still very expensive, although electric car batteries could provide some storage capacity (see Section 2.2). Demand side management is depending on shiftable loads, which can be deferred to times of high production without significantly hampering the consumer. Thus, the major part of complementing volatile renewable power falls on backup systems.

For backup functionality, especially systems for decentralized generation are well-suited. These facilitate many desirable characteristics of modern energy systems. One important quality is the resilience against outside threats (e.g. terrorism), which is facilitated by the good isolation properties of decentralized systems, which allow the isolation of (accidental or induced) faults. Another important quality is the high level of efficiency in the use of primary energy. Combined heat and power (CHP) plants can deliver 90% and more of the used primary energy (natural gas, biofuel) to the consumer, in the form of electricity and heat.

In order to establish an energy system with a high degree of decentralization, the political and economical framework must be provided. An increase in decentralized generation diminishes the (economic and political) power of big power providers, shifting profits from traditional utilities to smaller businesses. Such a prospect is likely to spark resistance, which has to be overcome by emphasizing the greater societal benefit of a decentralized infrastructure.

Power generation based on renewable resources complemented by decentralized generation (also by fossil fuels) seems like the perfect pair for achieving energy efficiency on the production side. Technical and societal challenges have to be addressed, however, before they can become the new gold standard for an electricity infrastructure.

3 Decentralized Coordination in Power Systems

With increasing numbers of decentralized generation, it becomes more difficult to ensure the efficiency, reliability and security of power supply. Real-time communication between the grid components, allowing generators and consumers to become an active part of the system can be a way of balancing the grid. However, it can be assumed that a direct control of electrical appliances through a grid operator or an energy service company will not be acceptable for the end user, especially not for private households.

More intelligent alternatives deliver price signals or incentives to customers who can then optimize their energy consumption based on these inputs. We assume that prices and payments or fees are the best way to make generators and loads produce and consume in a way that contributes to overall system efficiency. Price-based coordination can be realized through time-varying tariffs, such as time-of-use rates or real-time pricing (Section 3.1), or through dedicated payments to loads and generating units that turn a device on or off at the request of a coordinator (incentive-based mechanism, Section 3.2). A more radical implementation of this would be to let all loads and generators participate in a market mechanism to which they submit bids at any time. The decision to switch a device on or off would then be bound to the market result (Section 3.3). These concepts are described in the following.

3.1 Time-of-Use and Real-Time Pricing

An electricity tariff for end customers today typically comprises a fixed monthly customer charge and a variable energy charge for the amount of electricity consumed [7]. The energy charge is usually a fixed rate per kWh, independent of the time at which electricity is consumed. While this is comfortable for the customer, who can easily predict energy costs (by multiplying the fixed unit price with the units consumed), it hides the information of how valuable electricity is at different points in time. Consumers, thus, have no incentives to avoid consumption at times of expensive generation, and shift it to less expensive time slots.

Energy retailers have to ensure that the consumption of their customers is constantly matched by equal generation. In most European countries, retailers have to make sure that the energy amounts bought and sold are balanced within every 15 minute time interval. The most common strategy to ensure this balance is to apply structured procurement, a three-phase process with narrowing time horizon (see Fig. 1). Each procurement phase can be supported by energy exchanges or can be carried out bilaterally between generators and retailers (over-the-counter – OTC – trade).

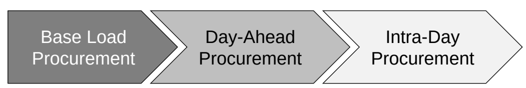

Fig. 1 Three phase procurement process

In the first phase, a retailer estimates the cumulative base load of his customers (i.e. the lowest load they exhibit in the long term) and usually buys generation of this load for months or even years in advance at a discount price. The second procurement phase would be day-ahead trading. By knowing details of the next day's events, he will create a detailed consumption forecast for his customers for the next day. Events could be e.g. the weather forecast (influencing both the consumption and the amount of renewable energy generated), local and regional holidays, or a deviation from regular demand that has been pre-announced by a larger business customer. The forecasted consumption that was not already covered by the base load will be procured in the second phase on energy markets. If it becomes evident during a day that the energy procured is insufficient or exceeds the load in a given slot (as the result of an incorrect forecast), blocks of energy can still be bought and sold in the intraday market, the third procurement phase.

Eventually, the retailer pays a different price for the energy delivered in each 15 minute time slot (resulting from the payments for each of the three phases of procurement). Since this price variability usually is not reflected in end customer's tariffs, the retailer conservatively sets a high price in order to cover his costs, to guard against risks, and to secure his desired margin.

With the introduction of time-of-use pricing or real-time-pricing, i.e. time-dependent prices per energy unit, the electricity retailer can hand over parts of the markets' price fluctuations to the end-customer. With time-of-use (TOU) pricing, fixed time intervals are defined in which different prices are valid. These intervals usually reflect long-time experience of when electricity is more expensive to procure and when it is less expensive, and the prices for each TOU block are fixed for long-term periods. The most common time-of-use pricing is *on-peak* and *off-peak* rates; however, more fine-grained TOU blocks are possible. If the pricing for different consumption time intervals changes frequently and is announced on shorter notice, i.e. day-ahead or even within a day, this is referred to as real-time pricing (RTP). An example for real-time pricing with day-ahead notice is the *Bi-directional Energy Management Interface* as presented in [21].

Hybrids of time-of-use and real-time pricing are also conceivable; they usually referred to as *Critical Peak Pricing* [27]. These concepts have a basic rate structure like in TOU pricing combined with a provision for replacing the normal peak price with a much higher critical peak event price under specified trigger conditions (e.g. when system reliability is compromised or supply prices are very high).

Time-dependent pricing of electricity consumption leads to two benefits. The more obvious one is that this will lead to higher efficiency. The reason for this is market prices accurately reflect the current supply and demand situation. In times of high supply and low demand (e.g. on a windy and sunny Sunday morning) energy is abundant and prices will be low. In this situation it would be good to trigger time-shiftable consumption events (like turning on washing machines or cooling down deep freezers) and turn down conventional consumption from fossil or nuclear sources. In the opposite situation where energy is scarce and market prices are high, the signalization of the high price to the user will motivate him to abstain from avoidable consumption. The higher the price on the market, the more economically inefficient generation equipment will be activated.

The second benefit is more indirect. The distribution of long-term trading vs. day-ahead vs. intraday is strongly inclined towards longer-term trading, i.e. most of the trading is made long in advance. [2] If price risks could be handed over to end customers, more retailers would probably choose to engage in more short-term trade. Given the fact that volatile generation from wind can be predicted very accurately in a time-scale of three to four hours ahead, this would lead to prices highly correlated with renewable generation, which would ensure the most effective incentive for customers to adjust their load to the current supply of renewable generation. Generally prices are expected to be lower, as indicated by consumer behavior on the Norwegian retail market, where approximately three-quarters of consumers have entered into some form of variable retail-price contract (such as a spot-market contract or a standard variable power-price contract) [4].

Flexible pricing, especially in the form of real-time pricing, also has its disadvantages. From the perspective of the consumers, it exposes them to a higher risk and makes forecasting of energy costs less predictable. Looking at the global system, some experts anticipate avalanche effects: At time of extreme prices, many customers may choose to adapt their consumption (or have automated systems that act

[2] To give an example, in Germany day-ahead and intra-day trading volumes at the European Energy Exchange currently only account for roughly one quarter of the total national power consumption [8, 12].

accordingly), leading to overcompensation and reversal of the situation. However, this can also be seen as normal market events that are only a problem if such short-term changes affect system stability. Generally, the probability of avalanche events might be low, since not all consumers adapt at the very same time and incentives to adapt become more and more unattractive as the extreme price converges to a usual price level as the first consumers adapt.

3.2 Incentive-Based Load Control

Incentive-based demand response programs give customers load reduction incentives that are separate from, or additional to, their retail electricity rate, which may be fixed or time-varying. The load reductions can be requested by the grid operator in order support his task of maintaining grid stability. They can also be activated by an energy service provider when prices are very high. Most demand response programs specify a method for establishing customers' baseline energy consumption level, so observers can measure and verify the magnitude of their load response. Examples for such incentive-based curtailment programs are given in the following [27].

- Demand bidding – in which customers offer bids to curtail their loads based on wholesale electricity market prices or an equivalent.
- Capacity market programs – in which customers offer load curtailments as system capacity to replace conventional generation or delivery resources. Customers typically receive day-of notice of events. Incentives usually consist of up-front reservation payments.
- Ancillary services market programs – in which customers bid load curtailments to the grid operator as operating reserves. If their bids are accepted, they are paid the market price for committing to be on standby. If their load curtailments are needed, they are called by the grid operator, and may be paid the spot market energy price.

It must be noted that the regulatory framework of a specific country may hinder the establishment of one or more of these incentive-based mechanisms. In addition, they are usually only practically feasible for large consumers, such as industrial or large commercial sites.

3.3 Market-Based Coordination

Centralized wholesale trading at power exchanges has established since many years, because it offers high liquidity and it delivers valuable price information to the energy sector [28]. As there are multiple generators and consumers in the energy market, the dominant market institution for electricity trading is the double-auction format. In a sealed bid double-auction, both buyers and sellers submit bids specifying the prices at which they are willing to buy or sell a certain good. Buying bids are then ranked from the highest to the lowest, selling bids from the lowest to the highest bid price. The intersection of the so formed stepwise supply and demand functions determines the market clearing quantity and gives a range of possible prices from which the market clearing price is chosen according to some arbitrary rule [19]. Double-auctions deliver efficient allocations if the number of sellers and buyers is sufficiently large [29].

While the efficiency of wholesale power markets is generally assumed, market-based mechanisms usually do not play a role at the retail level. However, concepts have been formulated to apply market-based coordination for the intelligent operation of virtual power plants or aggregations of distributed generation units or of flexible loads down to the household level, e.g. [11, 16, 17]. These concepts are motivated by the formal proof that the market-based solution is identical to that of a centralized omniscient optimizer, without requiring relevant information such as local state histories, local control characteristics or objectives [1]. The equilibrium price resulting from the market mechanism is, thus, used as the control signal for all units.

In a typical application of market-based coordination for power system scenarios, there are several entities producing and/or consuming electricity; extending the mechanism to allow for combinatorial trade with complementary products, such as natural gas or heat, is not considered here. Each of these entities can communicate with a (centralized) market mechanism. In each market round, the control agents create their market bids, dependent on their current state, and send these to the market. A market is generally defined by three components: a bidding language, which specifies how bids can be formulated, a clearing scheme, which determines who gets which resource, and a payment scheme, which defines the payments the individual users have to make depending on the allocation [23].

The bidding language defines the preferences that an agent can reveal to the market. Bids in a power system market can, e.g., be Walrasian demand functions, stating the amount of the commodity $d(p)$ the agent wishes to consume or generate at a price of p, where a positive and negative amount can be interpreted as consumption and generation, respectively [16]. Bidding languages can also allow for specifying technical constraints, such as minimum levels of generation/consumption, or for expressing how valuation changes depending on time. However, more expressive bidding languages usually lead to higher complexity and may also require the bidder to reveal more (private) information than she wants. Thus, market mechanisms in power system scenarios usually rely on restricted bidding languages, like the example given above.

After collecting all bids, the market agent searches for the equilibrium price, thus defining which agent will buy/sell which amount of electricity.

In practice, one challenging problem when implementing market-based control in real-world applications is to define the agent's policies for defining the bids. These policies differ between different types of appliances. Six different categories of appliances can be defined that can participate in the market [16]:

- *Stochastic operation devices*, where the timing and amount of output cannot be controlled. Examples: fluctuating generation such as wind energy converters or photovoltaic systems
- *Shiftable operation devices* that run for a certain duration, where the starting point can be shifted over time. Examples: washing, drying or ventilation processes
- *External resource buffering devices* that display a storage characteristic without direct electricity storage. Examples: heating or cooling processes
- *Electricity storage devices* such as batteries, capacitors. Examples: electric cars
- *Freely-controllable devices* that can be flexibly deployed within certain limits. Examples: thermal power plants
- *User-action devices* whose operation is defined by the user's needs and desires. Examples: lighting or entertainment devices

The bidding strategies must always take their specific characteristics into account.

4 Technological Challenges

The emerging smart grid is expected to be very much dependent on modern information and communication technologies (ICT). As near real-time communication and information dissemination among all entities is of key importance, a number of technologies that can be integrated into existing processes and enhance them or even provide innovative new services, has been identified. However, in order to realize them, key challenges will need to be adequately tackled. The following subsections provide an overview of the main technological issues related to smart metering (Section 4.1), interoperability and standardization (Section 4.2), real-time communication (Section 4.3), distributed data management and processing (Section 4.4) and security and privacy (Section 4.5).

4.1 Smart Metering

The true power of smart grids can be realized once fine-grained monitoring i.e. metering of energy consumption or production is in place. Real-time pricing or market-based operation, for example, can only provide incentives for the user to shift loads if her consumption is measured in small time intervals and billed with the according variable tariff. The promise of an advanced metering infrastructure (AMI) is that it will allow provide measurements and analyses of energy usage from advanced electricity meters through various communication media, on request or on a pre-defined schedule. These are usually referred to as *smart meters* and can feature advanced technologies. Today, many utilities have already deployed or are currently deploying smart meters in order to enable the benefits of the AMI. One example is the world's largest smart meter deployment that was undertaken by Enel in Italy, with more than 27 million installed electronic meters. AMI is empowering the next generation of electricity network as envisioned by, e.g., [3, 24] vision.

Smart meters will be able to react almost in real time, provide fine-grained energy production or consumption info and adapt their behavior proactively. These smart meters will be multi-utility ones and will be able to cooperate, and their services will be interacting with various systems not only for billing, but for other value added services as well [14]. Smart meters provide new opportunities and challenges in networked embedded system design and electronics integration. They will be able not only to provide (near) real-time data, but also process them and take decisions based on their capabilities and collaboration with external services. That in turn will have a significant impact on existing and future energy management models. Decision makers will be able to base their actions on real-world, real-time data and not on general less well-grounded predictions. Households and companies will be able to react to market fluctuations by increasing or decreasing consumption or production, thus directly contributing to increased energy efficiency.

4.2 Interoperability and Standardization

The smart grid is a vast ecosystem, composed of a large number of heterogeneous systems that have to interact in order to deliver the envisioned functionality. Up to today, the heterogeneity was hidden in islanded solutions. However, the opening up of the infrastructure as well as the high complexity of the new introduced concepts mean that interoperability will be the key issue that needs to be addressed. Several standards exist today, although many of them still require revisions, especially when it comes to the inter-operation with other standards and systems.

In a recently released report, the U.S. National Institute of Standards and Technology, NIST, provides an overview of standards and problems that will need to be tackled [22]. The priority areas where standards need to be developed and interoperability is required are:

- *Demand response and consumer energy efficiency*, i.e. mechanisms and incentives for electricity generators and consumers to cut energy use during peak times or to shift it to other times (concepts described in Section 3).
- *Wide-area situational awareness*, i.e. monitoring and display of power-system components and performance across interconnections and over large geographic areas in near real-time.
- *Energy storage*, which today mainly consists of pumped hydroelectric storage, but can also be millions of *electric car* batteries in the future.
- *Advanced metering infrastructure* as described in Section 4.1.
- *Distribution grid management*, which focuses on maximizing performance of feeders, transformers, and other components of networked distribution systems and integrating with transmission systems and customer operations; as smart grid

capabilities, such as AMI and demand response, are developed, and as large numbers of distributed energy resources and plug-in electric vehicles are deployed, the automation of distribution systems becomes increasingly more important to the efficient and reliable operation of the overall power system.

- *Cyber security*, which encompasses measures to ensure the privacy protection, integrity and availability of the electronic information communication systems and the control systems necessary for the management, operation, and protection of the respective energy, information technology, and telecommunications infrastructures.
- *Network communications* – given the variety of networking environments used in a smart grid, the identification of performance metrics and core operational requirements of different applications, actors, and domains in addition to the development, implementation, and maintenance of appropriate security and access controls becomes more and more important.

As in all standardization activities, a great effort is needed in order to develop and actively maintain standards via a collaborative, consensus-driven process that is open to participation by all relevant and materially affected parties, and not dominated by, or under the control of, a single organization or group of organizations [22].

4.3 Real-Time Communication

The systems concerned with the physical parameters of the grid always require real-time communication. If generation and consumption do not match, the quality parameters of the electricity delivered (like voltage and frequency) immediately deteriorate. This is why, already today, real-time systems constantly monitor electricity flows and other parameters, and automatically take action when detecting an unusual situation.

Unlike these critical core systems that ensure the physical stability of the grid, the more or less virtual trading layer on top of these systems only takes an *ex ante* and *ex post* view. The *ex ante* view, i.e. the trade phase until a certain deadline before physical execution of generation and consumption, ensures that the expected generation will match the expected consumption. During the execution phase, the trading systems are not involved in the effort maintaining grid stability. Only *ex ante*, i.e. after execution, the actual generation and consumption is assessed and the trading systems do the accounting. Unfortunate retailers that deviated from their announced schedule in the direction that harmed grid stability are punished. As an example, if there was not enough supply and a retailer's contracted generators generated less than announced or his customers consumed more, the retailer would have to pay penalties. The more lucky ones that deviated in a way that stabilized the grid would not pay penalties.

This strict distinction between trading and technical systems is challenged by new systems like market-based control, as explained in Section 3.3. This leads to challenges for the current vendors of today's trade systems, who are usually not familiar with real-time software engineering.

4.4 Distributed Data Management and Processing

As already motivated in the introduction, the operation of the electricity system is such a huge optimization problem that it cannot be solved centrally. The complexity can be handled by simplification and aggregation, and by pushing processing to the edge of the network. All the paradigms shown in Section 3 manifest in systems that do little coordination centrally and let most of it be done at the edge. The central controlling unit merely sets a price or an incentive and lets the end user (or an automated system on his behalf) decide how to react to the external stimuli. Core to all these systems are home, office, or factory gateways that receive the external signals. They have built-in, customizable logic that triggers if-then rules, e.g. if the price is below a certain threshold, then shiftable devices start operating.

There might be one scenario, however, where it makes sense to propagate and apply a central decision right down to a single device: the charging of plug-in (hybrid) electric vehicles. This scenario delivers the highest benefit if controlled centrally and executed strictly according to the central decision (of cause taking user preferences like his or her desired time of full charge into account). We base our judgment on the following assumptions: (1) a given topological area of the low-voltage distribution grid cannot support simultaneous charge of a car fleet that is highly electrified, (2) the possible time window for charging is longer than the time window needed to charge a single car battery, (3) users have set a desired mileage and the time it should be made available in the car's battery, (4) user preferences are communicated to a system that is responsible for the topological area, (5) the charging schedule for each car (i.e. the load curve needed to charge the battery) is known and communicated. If all these assumptions are valid, coordination of loading start points by the central system is an alternative to deploying more conductive material (i.e. new power lines) that is expected to come with a far lower price tag.

An alternative to direct control could be market splitting, leading to different prices in different topological areas of the grid, as transport line capacity is considered when matching demand with generation. This is also a general approach to consider physical capacity limitations in the economics of grid operation.

4.5 Security and Privacy

The trends (see Section 2), the paradigm changes in end-user market participation (see Section 3) and the enabling or implicated technological changes (see Section 4) necessitate development of new security and privacy measures and a review of the existing ones. Security and privacy of the used IT systems and protocols ensure trust in the market itself and therefore form an important factor for its successful operation.

In this section, we derive the security and privacy challenges that are implied by the emerging organizational and technical changes described in this chapter.

4.5.1 New Paradigms in Energy Trade and their Security Implications

New paradigms in the implementation of energy trade will cause significant implications for the involved systems' security:

The most apparent change is that communication between customers and suppliers of energy will become bidirectional. Before, consumers of energy reported the amount of used energy to their supplier once a year. With the emergence of time- or load-dependent or incentive-based tariffs prices, incentives or other coordination activities (see Section 3) have to be communicated back to the customer. In turn, the customer negotiates parameters or reacts to the received signals by adapting his electricity usage or generation. The utilized IT-systems must account for the resulting security and privacy implications: Data transmitted to the customer is highly sensitive as it influences the customer's behavior and is relevant for billing. Therefore, its integrity, authenticity and non-reputability must be ensured, allowing the customer to verify the received data's soundness.

The decentralized coordination approaches mentioned in Section 3 might involve another significant change in how communication works in the smart grid: Automated communication relationships with quickly changing heterogeneous partners will emerge. As customers will also become providers of services (control of appliances, reduction/increase in energy consumption), they can potentially have energy related communication relationships with multiple parties. Market-based coordination might even implicate that those parties are not fixed over time but change rapidly. Ensuring authenticity of a communication partner and ensuring integrity and timeliness of communication in such systems is not trivial to accomplish neither by organizational nor by technical means.

The mobility of energy consumers (see Section 2.2) represents another paradigm change and opens up a whole new field for IT. The mobility requires an authorization and billing infrastructure that features high-availability and confidentiality and potentially spans several countries or whole continents. The actual charging procedures and systems must ensure that neither involved parties can commit fraud (charging point operator by simulating a charging procedure, the customer by repudiation, supplier by claiming false charging records) nor that outsiders threaten the acceptance of electric vehicles by attacking the availability/credibility of the system.

The previously mentioned more frequent and bi-directional communication (see Section 4.5.1) implies that a huge amount of privacy-related data will be accumulated. This is also new for a field where, at least for consumers, only few data was gathered throughout a year. Smart meters will accumulate and transfer data that can be used to create personal profiles [25] of residents and can be subject to national data privacy laws. It can even be used to deduce the individual use of appliances [2].

Electric mobility creates information about the position of past and future charges that could be used for extortion (husband at unambiguous location) or industrial espionage (employee of company Y at headquarters of company X). It is crucial that architectures (or organizational measures) that are developed for the handling of this data account for its importance and prevent leakage of data to unauthorized parties and ensure retention times longer than necessary.

4.5.2 Requirements for Secure and Privacy-Preserving Energy Systems

All areas of the energy sector, from generation over transmission and distribution to consumption, will eventually be connected technologically in order to foster efficiency by communication and more cooperation. The necessary overarching architectures will probably face security challenges that are very hard to predict. It is safe to say that it will face the same challenges that all distributed systems face with regard to security.

Large-scale identity management measures can pose one building block to enable grid-wide trust relationships and to tackle the security problems associated with bi-directional communication, frequently changing heterogeneous communication partners and with the mobility of communication partners. The solutions to cope with the huge amount of privacy related data will certainly be twofold: Technologically, data gathering and sharing must be mitigated as far as possible while the remaining risk must be minimized organizationally.

However, the solutions to the aforementioned problems look like the move from previously confined devices with limited external interfaces to networking systems increases the resulting attack surface of the whole system significantly. In turn, this leads to the requirement that all software which is created must be designed and implemented using state-of-the-art secure software processes, to avoid potential implementation level vulnerabilities [20] as otherwise, software insecurities could expose the systems. For instance, [6] documented a buffer overflow vulnerability in a smart meter firmware. Based on this finding, it was demonstrated that this vulnerability could enable an adversary to create a bot-net like structure on these devices via self-replicating malware. A scenario in which an attacker fully controls a large number of smart meters could lead to potentially serious consequences.

In addition to secure development practices, properly defined processes for secure and timely software updates of all rolled-out devices are needed for risk mitigation. The sheer number of potentially affected devices will probably rule out on-premise updating of defective firmwares. Consequently, reliable mechanisms for updates over the network have to be investigated. This, in turn, requires sound proof of the authenticity and integrity of the transmitted firmware which has to be done via code-signing.

In addition to the security challenge, it is also very hard to create such a system to be safe and reliable in the first place. Reliability and safety are two attributes that, at least in history, have always been very high priorities for electrical grid operators but are also very heavily dependent on security.

One point that should be stressed here is the following: When the smart grid is fully realized, it will probably be the largest logical network of embedded devices (charging cars and smart meters), control systems (ICS) and traditional IT systems with a real impact on our everyday-life [5]. This means that a failure of such a system, how ever it was produced, would lead to a complete standstill of our society, unlike with similar networks (mobile phones, the Internet). Containment strategies in terms of organizational and technical means have to be devised in order to limit the impact range of attacks (security) or failures (safety).

5 Economic and Business Challenges

Distributed energy generation systems are usually located in close proximity to the actual consumption of the energy required and can be supported by storage or demand side management measures. Due to the close proximity additional energy i.e. thermal energy can be utilized, further losses through distribution and transmission are reduced making these systems overall often more efficient than central energy systems. In contrast, distributed energy systems operate at a much smaller scale, possibly making the marginal price for a single kilowatt-hour (kWh) more expensive than as this would apply for a central energy system. As production unit numbers of small scale systems increase these systems are becoming more and more economic to operate. Looking alone at the marginal price for a single kWh is in many cases not sufficient. Extended related energy applications for distributed energy systems take a further approach by providing more than an analysis of the marginal price perspective. As the systems are installed locally, many challenges of the past can now be tackled with greater precision on this local level. This includes the following: energy security concerns (power availability), power quality issues, tighter emissions standards and possible transmission and distribution bottlenecks.

The cost effectiveness of any power system can generally be characterized by comparison of revenue generated and costs involved. The aim of any business venture can be defined as to maximize profits. Especially for the energy sector investments in capital assets are involved with a high degree of initial investments. Furthermore, these assets have a long depreciation which makes it specifically important to best understand the capital streams involved over the lifecycle of such a system. The approach should be to look at economic viability of power systems by means of the cash flow involved, allowing to use valuation methods based on discounted cash flows.

For the involved stakeholder investing and operating, this party is interested in a capital return on his investments, whereas in a broader sense the opportunistic costs shall also be taken into comparison. Typical questions that need to be answered upon investing in such a power system as described above can be rendered as follows:

- Which kind of costs arise (prime costs, maintenance, commodities, site, emissions, etc.) ?
- When do they arise and how can they be valued?

- How long can the assets be utilized?
- What is the finance structure of the investment?

For methods of how the investment can be financed this involves the following possible sources of initial or continues capital streams:

- Sales of energy feed into the electric grid
- Avoided costs for grid access
- Opportunistic costs of energy that would have been utilized otherwise.

The challenge of realizing decentralized control mechanisms as described in Section 3 is that potential benefits are distributed across the whole value chain of electricity delivery, whereas under the impact of unbundling, single companies may only be active in one or two of these activities. If overall benefits can be gained by a technology, but the party that has to invest into it is not the same as the one who is profiting most from it, regulation must step into the game and set the framework in a way as to give incentives for the former party.

6 Summary and Conclusion

Power systems are currently undergoing considerable changes. In order to be able to accommodate the growing number of fluctuating renewable generation, the current consumption-driven generation pattern must make room for the opposite paradigm, i.e. a generation-driven consumption. Through flexible demand that can react to the scarcity situation (in real-time) generation, it can be possible to avoid large investments into stand-by power plants that balance out the fluctuations caused by renewable sources and into expensive grid-reinforcements, all along with safeguarding a high level of security and reliability of supply.

This flexible reaction to different grid situation requires several prerequisites. First, information about the grid status needs to be made available consumers and prosumers in order to make them aware of what the best times for their consumption and generation is. Second, customers also need incentives to behave in the desirable way, as given by the grid status. This involves detailed measurements of consumption and generation feed-in in for small time intervals, and a variable pricing scheme that pushes low and high prices down to the customer. Some possible ways of designing such pricing schemes or mechanisms that involve the customers more actively are described in this chapter.

Besides, a safe and interoperable communication infrastructure that allows for bi-directional communication between different actors within the electricity system is needed. It must also be ensured that the customers' privacy is preserved. At the economic level, it must be ensured that companies in different parts of the value chain can profit from an investment into the enabling technologies required for the necessary transition of the energy system. This may require a change in regulation or policies, and it also requires creativity for discovering new business models in the changed framework.

All these aspects have been discussed in this chapter, and were put into relation to the trends that can be perceived in today's energy systems.

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