Intelligence in Electricity Networks for Embedding Renewables and Distributed Generation

J.K. Kok, M.J.J. Scheepers and I.G. Kamphuis

Abstract Over the course of the 20^{th} century, the electrical power systems of industrialized economies have become one of the most complex systems created by mankind. In the same period, electricity made a transition from a novelty, to a convenience, to an advantage, and finally to an absolute necessity. World-wide electricity use has been ever-growing. The electricity infrastructure consists of two highly-interrelated and complex subsystems for commodity trade and physical delivery. To ensure the infrastructure is up and running in the first place, the increasing electricity demand poses a serious threat. Additionally, there are a number of other trends that are forcing a change in infrastructure management. Firstly, there is a shift to intermittent sources: a larger share of renewables in the energy mix means a higher influence of weather patterns on generation. At the same time, introducing more combined heat and power generation (CHP) couples electricity production to heat demand patterns. Secondly, the location of electricity generation relative to the load centers is changing. Large-scale generation from wind is migrating towards and into the seas and oceans, away from the locations of high electricity demand. On the other hand, with the increase of *distributed generators* (DG) the generation capacity embedded in the (medium and low voltage) distribution networks is rising. This form of generation is relatively small in individual capacities, but (very) high in numbers. Due to these developments, intelligent distributed coordination will be essential to ensure this critical infrastructure runs efficiently in the future. As compared to traditional grids, operated in a top-down manner, these novel grids will require bottom-up control. As field test results have shown, intelligent distributed coordination can be beneficial to both energy trade and active network management. In future electricity infrastructures, these functions need to be combined in a dual-objective coordination mechanism. In order to exert this type of control, alignment of power systems with communication network technology as well as computer hardware and software in shared information architectures will be necessary.

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1 Introduction

In the year 1888, Nikola Tesla presented his “New System of Alternate Current Motors and Transformers”, laying the foundation for today’s electricity infrastructure. Tesla’s ‘new system’ made it possible to transmit electrical power over long distances and to use one single infrastructure for all power delivery. Previously, generators needed to be located near their loads due to highly-inefficient transmission. Furthermore, multiple electric lines were needed for each application class (lighting, mechanical loads, etc) requiring different voltage levels. Over the course of the 20^{th} century, the electrical power systems of industrialized economies have become one of the most complex systems created by mankind. In the same period, electricity made a transition from a novelty, to a convenience, to an advantage, and finally to an absolute necessity. World-wide electricity use has been ever-growing. Especially, three major trends are accelerating its growth [2]:

- The rapid expansion of world population – the growth in the number of people needing electricity.
- The “electrification of everything” – the growth in the number of devices that require electricity.
- “Expectation inflation” – the growth in the sense of entitlement that turns electrical conveniences into essentials demanded by all.

The impact of these factors can be seen in Table 1 showing some related growth trends.

Table 1 Examples of Electricity Growth Trends [2]

Category	1950	2000	2050 (est.)
World Population	2.6B	6.2B	8.3B
Electricity as % of total energy	10.4%	25.3%	33%
Televisions	0.6B	1.4B	2B
Personal Computers	0	500M to 1B	6B to 8B
Cell Phone Connections* (USA)	0	0.8B	5B
Electric hybrid vehicles	0	55,800	3M

B = billion; M = million.

*Including machine to machine connections, e.g.: telemetering and telecontrol.

The worldwide electric power generation is expected to grow 2.4% a year at least until 2030. In spite of this relatively small annual increase, world electricity generation nearly doubles over the 2004 to 2030 period – from 16,424 billion kiloWatt hours (kWh) in 2004 to 30,364 billion kWh by 2030 [5].

In this chapter we will look into the electricity infrastructure, its peculiarities, its highly interrelated subsystems for commodity trade and physical delivery, and the intelligence that is essential to ensure this critical infrastructure runs efficiently in the future. To ensure the infrastructure is up and running in the first place, the ever-increasing electricity demand poses a serious threat. Additionally, there are a number of other ongoing changes in the electricity system that are forcing a change in infrastructure management. Firstly, there is a shift to intermittent sources: a larger share of renewables in the energy mix means a higher influence of weather patterns on generation. At the same time, introducing more combined heat and power generation (CHP) couples electricity production to heat demand patterns. Secondly, the location of electricity generation relative to the load centers is changing. Large-scale generation from wind is migrating towards and into the seas and oceans, away from the locations of high electricity demand. On the other hand, with the increase of *distributed generators* (DG) the generation capacity embedded in the (medium and low voltage) distribution networks is rising. This form of generation is relatively small in individual capacities, but (very) high in numbers. These are, for example, medium and small-sized wind turbines, domestic photo-voltaic solar panels, and CHPs in homes and utility buildings. A large part of this chapter focusses on how to keep the balance between demand and supply in these future power systems.

In Section 2 we describe some of the peculiarities of electricity and its infrastructure. In Section 3 the cohesion between the physical infrastructure and the commodity markets is described, while Section 4 treats the changing nature of electricity generation and the implications for infrastructure management. Section 5 describes coordination intelligence for electrical power systems, its requirements, the ICT technologies available to meet these and a specific dedicated implementation: the PowerMatcher. The chapter ends with a description of two field experiments (Section 6) and an outlook into an architecture for intelligent multi-goal coordination in electrical power systems (Section 7).

2 On the Special Nature of Electricity and its Infrastructure

Electricity is an example of a *flow commodity*: physical flows that are continuous, i.e., the commodity is (virtually) infinitely divisible. Other examples of flow commodities are physical streams in the gas or liquid phase such as natural gas, industrially-applied steam and water for heat transport or drinking. The continuous nature of flow commodities makes their infrastructure behavior fundamentally different from infrastructures transporting discrete objects such as cars or data packets. On top of which, electricity and its infrastructure has some peculiarities not found in any other infrastructure. In the following we will dive deeper in the electricity system's special features.

2.1 Power Loop Flows

The (greater part of) current electricity networks are passive networks, there is no way of directing the flow to follow a particular path. Instead, the commodity follows

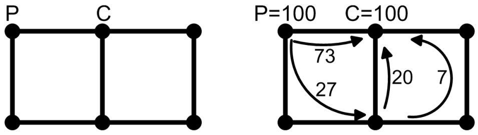

Fig. 1 Power loop flows in an electrical network. *Left*: simple example electricity network with six nodes and seven lines. At node *P* electricity is produced, at node *C* it is consumed, while the other nodes are passive. *Right*: the physical flows resulting from producing 100 units at node *P* while consuming the same amount at node *C*. The (resistance) characteristics of all seven lines have been chosen equal, while, for the sake of the example, transport losses have been neglected.

the path of least resistance, possibly using a number of parallel trajectories. This may cause unexpected *power loop flows* as is shown in Figure 1.

This behavior has great implications for network planning and day-to-day operations of the grid, for instance. To illustrate this, consider the lines in Figure 1 and suppose each of the seven lines has a maximum capacity of 73. Then, although the total sum of line capacity between nodes *P* and *C* would be 146, the transport capacity from *P* to *C* would be limited to 100.

In December 2004 and January 2005, such a loop flow nearly caused a black-out in Northwestern Europe. An unexpected surplus of wind energy in the North of Germany flew to the South of that country via the neighboring grids of The Netherlands and Belgium. The Dutch operator of the transmission network needed to take special measures to ensure the stability of the network.

2.2 Contract Paths and Transport Paths

In *directed* networks, such as those of road transportation and packet-switched information flows, the transport path follows the contract path quite closely. In the field of logistics, for instance, a specific post packet shipped to a particular destination will, if all goes well, arrive at that location. In contrast, in electricity, the contract path does not dictate the actual flow of the commodity, as is shown in Figure 2.

This has special implications for the way management is done in the electricity system. There are two separate sub-systems with limited interaction: the physical infrastructure and the electricity markets. We will delve deeper into this separation in Section 3.

2.3 Absence of Infrastructure-inherent Storage

Unlike many other infrastructures, in electricity, there is virtually no storage or buffering of the commodity in the network itself. In an electricity network, the supply/demand balance has to be maintained at all times to prevent instabilities,

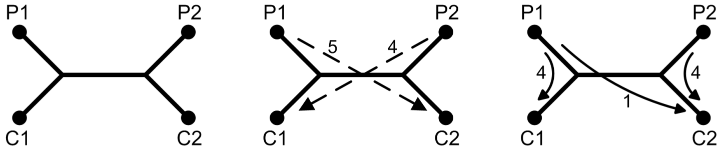

Fig. 2 Contract paths and transport paths in electricity. *Left*: simple example electricity network with two producers (P1, P2) and two consumers (C1, C2). *Middle*: two possible contract paths: P1 sells an amount of 5 to C2, while P2 sells 4 to C1. *Right*: the resulting physical flows. Only 1 out of the 9 produced units flows physically to the contracted customer. In spite of this, all actors meet their contractual obligations. Note that the flows in the right subfigure are the result of the *superposition* of the contracted flows. For the sake of the example, transport losses have been neglected here.

which would eventually result in a black-out. On a timescale of seconds, some infrastructure-inherent storage is present due to the rotating mass in power plant turbines. The inertia of this mass allows for small deviations in the momentary supply demand balance. However, these small deviations need to be compensated for on a seconds to minutes timescale to prevent the system sliding towards a black-out.

Consequently, electricity needs to be produced at exact the same time it is consumed. This is a feature unique to electricity. In Section 3.4 we will discuss the implications of this characteristic for the interaction between network management and electricity markets.

3 Electricity Networks and Electricity Markets

The special nature of electricity has consequences for the way the highly-complex electricity systems of developed economies are organized. One important consequence is the separation between commodity trades and network operations, both performed in two separate sub-systems with limited, yet crucial, interaction.

3.1 The Electricity System

The term *electricity system* is used to denote the collection of all systems and actors involved in electricity production, transport, delivery and trading. The electricity system consists of two subsystems: the physical subsystem, centered around the production, transmission, and distribution of electricity, and the commodity subsystem, in which the energy product is traded.

Figures 3 and 4 present a model[1] of the electricity system. In this text, the financial flows that result from the electricity trade are referred to as the commod-

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[1] This model and its description is adapted from [21], Section 3.1.

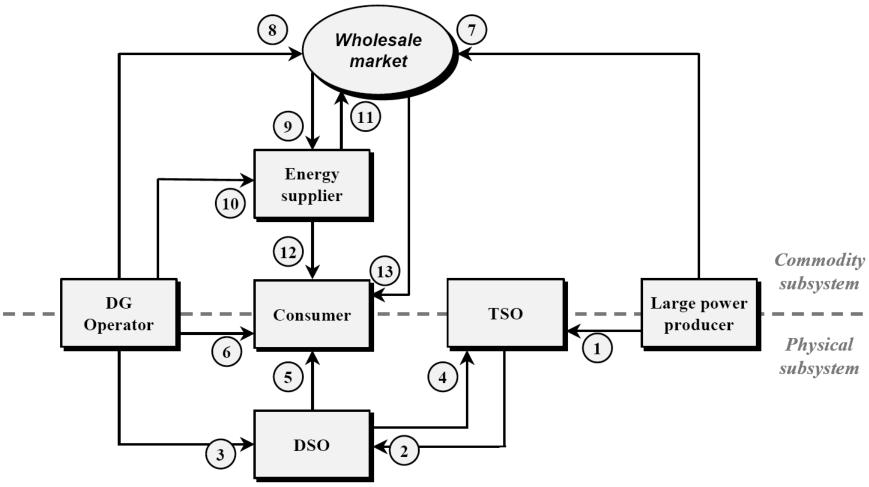

Fig. 3 Overview of transactions within the electricity market [21].

ity transaction, to distinguish it from transactions related to the physical electricity flows. In the figures, the physical and commodity subsystems have been separated. Note that the two subsystems are related but they are not linked one to one. A generator with a constant output may have fluctuating revenues as a result of variations in market price. Both subsystems need to operate within certain technical and regulatory constrains, such as safety limits, construction permits, operating licenses and emission permits for the physical sub-system, and competition law and market rules for the commodity subsystem. It is important to note that in the figures, for simplicity, different actors of the same type (such as different DSOs) are aggregated into one presented actor.

In the liberalized electricity market, several relevant parties can be distinguished (parties and their definitions are based on European regulations [14]):

- The *producer* is responsible for generating electricity (large power producers, as well as DG-operators who produce electricity with small-scale distributed generation).
- The *transmission system operator* (TSO) is responsible for operating the transmission system in a given area and, where applicable, its interconnections with other systems. It ensures the long term ability of the system to meet reasonable demands for the transmission of electricity. To carry out these responsibilities, the TSO ensures the maintenance and, when necessary, the development of the transmission system. In this context transmission stands for the transport of electricity on the high-voltage interconnected system, the transmission grid.
  The TSO is also responsible for providing system services in his control area. System services consist of balancing services (i.e., compensating the difference in the demand and supply, see also Section 3.4), reserve capacity (i.e., compen-

sating shortfall in power generating capacity), power quality (e.g., frequency control), reactive power supply, and black start capability.

- The *distribution system operator* (DSO) is responsible for operating the distribution system in a given area and the connections to the transmission grid. It ensures the long term ability of the system to meet reasonable demands for the distribution of electricity. To carry out these responsibilities, the DSO ensures the maintenance and, where necessary, the development of the distribution grid. In this context distribution means the transport of electricity on high-voltage, medium voltage and low voltage distribution systems with a view to its delivery to customers, but not including supply. The DSO is also responsible for system services, e.g., power quality.
- The *supplier* is responsible for the sale of electricity to customers (retail). Producer and supplier can be the same entity but this is not always the case. A supplier can also be a wholesale customer or independent trader who purchases electricity with the purpose to resell it within the system.
- The *final customer* purchases electricity for their own use and, in a liberalized market, is free to purchase electricity from the supplier of their choice. For different functions (lighting, heating, cooling, cleaning, entertainment, etc.) the final customer uses different electrical appliances.

3.2 The Physical Subsystem

The physical subsystem consists of all hardware that physically produces and transports electricity to customers, as well as all equipment that uses the electricity. The structure of the physical subsystem is determined by the nature of the components that make up the electricity supply system: generators (large power producers and DG operators), transmission network (TSO), distribution networks (DSOs) and loads (consumers) [4]. The physical subsystem is depicted in the lower part of Figure 3. The large power producers generate electricity that is fed into the transmission grid. Relation 1 represents the (regulated) agreement between the large power producer and the TSO. The power producer pays a *connection charge* (and sometimes also a *use of system charge*) for the transport of the produced electricity to the DSOs (2), who in turn, distribute it to the final consumer. Relation 5 represents the payment of the connection and use of system charges by the consumer to the DSO for the delivery of the electricity and system services. The figure shows that electricity generated by DG operators is directly fed into the distribution network based on a (regulated) agreement between the DSO and the DG operators (3). The DG operator pays a connection charge and sometimes also a use of system charge to the DSO for electricity transport and for system services. Most of this electricity is then distributed to the consumer by the DSOs (5), but due to the growing amount of DG capacity, a local situation can occur in which supply exceeds demand. In this case the surplus of electricity is fed upwards into the transmission grid (4), after which the TSO transports it to other distribution networks (2). The last relevant physical stream concerns the auto-production of DG electricity (6). This is the direct consumption of electricity produced on-site by a consumer, omitting the commodity purchase and sales process through the energy supplier.

3.3 The Commodity Subsystem

In contrast with the physical power streams, the economic transactions related to the commodity flow are merely administrative and depicted in the upper part of Figure 3. Its goal is an efficient allocation of costs and benefits, within the constraints imposed by the physical system. The commodity subsystem is defined as the actors involved in the production, trade or consumption of electricity, in supporting activities or their regulation and mutual relations [4]. The commodity subsystem controls the physical subsystem, but is constrained by it at as well. Large power producers (7) and some large DG operators (8) offer the commodity on the wholesale market, where the commodity is traded between different actors. Large electricity consumers (e.g., industrial customers) can buy the commodity directly on the wholesale market (13). Next to those consumers, energy suppliers buy commodity in the wholesale market (9) on the basis of wholesale contracts to serve smaller consumers. The trade on the wholesale market provides a payment for the produced electricity. Additional to the wholesale market trade, the energy supplier extracts the commodity directly via (small) DG operators (10). The energy supplier subsequently delivers the commodity from the wholesale market and the DG operators to the consumers (12) who pay for it. As energy suppliers are often ‘long’ (i.e., they have contracted more commodity than they plan to offer to consumers), there is a commodity stream backwards to the wholesale market (11). Therefore, the energy supplier is a third party trader that offers commodity to the wholesale market.

In the situation that the energy supplier has accurately forecasted the actual amount of electricity which his consumers use, the received payment for the commodity (12) perfectly corresponds to the amount of delivered electricity (5). However, deviations from forecasted use or planned generation often occur, and, due to the failing of the mechanism to balance supply and demand on the short-term, they create the need for an additional short-term balancing mechanism.

3.4 The Balancing Market

System operators and contractors have to estimate demand in order to make sure that sufficient supply is available on short (seconds and minutes), medium (hours), and long (days, months, years) timescales. As the electricity system is liberalized, the market itself is responsible for matching supply and demand on the long and medium terms. As stated before, the electricity supply (output from all generators including import) must be controlled very closely to the demand. This has to be

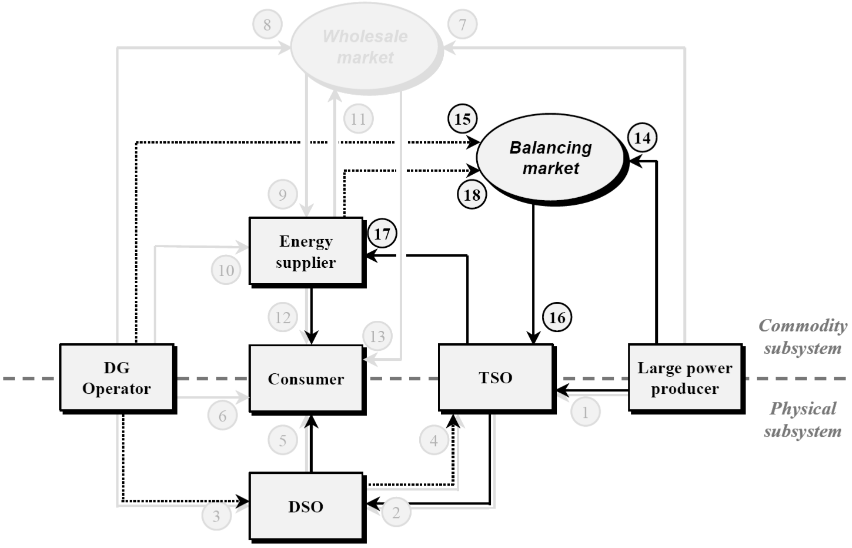

Fig. 4 Overview of transactions within the electricity market, including the balancing market [21]

maintained on the timescale of seconds. Maintaining the short and medium term balance is the responsibility of the system operator, which for this purpose uses forecasts of electricity production and demand which are submitted by market players (called energy programs or physical notifications). Deviations between electricity demand and production during the actual moment of execution of the energy programs become visible to the TSO as an exchange of electrical power with neighboring control areas, different from the agreed international exchange programs (involuntary or unintentional exchange). In this way the TSO has insight in the actual balance of the total system. In the case of shortage, the system is balanced by producing additional electricity (upward adjustment of production units) or making use of demand response (i.e., lower consumption). In the case of a surplus, production units are adjusted downwards.

In many European control areas the liberalization of the energy market has led to the establishment of a separate balancing market, apart from the wholesale and retail market. This market is controlled by the TSO, being the sole buyer. Access to the supply side of the balancing market is mainly limited to the large power producers, but DG operators (in particular large CHP-units) and energy suppliers also have access. Figure 4 shows the impact of the balancing market. The transactions that are less common in existing electricity markets are shown with dotted lines. As soon as a situation of shortage arises, the TSO corrects this by buying the lowest priced commodity offer in the balancing market (16). Most offers come from the large power producers (14), but sometimes DG operators offer electricity as well (15, CHP units), just as energy suppliers (18). The TSO charges the energy supplier(s) which caused the imbalance (17) on basis of the (relatively high) price that it has paid on the balancing market. In the case of a surplus of produced electricity, the TSO accepts and receives the highest bid in the balancing market for adjusting generating units downwards. Also, in this case, the energy supplier(s) pay the TSO so-called imbalance charges. Handling these imbalance charges is arranged in the energy contracts between all market players, but mostly energy suppliers are responsible for the demand of their contracted consumers and contracted DG-operators. Therefore, the energy supplier must pay the balancing costs in case there is a deviation of the forecasted use of its consumers or forecasted generation of its contracted DG operators. If a large power producer does not comply with its contracts, e.g., there is a malfunctioning of a generating facility, they must pay the balancing costs themselves, as large power producers are responsible for their own energy program. To stimulate market players to make their forecasts of electricity production and demand as accurate as possible and to act in accordance with these energy programs, the price for balancing power (imbalance charges) must be above the market price for electricity. Since balancing power is typically provided by units with high marginal costs, this is, in practice, always automatically the case.

3.5 System Support Services

Another relevant issue in the electricity system is the delivery of *system support services* or *ancillary services*, i.e., all services necessary for the operation of a transmission or distribution system. It comprises compensation for energy losses, frequency control (automated, local fast control and coordinated slow control), voltage and flow control (reactive power, active power, and regulation devices), and restoration of supply (black start, temporary island operation). These services are required to provide system reliability and power quality. They are provided by generators and system operators.

4 Changing Nature of Electricity Generation

In electricity generation two inter-related movements can be seen, both of paramount importance for the way the electricity system will be managed in the future:

1. The increase of electricity generated from **sustainable energy sources**.
2. **Decentralization** of electricity generation: electricity generating units are growing in numbers and moving closer to the load centers.

In the next two subsections we will describe these changes in more detail, and in the third subsection we will describe the impact on management of the electricity system.

4.1 Sustainable Electricity Sources

Worldwide, two thirds of the electricity is still produced from fossil fuels (natural gas, oil and coal) while approximately 15% originates from nuclear sources [6]. Of the sustainable options for electricity generation, hydro energy is currently most significant in the world wide power production (17%). Other sustainable energy sources (wind, solar, biomass, and geothermal) contribute for only about 2% to the world wide electricity generation[2].

However, there are important drivers to reduce the fossil fuel dependency and to substitute fossil fuels for sustainable energy sources. Two important drivers behind this are:

- **Environmental concerns:** pollution and climate change. Most fossil fuels are used as input for a combustion process which emit pollutants such as aerosols (e.g., soot), sulfur oxides and nitrogen oxides. Further, fossil fuel usage is one of the greatest contributors to global warming due to greenhouse gas emissions.
- **Diversification of energy sources:** the energy need of most western economies is largely imported from outside those economies. As energy demand continues to grow, this external dependence could grow steeply in the next decades. Moreover, a substantial portion of fossil fuels are imported from politically unstable regions. A higher portion of sustainable energy in the energy mix reduces this dependency.

Hydro energy is the only sustainable energy source with a substantial share in today's electricity supply. Worldwide, approximately 17% of electricity is generated by hydro power generators. However, the growth potential for hydro power is limited. Instead of large hydro power plants, in many countries there is a capacity increase because of new small hydro power facilities. These generators are connected to the medium voltage distribution grid.

With an annual growth of 25 to 30%, wind energy is becoming the second largest sustainable energy source for power generation. In 2008 the worldwide installed capacity was 121GW [16] (3.2% of total power generation capacity world wide). With an annual growth of 25%, the wind generation capacity in 2020 will be 1750GW, i.e., a share of at least 25% of the world wide power generation capacity. In 2008 Germany had 24MW wind generation capacity installed with a production share of 7.5%. Among the countries with the largest wind generation capacity in 2008 are the USA (25GW), Spain (17GW) and China (17GW). Initially wind turbines with a capacity up to 1000kW (solitaire or in a wind park) were connected to the distribution grid. Today, very large wind turbines with a generation up to 5MW each are installed offshore in large wind parks. Since the total generation capacity of these wind parks is often more than 100MW, they are connected to the transmission grid. At the same time there is a trend towards smaller wind turbines, i.e., turbines with a capacity of less than 50kW. These turbines are situated near dwellings and connected to the low voltage distribution grid.

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[2] Sustainable Electricity Sources are also refered to as *Renewable Energy Sources* (RES). In the remainder of this text we will use these terms interchangeably

The most abounded sustainable energy source world wide is solar energy. Solar energy can be converted to electricity through a thermal route using a steam cycle, as in conventional power plants, and through photo voltaic (PV) cells. The thermal technique is used on large plants (some hundreds of MW), so called concentrated solar power. Panels with PV cells are used in urban areas, mounted to the roofs of buildings and dwellings, and connected to the low voltage distribution grid. The total installed capacity of PV world wide in 2007 was 9100MWpeak [24] (of which 40% in Germany). If the average annual growth factor of about 30% continues, the installed total world wide generation capacity in 2020 may become 275GWpeak. Although this will be only a few percent of the total installed generation capacity world wide, locally the share of electricity production from PV may be much larger.

Biomass (wood, organic waste, etc.) has been used for power generation on a limited scale for decades. There is a large growth potential for this sustainable energy source. Different kinds of biomass can be co-fired in coal fired power plants (10 to 30%). Biomass can also be converted into electricity in dedicated biomass plants. The size of these plants is smaller than conventional power plants, i.e., up to a few hundred MW. Another form of bioenergy is biogas. Biogas, from waste water treatment or anaerobic digestion of manure, can be used as a fuel for gas engines producing electrical power. These units have a capacity of some MWs and are connected to the medium voltage distribution grid.

Other sustainable energy sources are geothermal energy and wave and tidal energy. These energy sources are only available in specific regions, but there they may be of significant importance, as is the geothermal electricity generation in Iceland.

4.2 Distributed Generation

Another ongoing change in electricity generation is the growing generation capacity located in the distribution part of the physical infrastructure. This trend breaks with the traditional central plant model for electricity generation and delivery. For this type of generation the term *distributed generation* (DG) is used:

Definition 1. Distributed Generation (DG) is the production of electricity by units connected to the distribution network or to a customer site.

Thus, DG units supply their generated power to the distribution network either directly or indirectly via a customer's private network (i.e., the network on the end-customer's premises, behind the electricity meter). Consequently, the generation capacities of individual DG units are small as compared to central generation units which are directly connected to the transmission network. On the other hand, their numbers are much higher than central generation and their growth is expected to continue.

Sustainable or renewable energy sources (RES) connected to the distribution grid fall under the definition of DG. However not all RES are DG as large-scale renewables, e.g., off-shore wind electricity generation, is connected to the transmission network. The same holds for Combined Heat and Power production (CHP – or Co-generation). A CHP unit is an installation for generating both electricity and useable heat simultaneously. Dependent of their size CHP units are either connected to the distribution grid (and, thus, fall under the definition of DG) or to the transmission grid. Table 2 categorizes different forms of CHP and RES into either large-scale generation or distributed generation.

Table 2 Characterization of Distributed Generation (adapted from [20])

	Combined Heat and Power	Renewable Energy Sources
Large-scale Generation	- Large district heating* - Large industrial CHP	- Large hydro** - Off-shore wind - Co-firing biomass in coal power plants - Geothermal energy - Concentrated solar power
Distributed Generation	- Medium district heating - Medium industrial CHP - Utility building CHP - Micro CHP	- Medium and small hydro - On-shore wind - Tidal energy - Biomass and waste incineration - Biomass and waste gasification - PV solar energy

* *Typically* $> 50MW_e$; ** *Typically* $> 10MW_e$

There are a number of drivers behind the growing penetration of DG [7]. Here, two important drivers, namely “Environmental concerns” and “Diversification of energy sources”, are shared with the drivers for RES increase (see Section 4.1 for a description). Additional to these, important drivers for DG are:

- **Deregulation of the electricity market.** As a result of the deregulation, the long-term prospects for large-scale investments in power generation have become less apparent. Therefore, a shift of interest of investors from large-scale power generation plants to medium and small-sized generation can be seen. Investments in DG are lower and typically have shorter payback periods than those of the more traditional central power plants. Capital exposure and risk is reduced and unnecessary capital expenditure can be avoided by matching capacity increase with local demand growth.
- **Energy autonomy.** A sufficient amount of producing capacity situated in a local electricity network opens the possibility of intentional islanding. Intentional islanding is the transition of a sub-network to stand-alone operation during abnormal conditions on the externally connected network, such as outages or instabilities, e.g., during a technical emergency. In this manner, autonomy can be achieved on different scales, from single buildings to wide-area subsystems.
- **Energy Efficiency (i).** In general, distributed generation reduces energy transmission losses. Estimates of power lost in long-range transmission and distribution systems of western economies are of the order of 7%. By producing elec-

tricity in the vicinity of consumption area, transport losses are avoided. There is, however, a concern that in cases where the local production outgrows the local consumption the transmission losses start rising again. But in the greater part of the world's distribution network we are far from reaching that point.
- **Energy Efficiency (ii).** Heat production out of natural gas can reach higher efficiency rates by using combined heat-power generation (CHP) instead of traditional furnace burners. CHP is a growing category of distributed generation, especially in regions where natural gas is used for heating. In Northern Europe, for instance, CHP is already commonly used in heating of large buildings, green houses and residential areas. The use of micro-CHP for domestic heating in single dwellings is also expected to breakthrough in the coming few years.

The growing share of DG in the electricity system may evolve in three distinct stages (adapted and extended from [8]):

1. **Accommodation.** Distributed generation is accommodated in the existing electricity system, i.e., network and markets. Distributed units are running free, beyond the control of the transmission grid operator or market-party to which the generated energy is delivered. The centralized control of the networks remains in place. Electricity supply companies treat DG as being negative demand: it is non-controllable and to a certain extend forecastable.
2. **Decentralization.** The share of DG increases. Clustered operation of DG devices gives an added value. Supply companies optimize the services of decentralized providers through the use of common ICT–systems (Virtual Power Plant concept). Distribution grid operators use the services of decentralized providers for grid operational goals, like congestion management. Central monitoring and control is still needed.
3. **Dispersal.** Distributed power takes over the electricity market. Local low–voltage network segments provide their own supply with limited exchange of energy with the rest of the network. The central network operator functions more like a coordinating agent between separate systems rather than controller of the system.

4.3 Implications for Infrastructure Management

Both the rising share of renewable energy sources and the decentralization are changing the characteristics of power generation in three aspects:

- **Intermittancy:** The energy sources for conventional power generation are continuously available and can be adjusted according to the electricity demand. Electricity from sustainable energy sources, such as wind and solar energy, can only be produced if the primary energy source is available. Additionally, electricity from those CHP units which are operated to follow heat demand are intermittent in nature as well. With the growing share of these intermittent energy sources it becomes more difficult to follow the changing electricity demand.

- **Cardinality:** The number of electricity generating units is growing rapidly while individual capacities are decreasing.
- **Location:** The location of power generation relative to the load centers is changing. Due to decentralization, the distance between generation units in the grid relative to the location of electricity consumption is becoming smaller. However, central generation from wind is moving further away from the load centers as large-scale wind farms are being built off-shore.

These changes are expected to have a number of implications for infrastructure management such as: power quality problems, e.g., local voltage increase due to in-feeding by DG units or voltage distortion due to injection of higher harmonics by inverter-based DG units; Changing current directions in distribution grids disturbing, for instance, systems for short-circuit localization; Stability problems due to a decreasing amount of rotating mass in the system, etc.

In this chapter text, the main focus is on the important topic of maintaining the balance between supply and demand in the electricity system. In the status quo, this balance is maintained by a relative small number of big central power plants following inflexible and partially unpredictable load patterns. As the supply side becomes more inflexible, a need emerges to utilize the flexibility potential of the demand side. With that, the nature of coordination within the electricity system is changing from centrally controlling a few central power plants into coordinating among high numbers of generators and responsive loads, with varying levels of flexibility and having a great variety in (production and consumption) capacity.

As distributed generation gradually levels with central generation as a main electricity source, distributed coordination will be needed alongside central coordination. The standard paradigm of centralized control, which is used in the current electricity infrastructure, will no longer be sufficient. The number of system components actively involved in the coordination task will be huge. Centralized control of such a complex system will reach the limits of scalability, computational complexity, and communication overhead.

As demand response plays such a crucial role in such a system, we will expand on that topic in the next subsection.

4.4 Demand Response

Crucial for an efficient and stable operation of future electricity networks is *demand response* (DR).

Definition 2. Demand response is the ability of electricity consuming installations and appliances to alter their operations in response to (price) signals from the energy markets or electricity network operators in (near-)real time.

Demand response can be achieved through avoidance of electricity use and/or by shifting load to another time period.

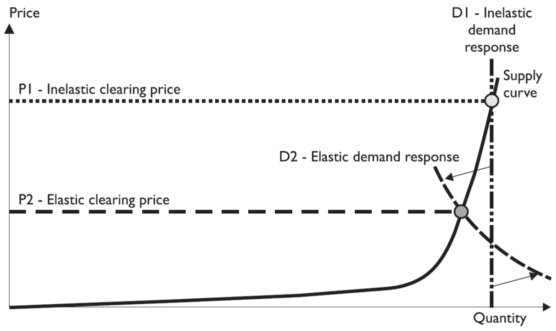

Fig. 5 Impacts of Demand Elasticity on Wholesale Price [9].

At present, *price elasticity* of electricity demand is very low in the electricity markets. This means that the quantity in demand stays cinstant with a changing price. Higher elasticity in electricity demand would lead to lower market power of producers and to a lower electricity price (see Figure 5). During the California energy crisis, a demand reduction of 5% during the periods of the highest price peaks would have reduced these prices by 50% [9].

Typical large flexible loads include different types of industrial processes, e.g., groundwood plants and mechanical pulping plants, electrolysis, arc furnaces, rolling mill, grinding plants, extruders, gas compressors, etc. In the commercial and residential sectors flexible loads can include space heating, water heating, cooling, ventilation, washing and drying, lighting, etc.

From the viewpoint of controllability, DG and DR are equivalent: increasing production has the same effect on the supply and demand balance as decreasing consumption, and vice versa. Due to this, demand response is sometimes treated as being a resource. As a result of the common nature of DG and DR (and distribution network connected electricity storage), the overarching term *Distributed Energy Resources* (DER) is used to refer to this threesome: DG, DR and storage.

5 Intelligent Distributed Coordination in Electricity

As a result of the electricity evolution, as described above, the electricity infrastructure will get more and more inter-linked with ICT-infrastructures. The architecture and algorithmics of this ICT-infrastructure must be adapted to the technical structure of the (future) electricity net and the connected producing and consuming installations, but also to the structure of the liberalized energy market. This ICT-architecture and associated algorithms must be designed using a strong system-wide viewpoint, but must also consider stakes of local actors in the system. In other words, there is a need for a multi-actor coordination system, which optimizes global system objectives (such as stability, power quality, and security of supply), in coherence with the interests of local actors in the form of installations for electricity production, consumption, and storage as well as their owners. These local actors vary greatly in characteristics defined by process type, purpose and size, and so do their specific constraints and objectives. This leads to a major shift in the requirements of the coordination system.

5.1 High-level requirements of the needed coordination system

Specific information system requirements of the ICT-infrastructure needed for the expected electricity evolution include [11, 12]:

- **Scalability:** A huge number of systems spread-out over a vast area will have to be involved in the coordination task. Especially on the level of the distribution grids, huge growth in the number of components actively involved in the coordination is expected. The ICT system must be able to accommodate this growth.
  This poses an important scalability requirement for the information systems architecture performing this task. Following the sector's paradigm of centralized control, the system may reach the limits of communication overhead rapidly.
- **Openness:** The information system architecture must be open: individual DER units can connect and disconnect at will and future types of DER —with own and specific operational characteristics— need to be able to connect without changing the implementation of the system as a whole. Therefore, communication between system parts must be uniform and stripped from all information specific to the local situation.
- **Multi-level Stakes:** The information system must facilitate a multi-actor interaction and balance the stakes on the global level (i.e., the aggregated behavior: reaction to energy market situation and/or network operator needs) and on the local level (i.e., DER operational goals).
- **Autonomy and Privacy:** In most cases, different system parts are owned or operated by different legal persons, so the coordination mechanism must be suitable to work over boundaries of ownership. Accordingly, the power to make decisions on local issues must stay with each individual local actor.

5.2 Multi-Agent Systems

The advanced technology of multi-agent systems (MAS) provides a well-researched way of implementing complex distributed, scalable, and open ICT systems. A multi-agent system is a system of multiple interacting software agents. A software agent is a self-contained software program that acts as a representative of something or someone (e.g., a device or a user). A software agent is goal-oriented: it carries out a task, and embodies knowledge for this purpose. For this task, it uses information from and performs actions in its local environment or context. Further, it is able to communicate with other entities (agents, systems, humans) for its tasks.

In multi-agent systems, a large number of actors are able to interact. Local agents focus on the interests of local sub-systems and influence the whole system via negotiations with other software agents. While the complexity of individual agents remains low, the intelligence level of the global system is high. In this way, multi-agent systems implement distributed decision-making systems in an open, flexible, and extensible way. Communication between actors can be minimized to a generic and uniform information exchange.

5.2.1 Electronic Markets

The interactions of individual agents in multi-agent systems can be made more efficient by using *electronic markets*, which provide a framework for distributed decision making based on microeconomics. Microeconomics is a branch of economics that studies how economic agents (i.e., individuals, households, and firms) make decisions to allocate limited resources, typically in markets where goods or services are being bought and sold. One of the goals of microeconomics is to analyze market mechanisms that establish relative prices amongst goods and services and allocation of limited resources amongst many alternative uses [13]. Whereas, economists use microeconomic theory to model phenomena observed in the real world, computer scientists use the same theory to let distributed software systems behave in a desired way. Market-based computing is becoming a central paradigm in the design of distributed systems that need to act in complex environments. Market mechanisms provide a way to incentivize parties (in this case software agents), that are not under direct control of a central authority, to behave in a certain way [3, 19]. A microeconomic theory commonly used in MAS is that of general equilibrium. In general equilibrium markets, or exchange markets, all agents respond to the same price, that is determined by searching for the price that balances all demand and supply in the system. From a computational point of view, electronic equilibrium markets are distributed search algorithms aimed at finding the best trade-offs in a multidimensional search space defined by the preferences of all agents participating in the market [23, 26]. The market outcome is *Pareto* optimal, a social optimal outcome for which no other outcome exists that makes one agent better-off while making other agents worse-off.

5.2.2 Market-based Control

In *Market-based Control*, agents in a MAS are competing for resources on an equilibrium market whilst performing a local control task (e.g., classical feedback control of a physical process) that needs the resource as an input. For this type of MAS, it has been shown by formal proof that the market-based solution is identical to that of a centralized omniscient optimizer [1]. From the viewpoint of scalability and openness of the information architecture, this is an important feature. In the centralized optimization all relevant information (i.e., local state histories, local control characteristics, and objectives) needs to be known at the central level in order to optimize over all local and global control goals. While in the market-based optimization the same optimal solution is found by communicating uniform market information (i.e., market bids stating volume-price relations), running an electronic equilibrium market and communicating the resulting market price back to the local control agents. In this way, price is used as the control signal. It is important to note that, whether — in a specific application — the price has a monetary value or is virtual and solely used as a control signal depends on the particular implementation and on the business case behind the application.

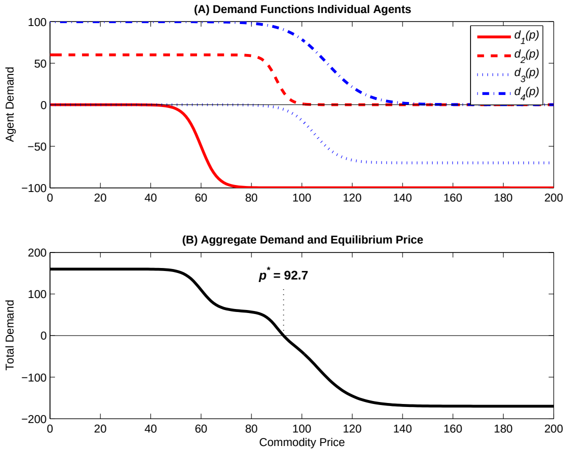

Fig. 6 Example general equilibrium market outcome. (A) Demand functions of the four agents participating in the market. (B) Aggregate demand function and general equilibrium price p^*.

In a typical application of market-based coordination, there are several entities producing and/or consuming a certain commodity or good[3]. Each of these entities is represented by a local control agent that communicates with a market agent (auctioneer). Each market round, the control agents create their market bids, dependent on their state history, and send these to the market agent. These bids are ordinary, or *Walrasian*, demand functions $d(p)$, stating the amount of the commodity the agent wishes to consume (or produce) at a price of p. The demand function is negative in the case of production. After collecting all bids, the market agent searches for the equilibrium price p^*, i.e., the price that clears the market :

$$\sum_{a=1}^{N} d_a(p^*) = 0 \tag{1}$$

where N is the number of participating agents and $d_a(p)$, the demand function of agent a. The price is broadcast to all agents. Individual agents can determine their allocated production or consumption from this price and their own bid.

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[3] Or a series of commodities. Here we treat the single-commodity case for simplicity

Figure 6 shows a typical small-scale example of price forming in a (single-commodity) general equilibrium market with four agents. The demand functions of the individual agents are depicted in graph (A). There are two consuming agents whose demand decreases gradually to zero above a certain market price. Further, there are two producers whose supply, above a certain price, increases gradually to an individual maximum. Note that supply is treated as negative demand. The solid line in (B) shows the aggregate demand function. The equilibrium price p^* is determined by searching for the root of this function, i.e., the point where total demand equals total supply.

5.3 A Decentralized Control Systems Design

This Section describes a novel control concept for automatic matching of demand and supply in electricity networks with a high share of distributed generation. In this concept, DG, demand response, and electricity storage are integrated using the advanced ICT technology of market-based distributed control.

This concept has been coined *PowerMatcher*. Since its incarnation in 2004, the PowerMatcher has been implemented in three major software versions. In a spiral approach, each software version was implemented from scratch with the first two versions being tested in simulations and field experiments [11, 10, 18]. The third version is currently under development and is planned to be deployed in a number of field experiments [17] and real-life demonstrations with a positive business case.

The PowerMatcher is a general purpose coordination mechanism for balancing demand and supply in clusters of *Distributed Energy Resources* (DER, distributed generation, demand response, and distribution grid-coupled electricity storage). These ‘clusters’ might be electricity networks with a high share of distributed generation or commercial trading portfolios with high levels of renewable electricity sources, to name a few.

The PowerMatcher implements *supply and demand matching* (SDM) using a multi-agent systems and market-based control approach. SDM is concerned with optimally using the possibilities of electricity producing and consuming devices to alter their operation in order to increase the over-all match between electricity production and consumption.

5.3.1 Logical Structure and Agent Roles

Within a PowerMatcher cluster the agents are organized into a logical tree. The leafs of this tree are a number of *local device agents* and, optionally, a unique *objective agent*. The root of the tree is formed by the *auctioneer agent*, a unique agent that handles the price forming, i.e., the search for the equilibrium price. In order to obtain scalability, *concentrator agents* can be added to the structure as tree nodes. A more detailed description of the agent roles is as follows:

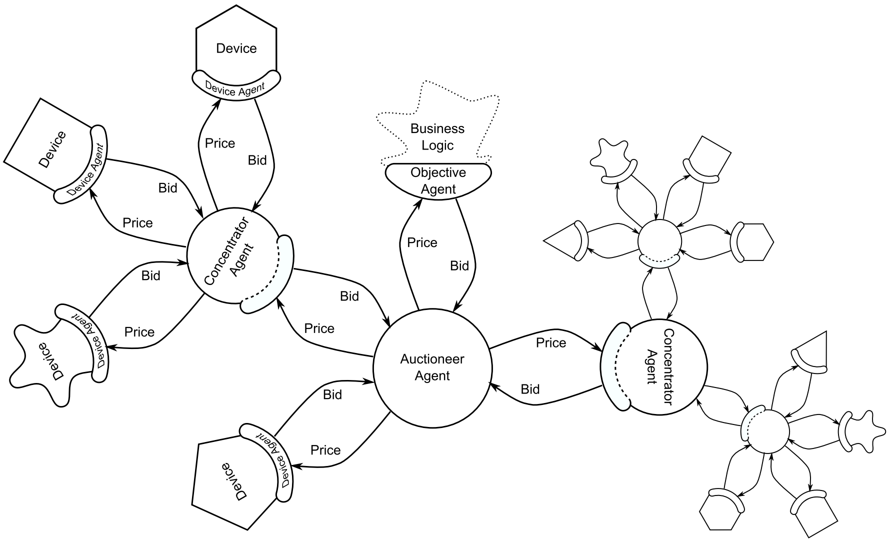

Fig. 7 Example PowerMatcher agent cluster. See the text for a detailed description.

- **Local device agent:** Representative of a DER device. A control agent which tries to operate the process associated with the device in an economical optimal way. This agent coordinates its actions with all other agents in the cluster by buying or selling the electricity consumed or produced by the device on an electronic market. In order to do so, the agent communicates its latest bid (i.e., a demand function, see Section 5.2.2) to the auctioneer and receives price updates from the auctioneer. Its own latest bid, together with the current price, determines the amount of power the agent is obliged to produce or consume.
- **Auctioneer agent:** Agent that performs the price-forming process. The auctioneer concentrates the bids of all agents directly connected to it into one single bid, searches for the equilibrium price and communicates a price update back whenever there is a significant price change.
- **Concentrator agent:** Representative of a sub-cluster of local device agents. It concentrates the market bids of the agents it represents into one bid and communicates this to the auctioneer. In the opposite direction, it passes price updates to the agents in its sub-cluster. This agent uses ‘role playing’. On the auctioneer’s side it mimics a device agent: sending bid updates to the auctioneer whenever necessary and receiving price updates from the auctioneer. Towards the sub-cluster agents directly connected to it, it mimics the auctioneer: receiving bid updates and providing price updates.
- **Objective agent:** The objective agent gives a cluster its purpose. When the objective agent is absent, the goal of the cluster is to balance itself, i.e., it strives for an equal supply and demand within the cluster itself. Depending on the specific application, the goal of the cluster might be different. If the cluster has to operate as a *virtual power plant*, for example, it needs to follow a certain externally pro-

vided setpoint schedule. Such an externally imposed objective can be realized by implementing an objective agent. The objective agent interfaces to the *business logic* behind the specific application.

This logical structure follows the CoTree algorithm [25]. By aggregating the demand functions of the individual agents in a binary tree, the computational complexity of the market algorithm becomes $O(\lg a)$, where a is the number of device agents. In other words, when the number of device agents doubles it takes only one extra concentrator processing step to find the equilibrium price. Furthermore, this structure opens the possibility for running the optimization distributed over a series of computers in a network in a complimentary fashion to power systems architectures.

5.3.2 Device Agent Types and Strategies

From the viewpoint of supply and demand matching, DER devices can be categorized by their type of controllability into the following classes:

- **Stochastic operation devices:** devices such as solar and wind energy systems of which the power exchanged with the grid behaves stochastically. In general, the output power of these devices cannot be controlled, the device agent must accept any market price.
- **Shiftable operation devices:** batch-type devices whose operation is shiftable within certain limits, for example (domestic or industrial) washing and drying processes. Processes that need to run for a certain amount of time regardless of the exact moment, such as assimilation lights in greenhouses and ventilation systems in utility buildings. The total demand or supply is fixed over time.
- **External resource buffering devices:** devices that produce a resource, other than electricity, that are subject to some kind of buffering. Examples of these devices are heating or cooling processes, whose operation objective is to keep a certain temperature within two limits. By changing the standard on/off-type control into price-driven control allows for shifting operation to economically attractive moments, while operating limits can still be obeyed (see Figure 8). Devices in this category can both be electricity consumers (electrical heating, heat pump devices) and producers (combined generation of heat and power).
- **Electricity storage devices:** conventional batteries or advances technologies such as flywheels and super-capacitors coupled to the grid via a bi-directional connection. Grid-coupled electricity storage is widely regarded as a future enabling technology allowing the penetration of distributed generation technologies to increase at reasonable economic and environmental cost. Grid-coupled storage devices can only be economically viable if their operation is reactive to a time-variable electricity tariff, as is present in the PowerMatcher concept. The agent bidding strategy is buying energy at low prices and selling it later at high prices.

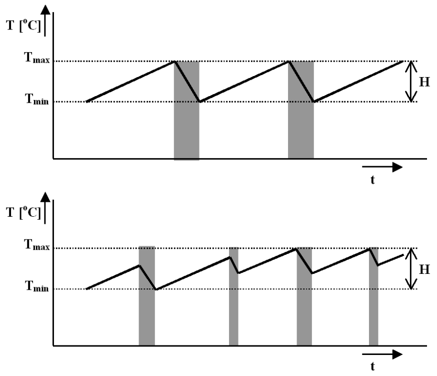

Fig. 8 Operation shifting in a cooling process whilst obeying process state limits.

- **Freely-controllable devices:** devices that are controllable within certain limits (e.g., a diesel generator). The agent bidding strategy is closely related to the marginal costs of the electricity production.
- **User-action devices:** devices whose operation is a direct result of a user action. Domestic examples are: audio, video, lighting, and computers. These devices are comparable to the stochastic operation devices: their operation is to a great extent unpredictable and has no inherent flexibility. Thus, the agent must accept any market price to let them operate.

In all described device categories, agent bidding strategies are aimed at carrying out the specific process of the device in an economically optimal way, but within the constraints given by the specific process.

5.3.3 Cluster-level Behavior

The self-interested behavior of local agents causes electricity consumption to shift towards moments of low electricity prices and production towards moments of high prices. As a result of this, the emergence of supply and demand matching can be seen on the global system level.

The PowerMatcher technology can be the basis of a *virtual power plant* (VPP). A VPP is a flexible representation of a portfolio of Distributed Energy Resources (DER), i.e.: distributed generation, demand response, and electricity storage [15]. One of the key activities of a VPP is the delivery of (near-) real-time balancing services, e.g., delivering reserve regulating power to the TSO, delivering active network management services to the DSO, or minimizing the imbalance costs of a commercial party. The aggregated, or concentrated, bid of all local control agents in the cluster — as is held by the auctioneer agent — can be regarded as a dynamic merit-order list of all DER participating in the VPP. On the basis of this list, the VPP is able to operate such the (near-)real-time coordination activity optimally.

6 Field Test Results

6.1 Commercial Portfolio Balancing

This subsection describes the first field experiment performed using the PowerMatcher. A more comprehensive and detailed description of the test, including an analysis of the business model, can be found in [10].

6.1.1 Value Driver: Balancing Responsibility

One of the tasks of a Transmission System Operator is maintaining the instantaneous demand and supply balance in the network. As described in Section 3.4, the system of balancing responsibility gives wholesale trading parties incentives to maintain their own portfolio balance. This system provides means to charge the costs made by the TSO when maintaining the real-time system balance to those wholesale market parties responsible of the unbalance. Central to this mechanism is the notion of *Balancing responsibility*, i.e., the obligation of wholesalers to plan their production and consumption and to make this plan available to the TSO. Parties having this responsibility are referred to as *balancing responsible parties* (BRPs).

As may be clear, the system of balancing responsibility imposes imbalance risks to the market parties. Among BRPs, this risk will vary with the predictability and controllability of the total portfolio of the BRP. BRPs with low portfolio predictability are faced with higher imbalance risks. Typically, wind power suffers from low predictability. This gives higher imbalance costs resulting in a lower market value for electricity produced by wind turbines. Using specialized forecasting techniques as post-processors to high-resolution meteorological models, the day-ahead predictability of wind energy production has been improved substantially in the last few years. However, a substantial error margin remains.

6.1.2 Field Test Set-up

For the purpose of the field test, five different installations were brought together in the portfolio of a virtual BRP. In reality, the installations represent a small part of the portfolios of two different BRPs, but for the sake of the experiment they were assumed to represent the full portfolio of one single BRP. Figure 9 gives the configuration of the field test. To all DER sites, hardware was added to run the local control agents on. These agents interacted with the existing local measurement and control system. Further, the local agents communicated with the auctioneer using a virtual private network running over a standard ADSL internet connection or (in one case) a UMTS wireless data connection.

Table 3 gives an overview of the capacities of the individual installations included in the test. In order to give the smaller sized installations a good influential

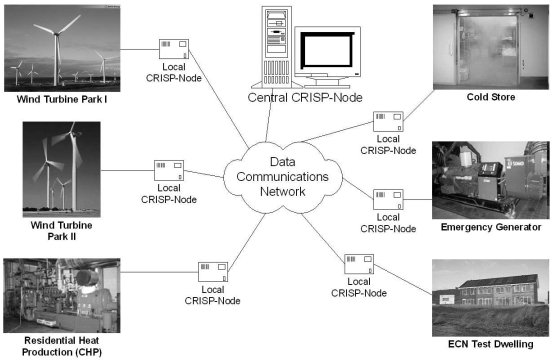

Fig. 9 Configuration of the imbalance reduction field test.

balance compared to the larger ones, two of the sites were scaled up via an on-line simulation.

Table 3 Production (P) and Consumption (C) Capacities of the Field Test Installations

Site	P/C	Capacity	Simulated
Wind Turbine	P	2.5 MW	-
CHP	P	6 MW	-
Cold Store	C	15 kW	1.5 MW
Emergency Generator	P	200 kW	-
Heat Pump	C	0.8 kW	80 kW

P = Production; C = Consumption.

6.1.3 Imbalance Reduction Results

The field test ran for a number of months in the first half year of 2006. In the real-life DER portfolio, with a wind power dominated imbalance characteristic, the imbalance reductions varied between 40 and 43%. As seen from an electricity market perspective, these benefits are substantial. This makes the approach a good addition to the current options for handling wind power unpredictability, like wind/diesel combinations, balancing by conventional power plants and large-scale electricity storage. Topics that need further research include, the factors that influence the flexibility level of the aggregate and the system behavior when the number of attached DERs is increased substantially. The operation of a similar cluster as a commercial VPP, by adding an appropriate objective agent to the agent set, is part of the current research.

6.2 Congestion Management

This subsection describes the second field experiment performed using the PowerMatcher. A more comprehensive and detailed description of the test can be found in [18] or [22].

6.2.1 Value Driver: Deferral of Grid Reinforcements

In the Northwestern region of Europe, decentralized generation of heat and power by micro-CHP units in households is expected to penetrate the market at high speed in the coming years. When the number of micro-CHP units in a region exceeds a certain limit, added value can be gained by clustered coordination via common ICT systems. In a field test a cluster of five Stirling based micro-CHP units of 1kW electric each has been operated as a virtual power plant[4]. The main goal of the field test was to demonstrate the ability of such a VPP to reduce the local peak load on the single low-voltage grid segment the micro-CHP units were connected to. In this way the VPP supports the local distribution system operator (DSO) to defer reinforcements in the grid infrastructure (substations and cables) when local demand is rising. Although not all micro-CHP units included in the field test were connected to the same low-voltage cable, during the trial a connection to a common substation (i.e., low-voltage to mid-voltage transformer) was assumed.

6.2.2 Field Test Set-up

The field test focused on the network utilization factor of the local distribution grid in three different settings:

- **Baseline:** domestic load profile of 5 households.
- **Fit-and-Forget:** load profile of 5 households plus micro-CHPs controlled in standard heat-demand driven manner (thermostat).
- **VPP operation:** CHP operation coordinated by PowerMatcher intelligent control to reduce peak-load, without any intrusion on comfort for consumers.

In the third setting, the micro-CHPs were controlled by local PowerMatcher control agents. These agents were clustered together with an objective agent monitoring the load on the shared transformer and demanding CHP electricity production when it exceeded a safety level.

The households participating in the field test were equipped with a Whispergen micro-CHP for heating of living space and tap water. For the latter, these systems were equipped with a tap water buffer of 120 liter. For the field test, the systems were extended with a virtual power plant node or VPP-node. The local agents ran on these

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[4] In total 10 micro-CHPs were equipped to be part of the VPP. The results presented are realized with 5 of these 10 participating.

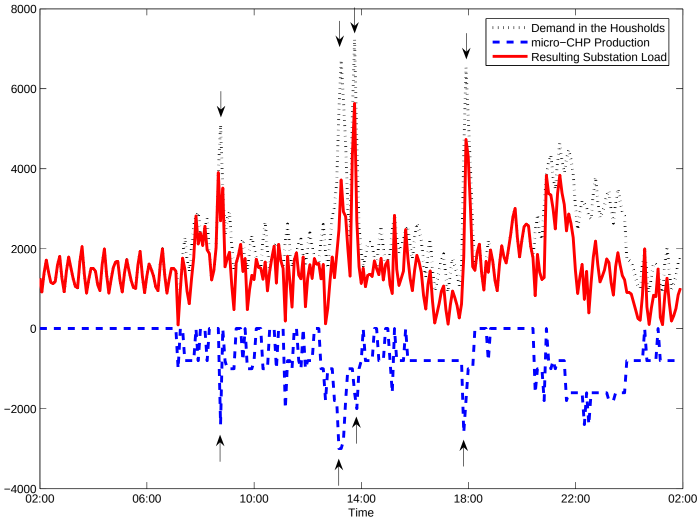

Fig. 10 Typical measured day patterns for 5 micro-CHPs with PowerMatcher coordination: synchronisation of CHP output (dashed line) with domestic peak-demand (dotted) leading to peak load reduction at the transformer (solid line).

VPP-nodes, communicating with the local infrastructure (micro-CHP, thermostat, and electricity meter) through power line communications and with the auctioneer agent through a TCP/IP connection. The end users communicated with the system by means of the thermostat.

The local agents aimed at producing CHP electricity in high-priced periods with a hard constraint of not infringing the users thermal comfort. When the transformer load exceeded the safety level, the objective agent issued a demand bid aiming at steering the load back to the safety level. This increase in demand caused a price rise on the electronic market, which, in turn, triggered those agents most fit to respond (i.e., the ones having the highest heat demand at that moment) to run their CHP. The micro-CHP units were only operated in case of local heat demand, either for space heating or for tap water heating. No heat was dumped. An additional simulation study was done to verify the findings in the field test and to investigate circumstances not engaged in the field experiment, such as winter conditions.

6.2.3 Congestion Management Results

The field test was conducted in May 2007, which was an exceptionally warm month for The Netherlands. Therefore there was no space heating demand in the households, only demand for tap water heating. Figure 2 shows a typical day pattern during the field test when five micro-CHPs were participating in the VPP. The PowerMatcher shifts the micro-CHP production so that electricity is produced when there is a high demand for electricity. This lowers the peak load on the substation.

The main findings of the field experiment and additional simulation studies were:

- The Fit-and-Forget policy did not provide benefits to the DSO in comparison to the baseline case. The load-duration curve was lowered on average by adding the micro-CHPs. However, the peak load remained virtually unchanged.
- Adding VPP operation, based on PowerMatcher intelligent control, led to a load-peak reduction of 30% in summer (field test result) and 50% in winter (simulation outcome).

7 Outlook

In the previous sections, we argued about the necessity of introducing distributed control in the electricity infrastructure in order to cope with the interrelated trends of increasing sustainable electricity sources and distributed generation. We have shown how a specific implementation of distributed control can be used for commercial portfolio balancing as well as for DSO congestion management. An important remaining question is: how to combine the two?

Such a dual-objective coordination mechanism needs to be designed for a future electricity system characterized by:

- Distributed Generation and Demand Response are a substantial factor in the electricity markets.
- A substantial portion of central generation is off-shore wind.
- Market parties and network operators optimize their stakes using the DER in their portfolio, or in their network area, respectively. Dependent on the situation, these stakes may be conflicting at one time and non-conflicting at another time.
- Incentives to market parties (generators, suppliers, and end users alike) reflect the true costs of both generation and infrastructure. On the one hand, this will increase efficient usage of the infrastructure (network load factor optimization) and on the other hand it gives the right market signals for investment decisions (Generation against Demand Response against Infrastructural investments).

Figure 7 shows an architecture that supports the market situation described above. It is a setting with multiple Market Parties (Balancing Responsible Parties, BRPs), each running a commercial virtual power plant (CVPP), and multiple Distribution System Operators (DSOs), each running a technical virtual Power Plant (TVPP). In the Figure the CVPPs are represented by the blocks labeled ”Commercial Aggregation” and the TVPPs by those labeled ”Network Service Aggregation”.

A BRP has special interests:

- Desire to aggregate a high number of DER units, as this smoothens-out the stochastic behavior of the individual DER.

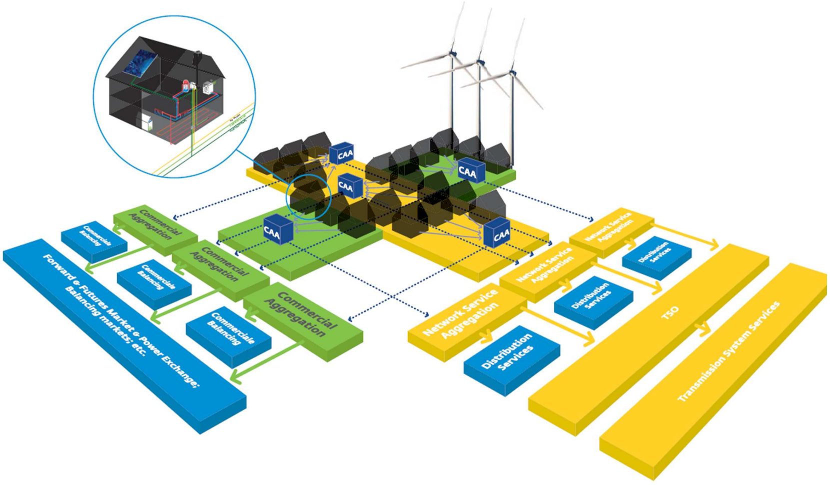

Fig. 11 Orthogonal dual market-based architecture for commercial and technical VPPs in future electricity systems.

- Aspiration to spread its DER portfolio over a big (national) area to increase spatial smoothing of weather influences on DG and on responsive loads.
- Has no locational aspects attached to the desired portfolio behavior for most of its operational parameters.
- Avoids balancing costs when their portfolio as a whole is in balance.

As a result the commercial portfolio of a BRP is most likely located in the grid area of more than one DSO.

A DSO has special interests as well:

- Preference to address only the DER units in its grid area, sometimes even dependent on individual grid cells or segments.
- Desire to incentivise DER to deliver system management services.
- Has a locational aspect in the desired behavior or the DER in its network.
- Avoids investments in infrastructural components by active management of the DER in their network.

In the orthogonal dual architecture, one CVPP has to deal with several TVPPs and one TVPP with several CVPPs. The individual DER units at the premises of one customer, in the Figure represented by a house, communicate with CVPP components only. The Commercial Aggregating Agent (CAA) aggregates all DERs in the portfolio of the corresponding BRP located in a common grid area. Each CAA provides commercial services directly to its CVPP, but it also provides local grid services to the DSO. Thus, each CAA responds to incentives of both the CVPP it is part of and the TVPP that covers its grid area. The stakes of BRP and DSO come together at this point. When these stakes are non-counteracting, the CAA can deliver the services requested by the DSO for a lower price compared to the situation in which the stakes do counteract. Accordingly, those CAAs without an internal conflict will respond to both the CVPP and TVPP request first. In this way, flexibility services from DER will be used based on merit order and the stakes of the different parties will be balanced automatically against each other.

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References

1. Hans Akkermans, Jos Schreinemakers, and Koen Kok. Microeconomic distributed control: Theory and application of multi-agent electronic markets. In *Proceedings of CRIS 2004 - 2nd International Conference on Critical Infrastructures*, 2004.
2. Jesse Berst, Philip Bane, Michael Burkhalter, and Alex Zheng. The electricity economy. White paper, Global Environment Fund, August 2008.
3. Rajdeep K. Dash, David C. Parkes, and Nicholas R. Jennings. Computational mechanism design: A call to arms. *IEEE Intelligent Systems*, 18(6):40–47, November/December 2003.
4. L.J. de Vries. *Securing the public interest in electricity generation markets, The myths of the invisible hand and the copper plate*. PhD thesis, Delft University of Technology, 2004.
5. Energy Information Administration. *International Energy Outlook 2007*. EIA, Paris, 2007.
6. Energy Information Administration. `www.eia.doe.gov/emeu/international/RecentElectricityGenerationByType.xls`, December 2008.
7. ENIRDGnet. Concepts and opportunities of distributed generation: The driving european forces and trends. Project Deliverable D3, ENIRDGnet, 2003.
8. International Energy Agency. *Distributed Generation in Liberalised Electricity Markets*. International Energy Agency, Paris, France, 2002.
9. International Energy Agency. *The Power to Choose – Demand Response in Liberalized Electricity Markets*. International Energy Agency, Paris, France, 2003.
10. Koen Kok, Zsofia Derzsi, Jaap Gordijn, Maarten Hommelberg, Cor Warmer, Rene Kamphuis, and Hans Akkermans. Agent-based electricity balancing with distributed energy resources, a multiperspective case study. In Ralph H. Sprague, editor, *Proceedings of the 41st Annual Hawaii International Conference on System Sciences*, page 173, Los Alamitos, CA, USA, 2008. IEEE Computer Society.
11. Koen Kok, Cor Warmer, and René Kamphuis. PowerMatcher: multiagent control in the electricity infrastructure. In *AAMAS '05: Proceedings of the 4th int. joint conf. on Autonomous Agents and Multiagent Systems*, volume industry track, pages 75–82, New York, NY, USA, 2005. ACM Press.
12. Koen Kok, Cor Warmer, and René Kamphuis. The PowerMatcher: Multiagent control of electricity demand and supply. *IEEE Intelligent Systems*, 21(2):89–90, March/April 2006. Part of overview article: “Agents in Industry: The Best from the AAMAS 2005 Industry Track”.
13. A. Mas-Colell, M. Whinston, and J. R. Green. *Microeconomic Theory*. Oxford University Press, 1995.
14. European Parliament and Council. Common rules for the internal market in electricity. EU Directive 2003/54/EC, June 2003.
15. D. Pudjianto, C. Ramsay, and G. Strbac. Virtual power plant and system integration of distributed energy resources. *Renewable Power Generation*, 1(1):10–16, 2007.

16. Angelika Pullen, Liming Qiao, and Steve Sawyer (eds). Global wind 2008 report. Market report, Global Wind Energy Council, March 2009.
17. Bart Roossien. Field-test upscaling of multi-agent coordination in the electricity grid. In *Proceedings of the 20th International Conference on Electricity Distribution CIRED*. IET-CIRED, 2009.
18. Bart Roossien, Maarten Hommelberg, Cor Warmer, Koen Kok, and Jan Willem Turkstra. Virtual power plant field experiment using 10 micro-CHP units at consumer premises. In *SmartGrids for Distribution, CIRED Seminar*, number 86. IET-CIRED, 2008.
19. Tuomas W. Sandholm. Distributed rational decision making. In Gerhard Weiss, editor, *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence*, pages 201–258. The MIT Press, Cambridge, MA, USA, 1999.
20. M. ten Donkelaar and M.J.J. Scheepers. A socio-economic analysis of technical solutions and practices for the integration of distributed generation. Technical Report ECN-C–04-011, ECN, 2004.
21. M.J.N. van Werven and M.J.J. Scheepers. The changing role of energy suppliers and distribution system operators in the deployment of distributed generation in liberalised electricity markets. Technical Report ECN-C–05-048, ECN, June 2005.
22. Cor Warmer, Maarten Hommelberg, Bart Roossien, Koen Kok, and Jan Willem Turkstra. A field test using agents for coordination of residential micro-chp. In *Proceedings of the 14th Int. Conf. on Intelligent System Applications to Power Systems (ISAP)*. IEEE, 2007.
23. Michael P. Wellman. A market-oriented programming environment and its application to distributed multicommodity flow problems. *Journal of Artificial Intelligence Research*, 1:1–23, 1993.
24. Christoph Wolfsegger, Marie Latour, and Michael Annett. Global market outlook for photovoltaics until 2012 – facing a sunny future. Market report, European Photovoltaic Industry Association, February 2008.
25. Fredrik Ygge. *Market-Oriented Programming and its Application to Power Load Management*. PhD thesis, Department of Computer Science, Lund University, Sweden, 1998. ISBN 91-628-3055-4.
26. Fredrik Ygge and Hans Akkermans. Resource-oriented multicommodity market algorithms. *Autonomous Agents and Multi-Agent Systems*, 3(1):53–71, 2000. Special Issue Best Papers of ICMAS–98.

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