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Abbreviations

AMI	Advanced Metering Infrastructure
BRP	Balance responsible party
CHP	Combined heat and power
DES	Distributed energy resources
DG	Distributed generation
DoE	Department of Energy
DR	Demand response
DSL	Digital subscriber line
DSM	Demand side management
DSO	Distribution system operator
EEX	European Energy Exchange (German electricity exchange market)
EROI	Energy return on energy investment
ESCo	Energy service company
ESS	ETSO Scheduling System
ETP	European Technology Platform
ETSO	European Network of Transmission System Operators for Electricity
EV	Electrical vehicle
FPS	Fixed program shift
GHG	Greenhouse gas
ICT	Information and communication technologies
MAS	Multi-agent system
MDS	Metering data system
MTS	Message transport system
OGEMA	Open Gateway Energy Management Alliance
OTC	Over-the-counter
PEV	Plug-in electrical vehicle
PPC	Price power control
PV	Photovoltaic
R&D	Research and development
RES	Renewable energy sources
RTP	Real-time pricing
SCO	State of charge
SH/SG	SmartHouse/SmartGrid
TCP	Transmission control protocol
TOU	Time-of-use
TSO	Transmission system operator
VPP	Virtual power plant
WS	Web service
WTC	World Trade Center

1. Introduction

This deliverable describes the architecture that could facilitate future business cases in a smart grid, as developed within the SmartHouse/SmartGrid (SH/SG) project. To be more precise, there are several architectural elements featuring several SH/SG concepts. Some of these are similar, some are complimentary, and some are distinct from one another. All share the same concept of decentralized decision making with an overall coordination component. All should be implemented by an enterprise that should be able to earn profits from the SH/SG business cases in the long run.

In the project, three field trials have been carried out in which the architectural concepts have been tested with real customers. The field trials also feature different functionalities of a smart grid. These are visualized in Figure 1. The experiences made in these trials will also be described in relation to the architecture presented in this deliverable.

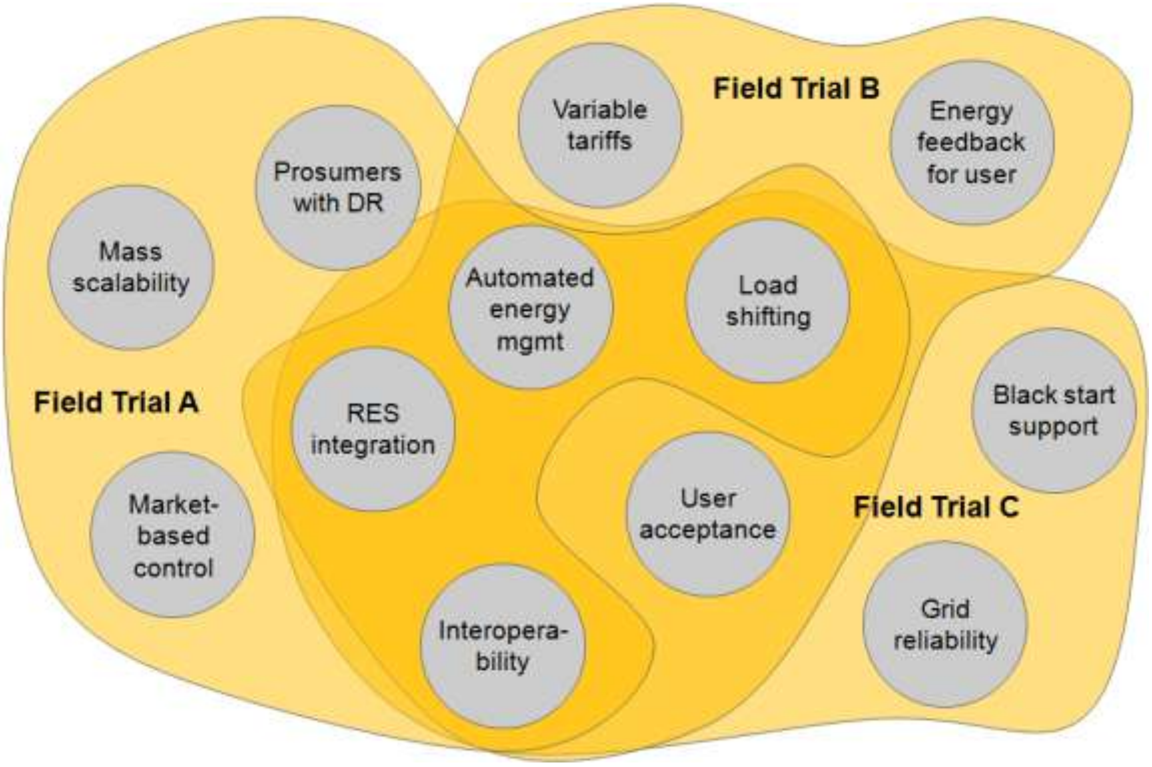

Figure 1: Complimentary foci of the three trials

This deliverable is structured as follows: In Section 2, entitled "Why "Smart" Electricity Networks?", the ongoing changes that the electricity system is facing in most European countries are described, which motivates smart grid approaches. A vision of an "Internet of Energy" derives from the presented arguments. Section 3 "Electricity ≠ Information" then explains where the analogy to the Internet fails, and why the electricity system is more complex than information systems. In 4 "Smart Grid Operations", those operations that could be supported by a smarter grid are described. Section 5 "SmartHouse/SmartGrid Functionalities" then describes what smart grid operations can be facilitated by the technologies developed within this research project; the descriptions follow from nine possible business cases that could justify investment into the SH/SG technologies. Section 6 "SmartHouse/SmartGrid Architecture and Experiences" summarizes the SH/SG architectural concepts and findings, drawing from the experiences made in the field trials and simulation experiments. Finally, Section 7 summarizes and concludes this deliverable.

2. Why "Smart" Electricity Networks?

In the year 1888, Nikola Tesla presented his "New System of Alternate Current Motors and Transformers" [Tesla 1888], laying the foundation for today's electricity infrastructure. Tesla's 'new system' made it possible to transmit electrical power over long distances using a 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 20th century, the electrical power systems of industrialized economies have become one of the most complex systems created by mankind. In the same period, "electricity has made a transition from a novelty, to a convenience, to an advantage, and finally to an absolute necessity" [Berst et al. 2008].

Figure 2: Electricity – from novelty to convenience, to advantage, and to an absolute necessity[3]

On the other hand, the technology of electricity transmission and distribution did not change significantly in the century after Tesla's inventions. Characteristics such as grid structures and systems control in the grid did not change much in the first century of electricity systems. Now, three major trends are forcing technological changes: (i) the transition to sustainability, (ii) the electrification of everything, and (iii) decentralization of generation. These are further detailed in the following sections.

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[3] Top: Nikola Tesla sitting in his laboratory in Colorado Springs, circa 1900 (photo: Carl Willis and Marc Seifer), electric street light in Paris (source unknown). Bottom: Electricity as telecommunications enabler (photo: Ericsson), premature baby in an incubator (photo: Thomas Hartwell).

2.1. Transition to Sustainability

There are a number of reasons why we should reduce our fossil fuel dependency and substitute fossil fuels for sustainable energy sources. Three of these reasons are:

- **Climate change and other environmental concerns** – Fossil fuel usage is one of the biggest contributors to global warming due to greenhouse gas emissions (GHG). On top of that there are other environmental concerns including different kinds of pollution. Most fossil fuels are used as input for a combustion process which emits pollutants such as aerosols (e.g. soot), sulfur oxides and nitrogen oxides. At the same time, there are environmental concerns associated with nuclear energy: the nuclear waste problem and contamination risks.
- **Depletion of oil reserves** – The world's oil and gas reserves are finite. Although the known reserves increased over the last few decades, we no longer find large easy-exploitable reserves. Oil and gas production is moving to more remote and challenging areas. One indicator is the *Energy Return on Energy Investment* (EROI) figure, which has been declining since the early days of large-scale oil production. The EROI is the number of barrels produced for each barrel (equivalent) used in extraction, transportation and refining. When large-scale oil production began around 1930, the EROI was approximately 100 [Hall/Cleveland 2005]. The EROI of the world oil production in 2006 was estimated to be 18 [Gagnon et al. 2009]. As this decline indicates, it is becoming harder to extract oil from the remaining oil reservoirs. When the EROI drops below 1, oil production is no longer a net energy source. Some expect the world oil production to peak in the near future, entering a stage of unstoppable exponential decline afterwards. On the level of single fields and regions this has been observed already [Campbell/Laherrere 1998].
- **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.

2.1.1. 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 [EIA 2008]. 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[4]. 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 emits 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 GHG 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. In many countries, the capacity increase is due to new small hydro power facilities, instead of large hydro power plants. These generators are connected to the medium voltage distribution grid.

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

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 121 GW [Pullen/Sawyer 2009] (3.2% of total power generation capacity worldwide). With an annual growth of 25%, the wind generation capacity in 2020 will be 1,750 GW, i.e. a share of at least 25% of the world wide power generation capacity. In 2008, Germany had 24 GW wind generation capacity installed with a production share of 7.5%. Initially, wind turbines with a capacity up to 1,000 kW (solitaire or in a wind park) were connected to the distribution grid. Today, however, very large wind turbines with a generation up to 5 MW each are installed offshore in large wind parks. Since the total generation capacity of these wind parks is often more than 100 MW, 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 50 kW. These turbines are situated near dwellings and connected to the low voltage distribution grid.

The most abundant sustainable energy source worldwide 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 photovoltaic (PV) cells. The thermal technique is used in 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 worldwide in 2007 was 9100MWpeak of which 40% in Germany [Wolfsegger et al. 2008]. If the average annual growth factor of about 30% continues, the installed total worldwide generation capacity in 2020 may become 275 GW_{peak}. Although this will be only a few percent of the total installed generation capacity worldwide, 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 bio-energy 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, wave and tidal energy**. These energy sources are only available in specific regions, where they may be of significant importance. Geothermal electricity generation in Iceland is an example of this.

2.1.2. The Problem of Supply Intermittency

The rising share of renewable energy sources in the energy mix is changing the characteristic of power generation. The primary energy sources of conventional electrical 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. With the growing share of these intermittent energy sources it becomes more difficult to follow the fluctuating electricity demand.

The total demand and supply in an electrical power network needs to be balanced on the timescale of seconds at all time. Without the balance, the system collapses with a black-out as a result. From the early days of electricity networks on, this balance is maintained by the supply side. The demand just occurs and the supply side is controlled to follow it.

Generally, electrical power is generated by a relatively small number of large power plants. Of these plants a substantial part is well controllable, while the demand side remains largely outside the reach of systems control. Demand patterns are generally well predictable, however an unpredictable fraction remains. With the introduction of renewable energy resources, both the uncontrollability and the unpredictability of the supply side increases. As a result, it will become harder to maintain the demand/supply balance in the electricity system.

2.1.3. The Traditional Reaction: Increase Regulation Capacity

The traditional reaction to unpredictability in the energy balance is adding controllability at the supply side. Following this, the introduction of renewables creates a need for more regulation capacity reserved from traditional power plants. At the same time, the share of power generated by these plants is inevitably going down.

Figure 3 visualizes profiles for demand and wind power in Denmark for 2008 and gives a projection for 2025. In 2025, 50% of the total demand is expected to be covered by wind power and wind power is expected to exceed total demand over 1,000 hours per year. At these moments, wind power needs to be exported or, when the same situation occurs in adjacent regions, needs to be curtailed.

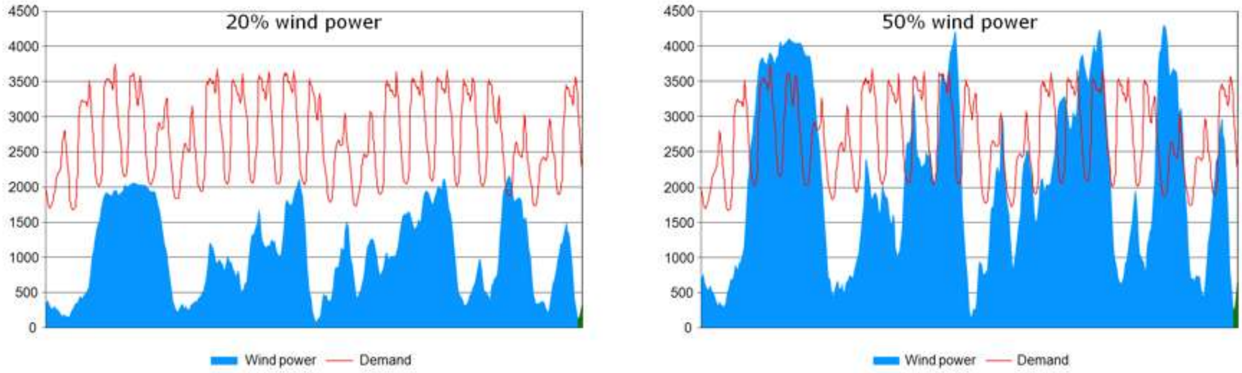

Figure 3: Current and future electricity demand and wind power generation in Denmark[5]

However, in periods of low demand and high wind, problems arise already before wind power exceeds demand. In off-peak periods, the demand is largely covered by base-load generators. These are must-run generators such as non-regulating power plants running on low-cost fuels like coal and uranium, or CHP plants providing heat to a residential area. As it is impossible to stop these plants for a few hours, the electricity market price will fall until other demand or supply units respond. In these situations, the base-load generation is operated below its marginal price, and the same holds for the wind plants when the price becomes negative. In the wholesale market of Denmark and Northern Germany negative electricity prices are permitted since 2009. When there are no other units responding[6] before the price become negative, wind power production needs to be curtailed. However, at present there is only a small part of the installed capacity that is technically equipped to do so.

A similar phenomenon happens in peak periods. Enough generation capacity must be available to serve the demand peak in low-wind periods. The rise in wind power capacity lowers the number of occasions in which this peak capacity will be running. As the operational and capital expenditure does not change, peak prices will increase.

2.1.4. The Smart Reaction: Demand Response

The smart reaction is to involve the demand side in the control mechanisms of the electricity system. A response from the demand side to the momentary electricity price would bring relief in the problematic situations as described above. A demand side response to market prices increases the instantaneous demand when the electricity price falls, and vice versa.

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[5] Left: Situation in western Denmark in 2008: 20% of total demand covered by wind power; wind power surpasses demand in 200 hours per annum. Right: Expected situation of the whole of Denmark in 2025: wind power production covers 50% of total demand; wind power exceeds demand in more than 1,000 hour each year (drawing courtesy of http://www.energinet.dk).

[6] See for example Nordpool Spotmarket News 2009/16, http://www.nordpoolspot.com/

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. At present, *price elasticity* of electricity demand is very low in the electricity markets. This means that the quantity in demand stays constant with a changing price. Higher elasticity in electricity demand would lead to:

1. A lower electricity price (see Figure 4). 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% [IEA 2003].
2. Direct reduction of energy usage in the case demand response is achieved by avoidance of electricity use.
3. Lower usage of conventional peak power plants, which are generally inefficient and environmental unfriendly. For a number of European countries, a concentrated demand response effort of 20 to 75 hours per year leads to a 5% peak load reduction [Feilberg et al. 2003].
4. Lower market power of producers. The number of market parties competing during peak load periods is generally low. This gives peak power producers high market power leading to price inflation. Price elasticity at the demand side will counteract this by increasing competitiveness.

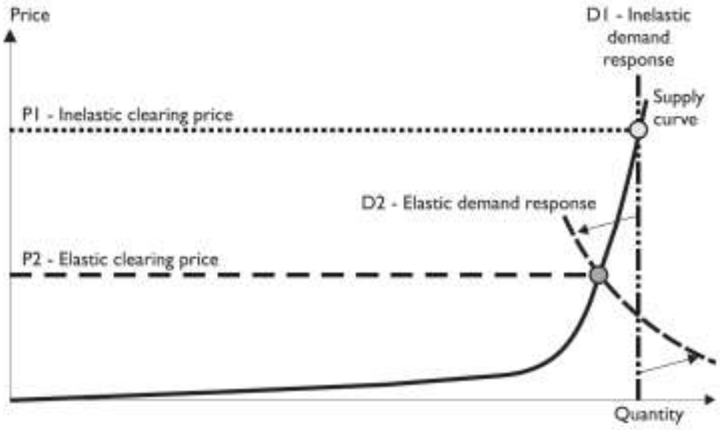

Figure 4: Impacts of demand elasticity on wholesale prices[7]

Typical large flexible loads include different types of industrial processes, e.g., ground wood plants and mechanical pulping plants, electrolysis, arc furnaces, rolling mills, grinding plants, extruders, gas compressors, etc. In the commercial and residential sectors, the largest electrical loads can be made responsive: space heating, space cooling, tap water heating, refrigeration, freezing, washing or drying. Figure 5 gives average appliance load profiles for a generic European home. For all listed appliances, operation can be shifted in time except for the water heater (when it is a water kettle rather than a hot tap water vessel) and the oven/stove.

Household appliances can be involved in demand response in two ways: smart timing of appliance cycles and/or interruptions of appliance cycles. In smart cycle timing, the start of an appliance cycle is chosen such that the complete cycle lies in a preferable time period. For appliances such as washing machines and tumble dryers, this may involve a user action to indicate the preferred maximal ending time of the cycle. For a refrigerator or a freezer this means that the cycle starts before the maximum allowable temperature (or higher control temperature) is reached. In cycle interruption, the appliance cycle is interrupted for a certain period in time. For a washing machine or a tumble dryer, this means that during a running batch the heating process is interrupted for a certain time. For a refrigerator or a freezer this means that the cycle ends before the lower control temperature is reached.

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[7] IEA 2003

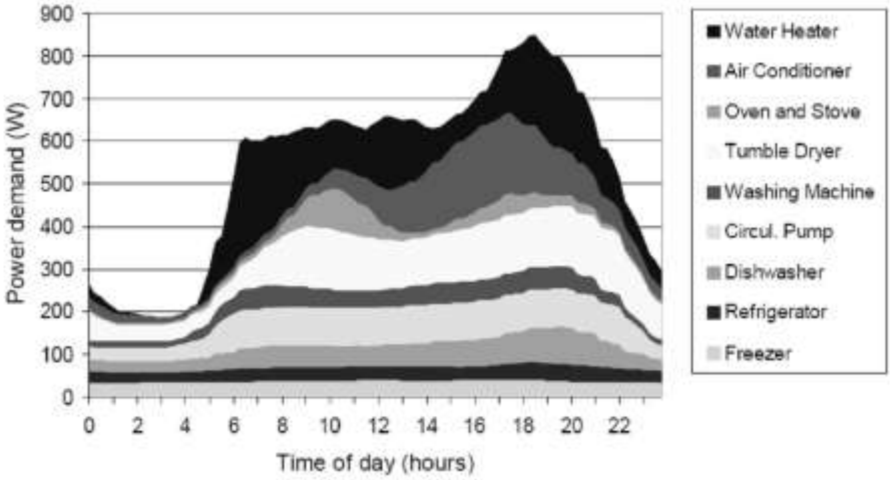

Figure 5: Appliance load profile of a generic European household[8]

Appliance	Smart timing of cycles	Interruptions of the cycle
Washing machine	Typical < 3 hrs; Maximum 9 hr	Typical < 10 min
Dryer		Typical < 30 min
Dishwasher	Typical < 6 hrs; Maximum > 12 hr	Typical < 10 min
Refrigerator / freezer	Typical < 30 min	Typical < 15 min
Other appliances	Typical < 15 min, …1 hr	Typical < 15 min

Table 1: Demand response by household appliances with flexibility boundaries[9]

2.2. Electrification of Everything

The world-wide electricity use has been ever-growing. Specifically, three major trends are accelerating its growth [Berst et al. 2008]:

- 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 2 showing some related growth trends. 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 kWh in 2004 to 30,364 billion kWh by 2030 [EIA 2007]. Only a small part of the world-wide growth in electricity usage takes place in newly electrified areas such as the county-side of upcoming economies such as India and Brazil. That means that most of the growth takes place in the existing infrastructure.

Further, the transition to a more sustainable energy system is an additional accelerator of electrification. The route to governmental sustainability goals, such as the 2020 targets of the European Union, heavily depend on a switch to electricity for a number of energy intensive activities. An example is the transport sector. Creating a more efficient transport sector, to a greater extent fueled by green energy, involves electrification

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[8] Averaged over a large number of households and over the period of one year [Timpe 2009]

[9] Adapted from [Timpe 2009]

of the contingent of smaller vehicles: passenger cars, delivery vans, etc. Electrification of these types of vehicles results in a better well-to-wheel energy efficiency when the electricity is generated from a fossil fuel. Further, it opens the possibility of CO_2-free transportation if the vehicles are charged with 100% green electricity. As may be clear, a major increase in energy efficiency and sustainable energy use depends on higher electricity usage in this case.

Another example is the introduction of heat pumps for space heating. Where a heat pump replaces a resistive heater or a gas boiler, primary energy is saved. In regions where homes and utility buildings are predominantly heated by gas boilers, this efficiency gain involves a switch in energy carrier from gas to electricity.

	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**

Table 2: Examples of electricity growth trends[10]

2.2.1. Ageing Networks Operated to Their Limits

The electricity infrastructures of the western economies have largely been built during the 1960ies and the 1970ies.find a graph of infra investments over time. So, a huge number of grid components such as cables, lines and transformers have reached the end of their economic and technical lifetime. To a great extend, the technical lifespan of grid components is dependent on their usage history. As the ageing process is mainly driven by thermal stress caused by higher power flows, grid components are ageing faster when frequently operated close to, or exceeding, their nominal power load. If never loaded more than 70 to 80% of the maximum allowable load, grid components have virtually an infinite lifespan. So, the growing use of electricity is a threat to our ageing electricity infrastructure. Without action, overloading of old cables and transformers will occur more and more frequently with a rising system downtime as a result.

2.2.2. The Traditional Reaction: Grid Reinforcements

The traditional reaction to capacity problems in the electricity grid are reinforcements, i.e. investments in higher network capacity. For about a century, the only answer to a grid load increase has been adding copper, iron and aluminum to carry the load increase.

Figure 6 gives an example for an increasing number of plug-in electrical cars (PEVs) in a residential area. A PEV charging its battery is a high load for the electricity network, even when it is using a 1 kW slow charger to charge its battery in around five hours. The synchronicity in power uptake from PEVs is much higher than that of other appliances. In a commuter's area most of the cars will be connected to the electricity grid just after the traffic rush hour, contributing to the rush hour in the electricity network. When, in a certain residential area, owning a PEV becomes fashionable, the operator of the distribution network has barely time to dig in extra cables and install additional transformers.

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[10] Berst et al. 2008

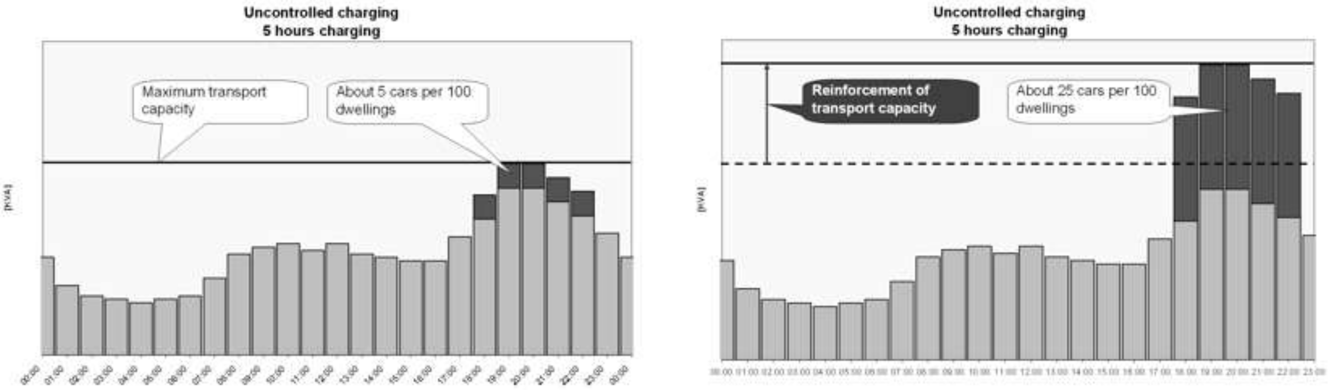

Figure 6: Introduction of PEVs in an existing grid[11]

2.2.3. The Smart Reaction: Active Distribution Management

The smart alternative is using the potential flexibility in local demand and generation to cope with these grid overload situations. In doing so, a step is made from the current passive management of the distribution networks to an active management. In the latter, not only the network itself is considered, but rather the system as a whole, including connected systems at end-customer's premises. For the plug-in electrical vehicles example, this solution is depicted in Figure 7.

Plug-in electrical cars do have a huge flexibility potential, as most car owners need to use their car not earlier than the next morning. A collective intelligent system can assure the user's mobility preferences are met while the electricity grid's loading remains within limits. The user's preferences may include a fully charged car battery by the next morning, while the car must be ready within a short time frame for a short unexpected drive, e.g. to the local hospital. Note that such a system should not be limited to one class of loads. A proper response of other loads and generators in the local network brings relief to the overloaded network.

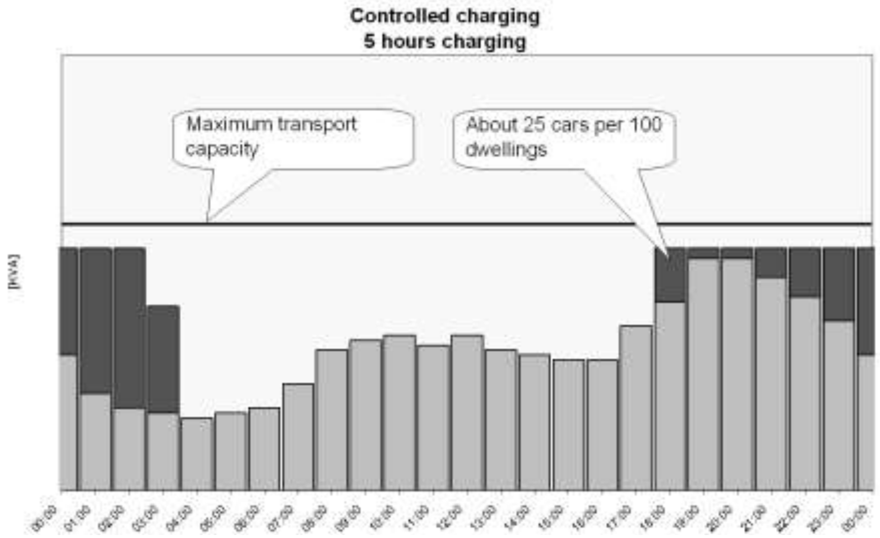

Figure 7: Controlled charging of PEV avoiding network overload and network reinforcements

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[11] Left: a typical mid-voltage load profile for a residential area having a demand peak at the beginning of the evening. There is room for a 5% penetration of PEVs. In the worst case, these cars are used for commuting and connect just before the evening peak. Right: Same situation with 25% PEV penetration. Grid reinforcement is needed (courtesy of the ITM project).

2.3. Decentralization of Generation

Another ongoing change in the electricity sector is a decentralization of generation. A growing share of the generation capacity is 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: 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 [IEA 2002].

2.3.1. Distributed Generation: Types and Drivers

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, are connected to the transmission network. The same holds for combined heat and power production (CHP – or cogeneration). 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 3 categorizes different forms of CHP and RES into either large-scale generation or distributed generation.

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

*** Typically >50MW$_e$; ** Typically >10MW$_e$**

Table 3: Characterization of distributed generation[12]

There are a number of drivers behind the growing penetration of DG (adapted and augmented from [ENIRDGnet 2003]:

- **Environmental concerns, depletion of oil reserves, diversification of energy sources** – All three as described in Section 2.1

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[12] Adapted from [ten Donkelaar/Scheepers 2004]

- **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 electricity in the vicinity of a 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.

2.3.2. Control Paradigm Mismatch

The decentralization of electricity generation is changing the characteristics of power generation in three aspects:

- **Intermittency** – The power production of most types of DG is intermittent in nature. In section 2.1.2 we already discussed the intermittent nature of renewables. Additionally, CHP units operated to follow heat demand are intermittent in nature as well. As stated before, with the growing share of these intermittent energy sources it becomes more difficult to follow the fluctuating electricity demand.
- **Cardinality** – As a result of generation decentralization, the number of electricity production 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. On the other hand, central renewable generation is moving further away from the load centers as large-scale wind farms are being built off-shore and large-scale solar power plants in desert areas.

Distributed generation does not fit into the standard paradigm of centralized control of a relatively small number of big central power plants. As distributed generation gradually levels with central generation, the centralized control paradigm will no longer suffice. 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. The need to involve demand response in the coordination task, as discussed in 2.1.4, only adds to this problem.

2.3.3. The Traditional Reaction: “Fit and Forget”

The traditional reaction to DG is *accommodation* in the existing electricity system, i.e., network and markets. This is the *“fit and forget”* approach. Distributed units are running free, beyond the control of the grid operator or the market-party to which the generated energy is delivered. The individual capacity of each separate DG unit is too small to be active on the wholesale market for electricity. Therefore, electricity supply companies treat DG as being negative demand: it is non-controllable and, to a certain extent, forecastable. As with renewable energy sources, a growth in DG decreases controllability and predictability in the electricity system. Again, the traditional reaction is to increase the capacity of regulating plants, while the total generation share of central generators goes down.

2.3.4. The Smart Reaction: Distributed Coordination

In the smart reaction, distributed generation, demand response, and future options for electricity storage, are integrated in the coordination mechanisms of the electricity system. As argued above, this cannot be done by following the traditional paradigm of centralized control. Thus, a new paradigm for coordination tasks in electrical power systems is needed. The new coordination mechanism is likely based on the state of the art in information and communication technology (ICT).

Before we look into the requirements of the needed ICT system, we take a closer look into the systems that need to play a role in the coordination task at hand. 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 can be treated as a resource. The same holds for distribution network connected electricity storage. Due to this common nature, the overarching term *Distributed Energy Resources* (DER) is used to refer to this threesome: DG, DR and storage.

The high-level requirements of the coordination system that integrates DER in power systems operations and markets include:

- **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 coordination mechanism must be able to accommodate this growth.
- **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.

These requirements ask for a *distributed system*, also referred to as a *multi-agent system* (MAS) for a number of reasons:

- In multi-agent systems a large number of actors are able to interact, in competition or in cooperation. Local software agents focus on the interests of local sub-systems and influence the whole system via negotiations with other software agents. While the complexity of an individual agent can be low, the intelligence level of the global system is high.

- Multi-agent systems implement distributed decision-making systems in an open, flexible and extensible way. Communications between actors can be minimized to a generic and uniform information exchange.
- By combining multi-agent systems with micro-economic principles, coordination using economic parameters becomes possible. This opens the possibility for the distributed coordination process to exceed boundaries of ownership. The local agent can be adjusted by the local stakeholder, and does not fall under the rules and conditions of a central authority. Further, a Pareto efficient system emerges, i.e. a system that optimizes on a global level, while at the local level the interests of all individual actors are optimally balanced against each other.

2.4. The Internet as Metaphor for a Smart Grid

2.4.1. Desirable Properties of the Internet

The internet is used more and more as a metaphor for a smart electricity grid. Two of the three governmental policy visions described above explicitly mention the *internet of energy*. The internet has some interesting properties desirable in the smart electricity grid. To name a few:

- **User interaction and collaboration –** The smart electricity grid does not just connect consumer's installations and generation units to a point of common coupling in the public network. The smart grid rather integrates them in the electricity *system*, it gets end-customers and their installations actively involved in the management of the electricity infrastructure. This is a strong analogy with the Web 2.0, where the user is in the center, in full interaction and collaboration with others.
- **Network of networks –** The two-way power flows in the future electricity networks resemble the two-way data flows in the internet. With the introduction of distributed generation, power can be generated and consumed everywhere in the network. This allows for an internet-like topology of a network of networks. Local network segments provide their own supply with limited exchange of energy with the rest of the network. Then, comparable to the internet, network-operational decisions are taken on the local level.
- **Emergent self-organization –** The internet is a *complex network*, a large collection of interconnected nodes exhibiting overall behavior that cannot be explained by looking into the behavior of individual nodes or links [van Steen 2010]. In complex networks, properties such as self-organizational and self-healing behaviors are emergent. Emergence is the way complex systems, patterns and behaviors arise out of a multiplicity of relatively simple interactions. The current electricity network is lacking these properties.

2.4.2. Emergence of Self-healing Behavior

It is interesting to look a little deeper into the emergence of self-healing behavior in the internet. A strong example of the self-healing capability of the internet was seen after the suicide attack on the World Trade Center (WTC) in New York City on the 11th of September 2001. The WTC complex formed a major connection node in the internet, as three transatlantic data cables connected to the continental data network there. This connection center was located in WTC building 7, which was destroyed by debris from the collapsing towers. Further, in the vicinity of the WTC complex, an internet switching station and two internet exchange points were damaged. [Salus/Quarterman 2002] have measured the Internet's performance over a long time by monitoring the reachability of more than 1,200 Internet servers in the world. At regular intervals, they send off 'ping' messages to these servers and record whether an acknowledgement message is received back. A reachability of 100% means that all servers in their list responded. A lower reachability means that some servers could not be reached either because of these servers were down or due to a disrupted link in the communications path. Just after the attacks the reachability dropped almost 9%. However, within half an hour, reachability rose again 6% [Salus/Quarterman 2002, van Steen 2010].

”This example illustrates two important properties of the internet. First, even when disrupting what would seem as a vital location in the Internet, such a disruption barely affects the overall communication capabilities of the network. Second, the Internet has apparently been designed in such a way that it takes almost no time to recover from a big disaster. This recovery is even more remarkable when you consider that no manual repairs had even started, but also that no designer had ever really anticipated such attacks (although robustness was definitely a design criterion for the Internet). The Internet demonstrated emergent self-healing behavior”.

2.4.3. The Internet of Energy

The internet has been built with two assumptions in mind: scarcity of bandwidth, and fragility of communications channels. Being dependent on telephone-line-based data connections, the engineering of the early internet avoided reliance on anything beyond the own control. This put an emphasis on local management to cope with uncertainty of connections. “Every engineering decision was based on occasional connections, local management, and the knowledge that it was risky to rely on anything that was not controlled in-house” [Considine 2010].

The smart electricity grid needs to cope with uncertainty and variations in production from wind and solar, increasingly unreliable and overloaded lines and cables. The engineering of the future electricity grid needs to prepare for intermittent energy sources distributed unevenly over an infrastructure of inadequate and expensive transmission and distribution connections. “We will have to make our energy decisions assuming occasional connections, local management of use, and the certain knowledge that it is risky to rely on anything that we do not manage in-house.

For a while, we will try to solve these problems with central decision-making and a hierarchical organization. Utility-based management of home and business use will make sense to traditional power engineers. […] This will fail under its own internal contradictions. The US Department of Energy DoE envisions homes and businesses able regularly to operate off-grid for a week; it is unlikely that such remote energy management will work when the grid is down.”

2.4.4. Open Standards and Protocols

Much like the Internet, 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. If the systems should be made interoperable and able to connect to each other like in the Internet, common standards and protocols have to establish. 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 [NIST 2010a]. 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 **Error! Reference source not found.**).
- **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 5.2.1.

- **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 [NIST 2010a].

Security, trust and privacy are key aspects on the emerging smart grid infrastructure that we need to consider. A recently released NIST report [NIST 2010b] provides some considerations and guidelines.

A move towards more intelligent devices that can provide information in an interoperable way to 3rd parties as well as adjust their energy behavior in a flexible manner is a must. It is expected that in the next years, such appliances as well as industrial devices will be available on the market and that could communicate via Internet technologies e.g. web services. This will enable a new generation of smart applications to be developed. Existing standards (described in D1.2) such as DPWS, ZigBee, 6LoWPAN etc would play a key role towards this direction.

Special focus should be given to open approaches and Internet based technologies as the smart grid is seen as part of a larger ecosystem strongly related to the Internet technologies and approaches.

Finally, great expectations are put on the market driven approaches as well as the possibility to open the access via standardized interfaces. Towards this end work carried out in fora such as OASIS and in detail within the OASIS Energy Interoperation TC and OASIS Energy Market Information Exchange (eMIX) TC.

Standards are a necessary part of the smart grid. The goal of such activities is to help with independence of single suppliers (commoditization), compatibility, interoperability, safety, repeatability, or quality. Smart grid related work is carried out in several fora and standardization organizations; however it must be made clear that common agreements that apply globally need to be reached soon. Otherwise we risk having many (sometimes fragmented or incompatible standards) which will further hinder rather than promote the development of the smart grid vision.

3. Electricity ≠ Information

Thus, the internet is used as a metaphor for the intelligent electricity network, the internet of energy. This is a strong image when it comes to explaining the desired properties of the future smart grid: coordination by decentralized decision making, self-organizing and self-healing behavior, user participation etc. The internet is a useful example of a well-performing complex network that demonstrates the desired features and is familiar to everyone. However, when one goes down to the details below the general vision, the analogy does not hold anymore. As *electricity is not information*, electricity networks are different than computer networks. In this chapter we will discuss how.

3.1. Why is Electricity Different?

The most important difference between information and electricity is the continuous nature of the latter. Electricity is a *flow commodity*, an infinitely divisible physical stream. Other examples of flow commodities are flows of gas or liquid such as natural gas, industrially-applied steam and water for heat transport or drinking. Electricity is mainly transported using *passive networks*, in which there is no way of directing the flow to follow a particular pathway through the network. Instead, the commodity follows the path of least resistance, possibly using a number of parallel trajectories. Further, there is no way electricity can be stored in high quantities efficiently, nor in the network itself or at network nodes. These three differences make the electricity infrastructure fundamentally different from data networks, but also from those transporting discrete physical objects such as vehicles. In the following subsections, we will look into this further.

3.1.1. Passive Flow Networks

There are some special behaviors attached to transporting a continuous flow in a passive network:

- **Loop Flows:** In a passive network, a flow from a source to a sink will follow parallel trajectories whenever this is possible. The path with the lowest total flow resistance (i.e. the highest conductivity) will carry the main part of the flow. However, pathways of higher resistance will be loaded proportionally to their conductivity. This phenomenon is known as a *loop flow*. Figure 8 gives an example of this.

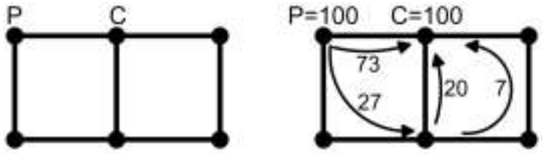

Figure 8: Power loop flows in an electrical network[13]

This behavior has great implications for network planning and day-to-day operations of the electricity grid. To illustrate this, consider the lines in the figure 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 [TenneT 2005].

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[13] 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.

- **Transport path different than contract path:** 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. Figure 9 gives an example of this in a simple example electricity network with two producers (P1, P2) and two consumers (C1, C2). A situation with two contract paths is shown in the middle of the figure: P1 sells an amount of 5 to C2, while P2 sells 4 to C1. The resulting physical flows are depicted in the right-hand side of the figure. Note that 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 further that the flows in the right subfigure are the result of the *superposition* of the contracted flows.

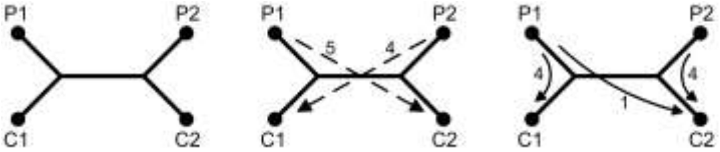

Figure 9: Contract paths and transport paths in electricity[14]

These special behaviors have special implications for the way the electricity system is managed. 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.

3.1.2. Absence of 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, which could eventually result in a black-out. This means that, on a timescale of tens of seconds, the total supply in the system must equal total demand. On a timescale of seconds, some infrastructure-inherent storage is present due to the rotating mass of turbines in bigger power plants. 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 feature is unique to electricity. In Section 3.2.4 we will discuss the implications of this characteristic for the interaction between network management and electricity markets.

3.1.3. Causal Relation Between Demand/Supply & Network Loading

The purpose of communication networks is getting messages from their source to their intended destination(s). Hence, the main operational process is message routing. For each node in the network, this involves defining what must be done if a message is received from source *A* destined for node *B*. Here, the causal relations are from the inside behavior to the outside behavior. Efficient packet switching at the nodes gives an efficient loading of the data connections and, hence, leads to a good data throughput for the users at the terminal nodes. Algorithms used in message routing and network analysis (Google) are rooted in discrete mathematics, with graph theory and discrete logic as main tools.

In passive flow networks, routing is not the problem. When at a source *A*, a certain amount of the flow commodity is produced while at destination *B* the same amount is consumed, the network takes care of the

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[14] Left: simple example electricity network with two producers (P1, P2) and two consumers (C1, C2). Middle: Example situation with two contract paths. Right: The resulting physical flows. For the sake of the example, transport losses have been neglected.

routing, fully automatically. The problem is rather to coordinate A and B to produce, respectively consume, the same amount at the same time. Assuring the demand/supply balance is the key task in the operation of a flow network such as the electricity network. This task is constrained by the capacity of the individual links in the network. Overload situations must be avoided for all network components. Note that for passive flow networks the causal relations are from the outside to the inside. Both subtracting and injecting the flow commodity at terminal nodes is an active deed of a network user. The combination of all these actions leads to a certain loading of the individual connections in the network.

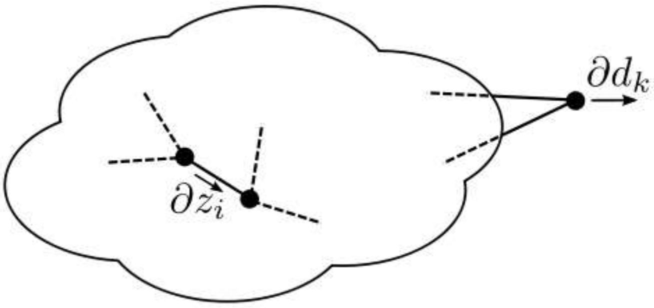

Figure 10: Outside to inside causality in passive flow networks[15]

3.2. 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.

3.2.1. 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.

Figure 11 and Figure 12 present a model[16] of the electricity system. In this text, the financial flows that result from the electricity trade are referred to as the 'commodity transaction', to distinguish it from transactions related to the physical electricity flows. In these 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.

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[15] A change in demand at node k results in a change in the flow through line i. Note that, contrarily, in a packet-switched data network the causality is from the inside to the outside: efficient switching at the inner nodes gives good data throughput at the terminal nodes.

[16] This model and its description is adapted from [van Werven/Scheepers 2005], Section 3.1.

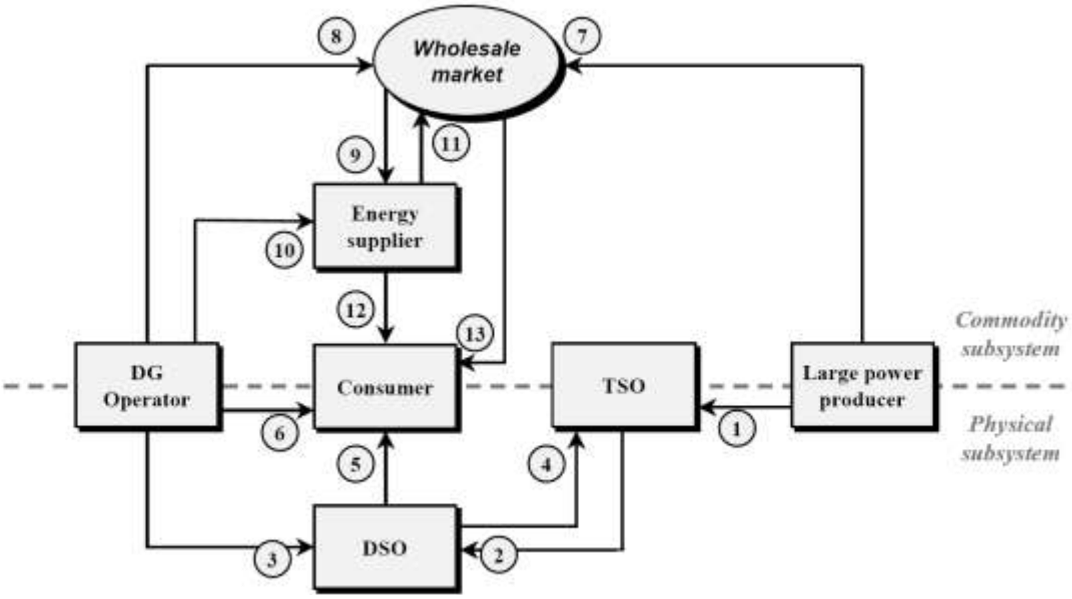

Figure 11: Overview of transactions within the electricity market[17]

In the liberalized electricity market, several relevant parties can be distinguished (parties and their definitions are based on European regulations [EU 2003]):

- 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 system's long-term ability 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 3.2.4), reserve capacity (i.e., compensating 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 system's long-term ability 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.

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[17] van Werven/Scheepers 2005

3.2.2. 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 distributed generators), transmission network (TSO), distribution networks (DSOs) and loads (consumers) [de Vries 2004]. The physical subsystem is depicted in the lower part of Figure 11. 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, distributes it to the final consumer. Relation 5 represents the connection and use of system charges paid 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 local consumption 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.

3.2.3. 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 11. 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, including their mutual relations, any supporting activities and regulation (adapted from [de Vries 2004]). 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.

3.2.4. The Balancing Market

System operators and contractors have to estimate demand in order to ensure 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 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 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.

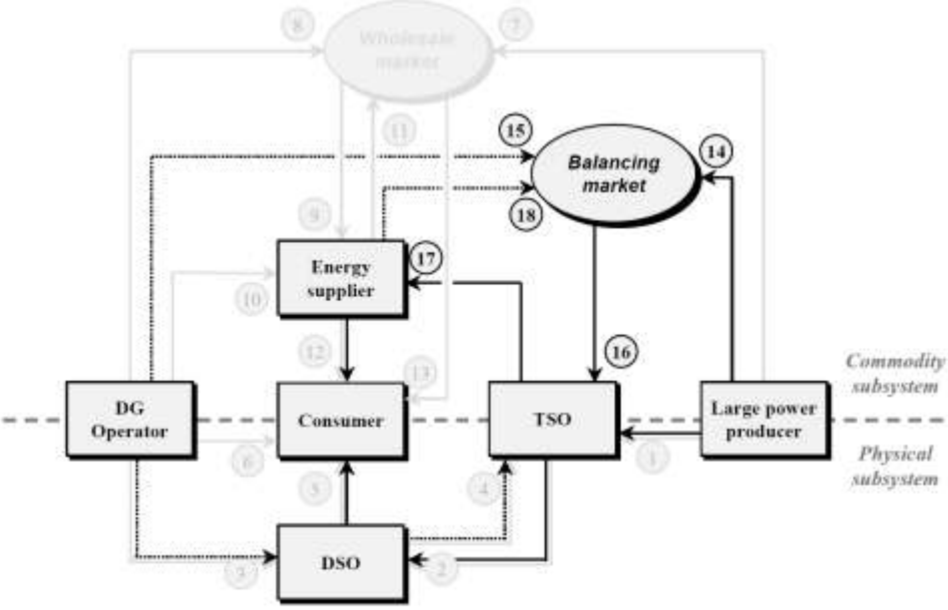

Figure 12: Transactions within the electricity market, including the balancing market[18]

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 12 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 (15, CHP units) or energy suppliers (18) offer balancing power as well. 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's 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.

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[18] van Werven/Scheepers 2005

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.

3.2.5. 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, currently provided by generators and system operators, are required to provide system reliability and power quality.

4. Smart Grid Operations

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. Therefore, more intelligent decentralized alternatives have been developed within the SmartHouse/SmartGrid project. They deliver price signals or incentives to customers who can then optimize their energy consumption based on these inputs. Price-based coordination can be realized through time-varying tariffs, as implemented in Field Trial B (termed as time-of-use rates or real-time pricing, see Section 4.1.2). 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; this has been tested in Trial A (see Section 4.1.5). Dedicated procedures to negotiate appliance operation in critical grid situations, like those tested in Trial C (termed event-based mechanism, Section 4.1.7).

4.1. Optimization in Electricity Trade & Supply

Parties involved in energy trade and supply are having a competitive advantage when the electricity consuming and producing units under contract are either well predictable or well controllable. Unleashing the inherent flexibility of the DER at their contracted end-customer's premises drastically increases the controllability in the customer pool. This, in turn, can provide added value to the supplier's wholesale electricity trade. To understand how, it is important to understand the workings of, and the relationships between, the different electricity markets and the trading position of a supplying company in it.

We focus here on parties that are active on the wholesale markets with the purpose of supplying electricity to end-customers. The high-level interactions of such an 'energy supplier' were discussed in section 3.2 in the context of Figure 11. Here we further detail the trading actions of an electricity supplier on the different wholesale markets for electricity.

4.1.1. Wholesale Market Timescales and Electricity Profiles

The contract portfolio of an energy supplier consists of end-customers of different types: industries and households in various customer segments. The aggregate of these customers follows a certain profile of electricity exchanged with the electricity grid. It is in the supplier's commercial interest to buy this load profile on the wholesale market in advance and as precise as possible. Any remaining difference between the traded profile and the actual profile is automatically traded on the balancing market without any actions of the supplier. As prices on the balancing market are more volatile and on average higher, this imposes higher price risks on the supply party.

The "electricity wholesale market" consists of a collection of markets working in different time scales, as shown in Figure 13 (a). 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 process with narrowing time horizon. Each procurement phase can be supported by energy exchanges or can be carried out bilaterally between generators and retailers (over-the-counter – OTC – trade). An energy supplier trades on these different markets in order to minimize both its procurement costs and its price risk level.

Figure 13: Wholesale electricity markets[19]

- **More than 1 year ahead:** An energy supplier buys part of the load profile he expects to deliver in a certain time period already years ahead on the futures market. The amount of energy he buys depends on the expected contract portfolio for that future time period, the average load profile of that portfolio and his estimation of the price risk of the different wholesale markets. At the futures market, common products are *base load* blocks and *peak load* blocks (e.g. 8am to 8pm) for complete calendar years or year quarters. These power blocks are either bought via an over the counter bilateral trade, for instance with a production plant owner, or via a futures market operator. An example of the latter is *Endex*, see Figure 14.

NL Power (€/MWh)

Tue, 05 May 2009 12:13

	base load	peak (8-20)	16hrs peak (7-23)
Jun-09	36.42↘	50.44↘	47.15↘
Jul-09	40.17↘	55.28↘	51.97↘
Aug-09	36.76↗	50.65↗	47.65↗
Sep-09	42.87↗	57.92↗	55.12↗
Q3-10	50.36↗	70.64↗	67.53↗
Q4-10	63.13↗	92.35↗	87.08↗
Cal-10	54.99↗	78.42↗	74.43↗
Cal-11	59.09↗	85.88↗	82.08↗

VATTENFALL TRADING SERVICES JOINS ENDEX

ENDEX has admitted Vattenfall Trading Services GmbH as a new trading member on its Futures Exchange.

New Dutch Power Peak Load (8-20)

Figure 14: Market price data of the Endex futures market in the Netherlands[20]

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[19] (a) Timescales of and traded volumes on different wholesale markets. (b) An electricity provider, actively trading on different markets to match the load profile of its clients

[20] The Endex matches buyer and sellers of electricity for three different products: base load, peak load (from 8am to 8am) and 16-hours peak load, from 7am to 11pm. Period lengths vary from 1 month for the next 6 months to complete calender years up to 5 years ahead. This screenshot is dated May 5th, 2009.

Suppose an electricity supplier has an expected daily load profile for a certain period as depicted by the solid line in Figure 15. Suppose further that this supplier does not own generation assets of its own, so all energy supplied to its customers must be bought on the markets. One to five years in advance, this supplier is able to buy the power blocks indicated in gray on the futures market. Note that this is an iterative process in which year blocks are bought first, which are adjusted for seasonal influences when the year-quarter products become available, etcetera.

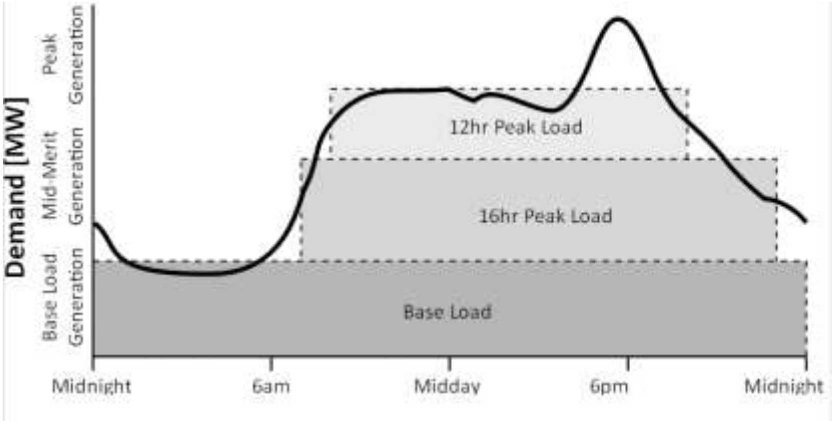

Figure 15: Futures market products bought to cover an expected load profile

- **1 year to few days ahead:** Uncertainty in the expected load profile decreases over this period for a number of reasons. Firstly, the exact composition of the contract portfolio becomes clear, with new customers acquired and old ones leaving as client. Secondly, the uncertainty in the weather forecast reduces over this period. By buying and selling base load and peak load blocks for specific months the supplier is able to detail its profile to the level of individual months. In bi-lateral trades with power producers or middle-man traders, the supplier can do the same for individual weeks or days.
- **1 day ahead** On the day-ahead market, the supplier buys and sells power, again, in order to get closer to the current expectation of the profile. Weather forecast uncertainty has decreased further and special events (the national team plays the World Cup Final) have become known. Virtually all day-ahead trading takes place via the *Power Exchange* operated by a market operator that pools all demand and supply for each of the 24 hours of the next day. Trading in hourly blocks allows the supplier to detail its coarse profile of base and peak load blocks bought on the futures market into a profile of hourly blocks. From Figure 16 it can be seen that this may involve both buying and selling.

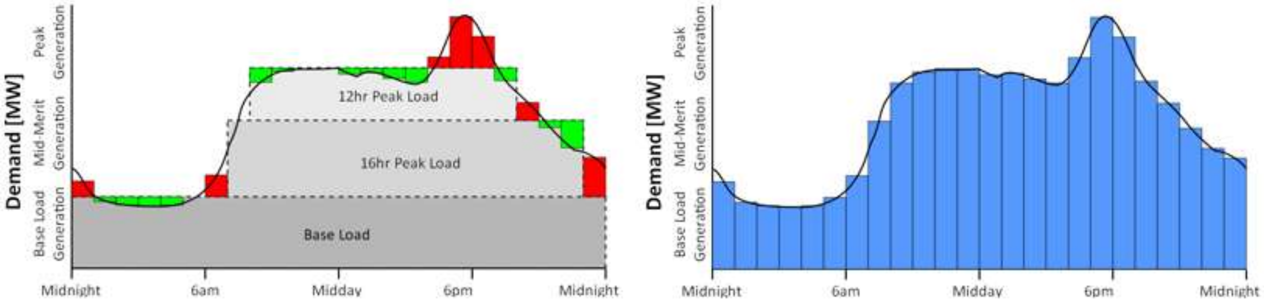

Figure 16: Power exchange (day-ahead market) trades to cover an expected load[21]

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[21] (a): Power exchange adjustments made to the profile bought on the futures market. Power is bought for those hours where the expected load is higher than the power bought on the futures market. Likewise,

- **Few hours ahead:** Market parties are allowed to trade until a certain *gate closure* time, which is typically a few hours before *real time*, i.e. the time of actual delivery. The gate closure is further discussed in section 4.1.3. Until gate closure, intraday-trades are possible either via a market operator (intra-day market) or via bi-lateral trades with individual market parties.

At the time of delivery, all customers in the suppliers' contract portfolio exchange a certain amount of electrical energy with the electricity network. When the supplier's forecasts were right, there is little discrepancy between the net volume actually exchanged with the network and the traded energy volume. However, all remaining discrepancy is automatically traded on the balancing market. We will look at this in greater detail in the next section.

4.1.2. 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 [Doty/Turner2009]. 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.

Since this price variability on the wholesale markets described in Section 4.1.1 is usually 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. However, 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 [Nestle/Ringelstein 2009].

Hybrids of time-of-use and real-time pricing are also conceivable; they usually referred to as *Critical Peak Pricing* [U.S. DOE 2006]. 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.

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power is sold for the hours where the expected load is lower. (b): The resulting profile in hourly power blocks.

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.[22] 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) [Bye/Hope 2005].

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 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.

4.1.3. The Balancing Market Revisited

The *Balancing Market Mechanism* is used by TSOs throughout the world. The balancing market has been described from a bird-eyes view in subsection 3.2.4. Here, we zoom in on some of the implementation details of the balancing mechanism relevant to balancing services delivered by virtual power plants. The European variant of this mechanism is part of the ETSO Scheduling System (ESS) and is widely implemented by European TSOs. In this context, an actor that is responsible for a balanced energy volume position is called *Balance Responsible Party* (BRP). The Balancing Mechanism consists roughly of three parts:

1. **Balancing responsibility –** The obligation of BRPs to plan or forecast the production and consumption in their portfolio and to notify this plan to the TSO. The granularity of notified plan is given by the settlement period length, typically 30 or 15 minutes. The notification is done before some gate-closure time, a predefined period ahead of the start of the settlement period.

2. **Reserves for frequency response –** The TSO contracts generation capacity for primary, secondary and emergency reserve. Production sites of a certain capacity are obliged to make available a predefined portion of their capacity to the TSO. Market parties signal the availability of reserve capacity by sending a bid to the TSO. In case of (smaller or bigger) system-wide imbalance, the TSO calls off the reserves available in the order of their bid prices, in order to restore the instantaneous system balance.

3. **Settlement of imbalance costs with the balancing responsible parties –** In a later stage, the TSO charges the actual costs for the used reserve and emergency capacity to those BRPs that had deviations from their energy programs. These charges are referred to as imbalance costs.

This system gives wholesale trading parties incentives to maintain their own portfolio balance, while it provides means to charge the costs made by the TSO when maintaining the real-time system balance to those parties responsible of the unbalance.

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[22] 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 [EEX 2010, BMWi 2010].

Depending on the nation-specific regulations, the plan notified to the TSO is valid for a certain grid area, referred to as a control zone. The BRP is obliged to provide a plan for each control zone it has contracted generation or load in, and needs to follow the plan for each zone individually. So, a BRP is allowed to compensate for imbalance occurring in one part of a control zone using units in another part of the same zone. Typically, control zones cover a large geographical area: The Netherlands, for instance, is a single control zone, while the United Kingdom is divided in 14 of such zones. In real time, deviations between the planned electricity production and consumption in a specific control zone become visible to the TSO through deviations in the planned import to or export from the zone. In real time, the TSO monitors the zonal balance and maintains the real-time zonal balance by adjusting generation up and down using the contracted reserve capacity. By doing this, the TSO compensates the net imbalance of the group of BRPs having a deviation from their notification. Afterwards, the TSO compares the real, measured, energy profile of the full portfolio of each BRP, with its notification. For every settlement period, the costs made for the usage of reserve and emergency capacity made by the TSO are spread over all BRPs that caused imbalance in that particular period. Although the TSO balances the over-all system on a second’s basis, settlement of imbalance caused by BRPs is done on a longer timescale, typically 15 or 30 minutes.

In the remainder of this chapter, we consider the situation in one single control zone. Consequently, if we refer to a BRP having a contract portfolio and taking measures to influence the imbalance position of this portfolio, we assume this to take place in one control zone.

4.1.4. Portfolio Imbalance: Wind Energy

As imbalance prices are generally more volatile and on average higher than day-ahead prices, the system of balancing responsibility imposes imbalance risks to market parties. Among BRPs, this risk will vary with the predictability of the total portfolio of the BRP. BRPs with low portfolio predictability are faced with higher imbalance risks.

Typically, wind power production suffers from low predictability. This gives higher imbalance costs resulting in a lower market value for electricity produced by wind turbines. In general, any market disadvantage due to high imbalance costs can be reduced by increasing either the predictability or the controllability. Using specialized forecasting techniques as post-processors to high-resolution meteorological models, the day-ahead predictability of wind energy production has been improved substantially over the last decade [Ernst 2005, Brand/Kok 2003]. However, a substantial error margin remains.

Figure 17 shows a typical remaining forecasting error profile of such a system. The figure shows three main sources of wind energy forecasting errors in three consecutive windy periods. In the first windy period in the figure, around March 8th, the forecast is relatively good, but the turbine is out of operation for a certain period of time, supposedly for some technical reason. For the next windy period, both the complex shape and wind magnitude of a passing weather system were forecasted fairly well, but the timing was wrongly forecasted. Finally, around March 11th, the forecasting system gives a good forecast for both shape and timing of the passing weather system. Unfortunately, the magnitude of the electricity output is seriously underestimated, resulting in a high imbalance level.

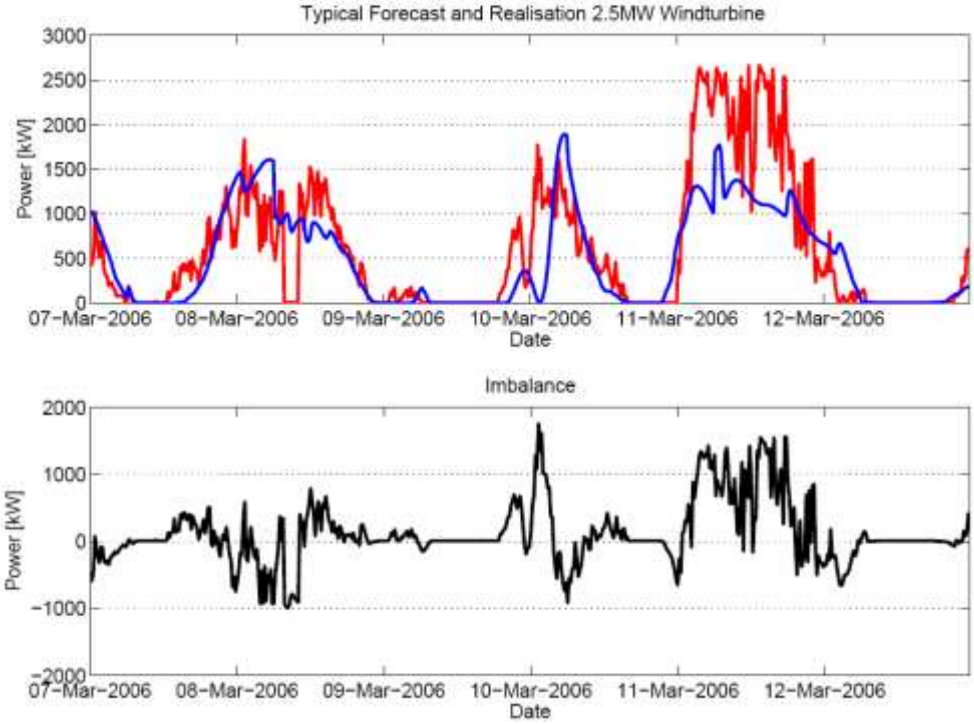

Figure 17: Typical wind electricity unpredictability[23]

4.1.5. 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 [Weidlich 2008]. 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 [McAfee/McMillan 1987]. Double-auctions deliver efficient allocations if the number of sellers and buyers is sufficiently large [Wilson 1985].

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. [Kok et al. 2009, Franke et al. 2005, Lamparter et al. 2010]. 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 [Akkermans et al. 2004]. 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

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[23] Top: Actual production (red) of a 2.5 MW wind turbine in Kreileroord, The Netherlands, and the day-ahead forecast (blue) of the same turbine. Bottom: Resulting imbalance (actual minus forecasted). The forecasting model used is the one described in [Brand/Kok 2003].

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 [Schnizler et al. 2008].

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 [Kok et al. 2009]. 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 [Kok et al. 2009]:

- **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.

4.1.6. Virtual Power Plant Balancing

As described above, the system of balancing responsibility imposes imbalance risks to market parties. In practice, there is virtually always a smaller or bigger discrepancy between the traded energy volume, as notified to the TSO, and the real measured profile. Figure 18 shows such a discrepancy. To reduce this risk, market participants undertake balancing activities. These activities can both take place before gate closure as well as in the settlement period itself:

- **Pre gate closure –** Typically, balancing activities before gate closure occur in the power exchanges. Market parties fine tune their positions close to real time by contracting with generators or suppliers in order to adapt their position according to short-term load forecasts. This is the day-ahead and intra-day trade as described in subsection.
- **Within the settlement period –** After gate closure, each BRP is on its own: each trade with other market parties cannot be notified to the TSO and, thus, will contribute to the BRP’s imbalance. The BRP can only

influence the producing and consuming units in its own portfolio to achieve in real-time the desired net physical energy exchange with the network for each control zone.

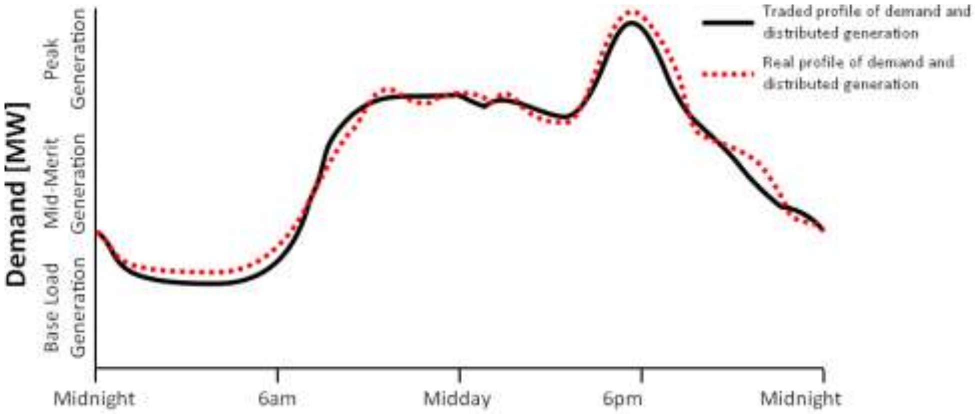

Figure 18: Traded and real electricity demand profiles

The exact meaning of the word ’desired’ depends on the information the BRP has in real-time regarding the system-wide balance and/or the momentary imbalance prices. Here, three different information levels can be distinguished:

1. **No information** on the system-wide imbalance or on the expected imbalance prices for the current moment in time is available to the BRP. This is the case when the TSO does not publish imbalance (price) information in real-time. Further, the BRP has no means to estimate the sign and magnitude of the current imbalance. In this case, the best strategy of a BRP is minimizing its portfolio imbalance in each settlement period.

2. **Information on the system-wide balance magnitude** is available to the BRP. This is the case in regions where the TSO publishes in (near-)real-time the current imbalance volumes, see Figure 19. With this information, a BRP can determine whether its current imbalance position will result in imbalance costs (when the imbalance directions of both the BRP and the system are the same) or in imbalance revenues (when the portfolio imbalance is opposite to the system imbalance). A semi-passive strategy of a BRP is minimizing its portfolio imbalance only in cost situations. An active strategy is to counteract the system imbalance when it is relatively high and, thus, imbalance prices are expected to be high.

3. **Information on the actual imbalance prices** is available to the BRP. This is the case when the TSO publishes the imbalance prices in real-time (see Figure 19) or, alternatively, when the BRP has means to estimate the current imbalance price level. In some regions, the TSO publishes the momentary imbalance prices in (near-)real-time. When prices are not published in real-time, those BRPs actively offering frequency regulating reserve capacity to the TSO bid ladder are able to make an estimate of the going imbalance prices. It is known to these parties which of their own reserve capacity bids are called off by the TSO. By strategically placing their reserve capacity bids spread over the bid ladder price range, a BRP is able to make a good estimate of the going imbalance price.

Time indication			Activated power					Price development	
			Regulating		Reserve		Emerg. (0/1)	Highest price	Lowest price
Number	Seq. nr.	Time	Up	Down	Up	Down	Up	Up	Down
1	1309	21:48	0	133	0	0	0		20,01
2	1308	21:47	0	156	0	0	0		20,01
3	1307	21:46	0	165	0	0	0		20,01
4	1306	21:45	0	167	0	0	0		20,01
5	1305	21:44	0	168	0	0	0		17,55
6	1304	21:43	0	168	0	0	0		17,55
7	1303	21:42	0	168	0	0	0		17,55
8	1302	21:41	0	165	0	0	0		17,55
9	1301	21:40	0	158	0	0	0		19,55
10	1300	21:39	0	154	0	0	0		20,01
11	1299	21:38	0	151	0	0	0		20,01
12	1298	21:37	0	144	0	0	0		20,37
13	1297	21:36	0	142	0	0	0		20,55
14	1296	21:35	0	139	0	0	0		20,55
15	1295	21:34	0	135	0	0	0		21,00
16	1294	21:33	0	134	0	0	0		21,00
17	1293	21:32	0	131	0	0	0		21,00

Figure 19: Momentary system-wide imbalance as published by the Dutch TSO[24]

The flexibility of a virtual power plant can also be used to reduce ramping steepness. The ramp rate of a generator is the speed at which the power output of the generator can be regulated upwards (ramp-up rate) or downwards (ramp-down rate). For every generation unit these rates are limited to a certain level which is set by the technical capabilities of the unit. For thermal power plants, especially the ramp-up rate is limited.

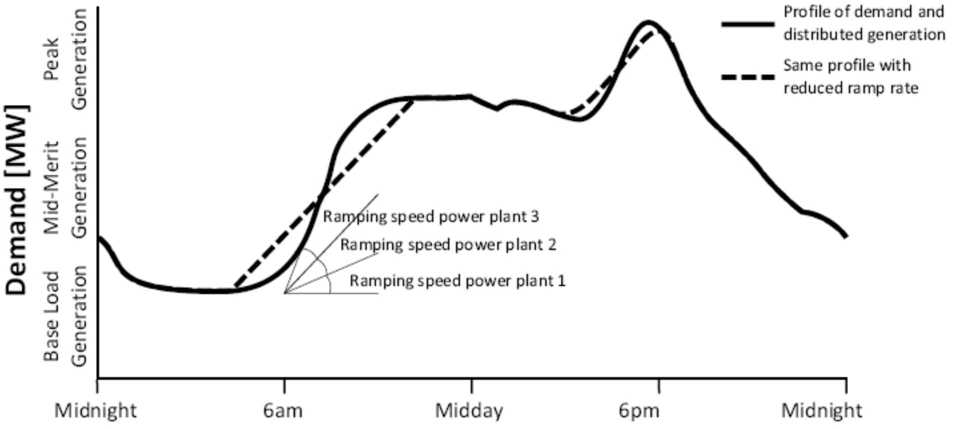

Figure 20: Reducing the ramping speed of a customer pool's daily profile[25]

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[24] The table as available since September 2009 when info on the prices of the price setting bids was added; the web site publishing this table is updated every minute with a 2 to 3 minute delay [TenneT 2010]. TenneT publishes this information in order to make the energy market more transparent [TenneT 2009].

[25] Traditionally, the rising flanks of a daily profile are matched by ramping a number of power plants simultaneously. Reducing the profile's flank steepness decreases the number of power plants needed to follow the ramping. Figure adapted from [Pelgrom et al. 2009], courtesy of Essent.

As Figure 20 shows, load profiles of bigger groups of consumers may exhibit rising flanks that cannot be matched by the ramp rate of any of the generation units in the set of units collectively following the load. In these cases, a number of units need to be ramped up simultaneously in order to follow the ramping rate of the load pool. A VPP gives the opportunity to reduce the number of traditional power plants needed in such a situation. A VPP would be able to manage the demand in such a way that the overall steepness of the load pickup gets lower. At the same time, the VPP would be able to ramp up the distributed generators in the VPP cluster. As the number of generating units in a typical VPP will be high, a VPP will be able to reach a high ramp rate.

On the level of a BRP, reducing ramping steepness of the contracted load pool has a number of potential benefits. Firstly, wear of thermal power plants is reduced by avoiding fast thermal fluctuations in the steam boilers. Secondly, the number of traditional power plants needed to follow the cumulated load ramp of the BRP's clients may be lower. Thirdly, it makes ramping power available to deliver to the TSO as regulating power.

4.1.7. Event-Based Load Control

Another operation that is supported by the systems of the SmartHouse/SmartGrid concept is the identification of emergency events. This process requires fast reaction to certain events, usually under unusual situations. In order to support the event-based operation, some characteristics are very important.

The primary characteristic is the fast event detection which requires a complicated measuring system. For example, the MAGIC system has several measuring points with the central in the panel level to be the most powerful. For example this system has the ability to measure:

- RMS values of voltage, current and power (minimum refresh rate 60 ms)
- Voltage dips (minimum duration 100 ms)
- Over current (minimum duration 100 ms)

However, a fast detection system is not the only necessary system since the central processor should powerful enough in order to process these events, thus special software routines were implemented.

The next issue related to the event-based control is the communication infrastructure. The existence of a reliable system with sufficient bandwidth and minimum latency is mandatory. Furthermore, the event based control in the MAGIC system is supported by a complicated communication-messaging system. The message exchanges in the system are complicated and require a flexible communication system. This is provided by the message transport system (MTS) which is in charge of delivering messages between agents within the same agent platform or other agent platforms. [FIPA] specifies the requirements and the characteristics for the MTS regarding the communications between agents in different agent platforms (IIOP or HTTP). By this way, the interoperability between agent platforms is ensured.

The last issue has to do with the reactions to an event especially those events that require the collaboration of several agents. This type of events is the black start and the load shedding. In order to achieve that, special algorithms are required in order find the correct solution quickly. The primary concern in this system is the communication delays which leads to a special design of the algorithm. The key characteristic is that the agents constantly exchange information about the system status and know what the necessary actions are in case of any emergency.

4.2. Active Distribution Management

Future power systems will be much different due to the reasons discussed in Section 2. Future distribution network management systems adopt the term "active distribution network" in order to describe a network with totally new functionalities in order to deal with a set of new problems. The major issues facing future distribution networks are summarized in the following.

Voltage Control

One of the major problems that derive from the existence of DGs in the low voltage distribution networks is voltage problems. Voltage quality describes the main characteristics of voltages in three phase systems:

- Network frequency
- Slow voltage fluctuations
- Fast voltage fluctuations (flicker)
- Voltage dips
- Transient over voltages
- Voltage asymmetry
- Harmonics

DG may have an impact on local voltage quality. Network frequency may vary stronger in island operation mode. Voltage asymmetry becomes an important topic if small scale generation is connected only to a single phase and different generation units are not equally distributed between the phases. Voltage fluctuations are higher due to fast changes in active and reactive power generation especially of renewable energy resources.

Protection Issues

The structure of a traditional power system considered the feeding of the loads by large power stations through the transmission and distribution network. However, this one-direction power flow will change with the introduction of DGs. Thus, the future protection system should also identify the source or direction of the fault current. Furthermore, the extended usage of power electronics cannot provide the required levels of fault currents.[26]

Furthermore, the future distribution network requires a new look into the design and operation of the protection. The proposed solution requires the adoption of fault ride through capabilities, distance and differential protection as well the usage of coordinated protection devices. These devices should be supported by strong ICT infrastructure.

Safety of Supply

Next issue is about the reliability of the network and the increase of power quality indexes such as SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index) that describe the power outages in the distribution network.[27] The existence of DG in the distribution networks may improve these indexes. They can further be improved by the introduction of coordinated operation. However, this requires the usage of complex ICT infrastructure considering that the main problem is the large number of the devices in the network.

Advanced Operations

Next to the increase of power quality indexes, some advanced functionalities may be introduced such as the islanding operation, the black start and the congestion management in the distribution network. These operations required an active distribution network with advanced control capabilities in order to manage all the DG sources during the emergency operation. It is beyond any doubt that the existence of control and management mechanisms is mandatory for these operations.

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[26] This topic is extensively discussed in reports of the *More Microgrids* project (http://www.microgrids.eu/).

[27] This is also discussed in the *More Microgrids* project.

Aging Equipment and Network Extensions

Another significant issue that should be considered in the distribution networks is the aging equipment, which becomes a serious problem for all utilities across Europe. Furthermore, network extensions, both in distribution and transmission network, become more expensive and difficult during the years. The introduction of DG production in close proximity of the consumption and the active management of it may allow postponing large investments. The cost of equipment for creating the active distribution network seems to be lower than the new investments.

Electric Vehicles

Another topic that most utilities focus in the future is related to the introduction of electric vehicles (EV). EVs will significantly increase the load in the distribution network when their penetration will be very high. Therefore, the infrastructure for the management of the EVs will be important in order to shift the electricity demand for charging in the low load hours (valleys) and avoid the increase of the peak load. Furthermore, studies and projects[28] investigate the possibility of management of the EV's battery in order to support the network operation by injecting energy during peak hours.

Market Operation

Finally, one of the most important issues in the distribution network operation is the market functionalities. Thus, in the unbundled environment, a set of new entities exist, such as DSO, retail companies, ESCos or metering services providers. All these entities interact directly or not with the network leading to a very complex environment. The fully automated distribution network is mandatory in order to support and allow the operation of all these new entities.

Active Distribution Networks

In the previous sections, some of the major problem and challenges in the distribution networks were presented. The key conclusion is that future distribution network should become smarter and active. The installation of advanced control and communication equipment is mandatory in order to ensure smooth operation. The active distribution network that incorporates all these control and ICT functionalities is the evolution of the traditional distribution network and this fact is identified by all the utilities.

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[28] E.g. the EU co-funded projects MERGE (http://www.merge.eu/) or Green eMotion

5. SmartHouse/SmartGrid Functionalities

The technological developments in the SmartHouse/SmartGrid project have been based on nine business cases that describe how smart grid approaches could be applied by single stakeholders in the electricity supply business. As shown in Figure 21 (which is based on Figure 11), not all business cases are applicable to all stakeholders, but each stakeholder has more than one business case that he can apply.

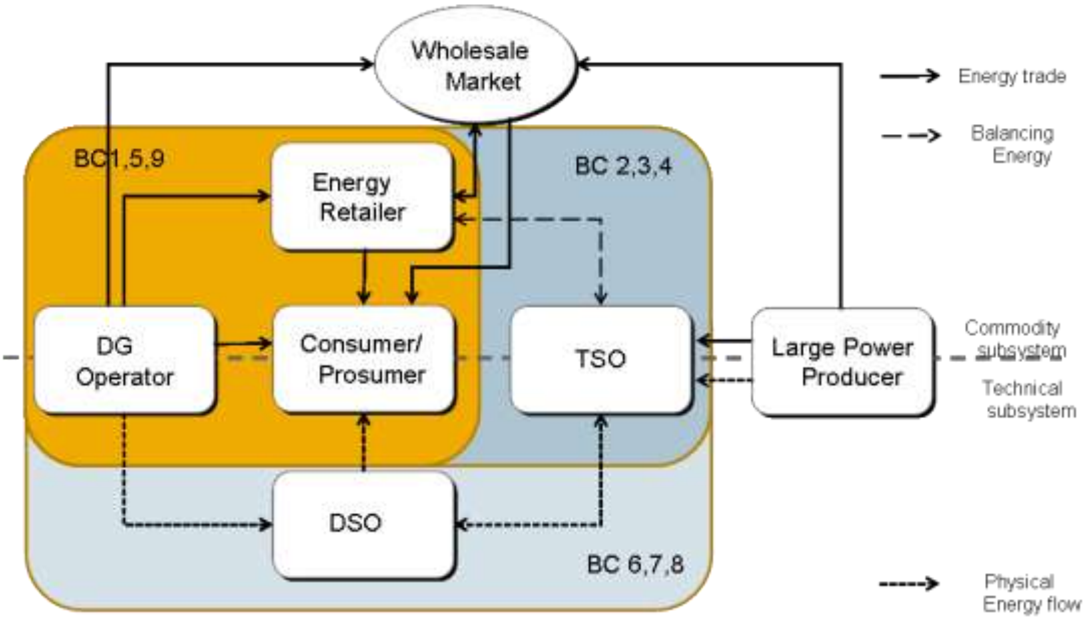

Figure 21: Mapping the business cases to the market participants

In the following, the nine business cases are summarized (Section 5.1). Detailed descriptions of them are given in deliverable D1.1. Based on these business cases, the common prerequisites that we take as given in the SmartHouse/SmartGrid project are summarized in Section 5.2, and the functional and non-functional requirements of SmartHouse/SmartGrid technologies are derived in Sections 5.3 and 5.4.

5.1. Business Cases

In the SmartHouse/SmartGrid project, nine business cases have been described. They formed the first step towards the architectural design of the ICT systems developed within the project. A short description of each case is provided in the following subsections 5.1.1 through 5.1.9. A more detailed description of each case is given in the project deliverable D1.1, which is publicly available at the project website.[29]

5.1.1. Aggregation of Houses as Intelligently Networked Collaborations

SmartHouse/SmartGrid concepts will exploit the potential that is created when homes, offices and commercial buildings are treated as intelligently networked collaborations. When SmartHouses are able to communicate, interact and negotiate with both customers and energy devices in the local grid, the electricity system can be operated more efficiently, because consumption can be better adapted to the available energy supply, even when the proportion of variable renewable generation is high. A commercial aggregator could exercise the task of jointly coordinating the energy use of the smart houses or commercial consumers that have a contract with him.

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[29] All public deliverables and further project related publications are accessible at http://www.smarthouse-smartgrid.eu/index.php?id=146

The joint management of a collection of houses and commercial sites can be done in two ways. The aggregator might directly control one or several participating devices (e.g. deep freezers, air conditioning); this would require the end-users to allow direct access to the control of these appliances. Another way is that an aggregator can only provide incentives to the participating devices, so that they will behave in the desired way with a high probability, but not with certainty. The second option leaves the power of control to the end-user, i.e. the owner of the appliances, and might thus be more acceptable, and also easier to implement from a legal perspective.

One important concern in the aggregation of smart houses as intelligently networked collaborations is to avoid tipping effects in a mass application scenario: if all customers are controlled in a uniform way or all customers are given the same incentive at the same time, the overall system might destabilize by the sum of all reactions. This would compromise the objective behind the coordinated control, i.e. a more efficient operation of the energy system. Therefore, solutions for aggregating and jointly controlling smart houses have to deal with the implications of a mass use scenario and avoid tipping effects.

5.1.2. Real-Time Imbalance Reduction of a Retail Portfolio

This business case is rooted in the balancing mechanism as applied in Europe and defined by the ETSO Scheduling System. It is described in Section 4.1.3. As imbalance prices are very volatile, the system of balancing responsibility imposes imbalance risks to market parties. Among BRPs, this risk will vary with the predictability of the total portfolio of the BRP. BRPs with low portfolio predictability are faced with higher imbalance risks. For instance, parties with a high share of wind energy in their portfolio are faced with higher imbalance costs. To manage imbalance risk, market participants undertake balancing activities. These activities can both take place before gate closure as well as in the settlement period itself (see Section 4.1.6 for a description of the two time horizons).

This business case scenario focuses on the balancing actions by a BRP during the settlement period. Traditionally, these real-time balancing actions are performed by traditional power plants within the BRP’s portfolio. The key-idea of this business case is the utilization of real-time flexibility of end-user customers to balance the BRP portfolio. For each control zone, the BRP aggregates all its contracted flexible distributed generation and responsive loads in a *virtual power plant* (VPP). The BRP uses the VPP for its real-time balancing actions.

5.1.3. Offering (Secondary) Reserve Capacity to the TSO

This business case is rooted in the ancillary services as initiated by TSOs throughout the world. This business case will be based on the Dutch grid management concept as described by TenneT, the Dutch TSO[30]. The scenario described is an enhancement of the business case “Real-time Imbalance Reduction of a Retail Portfolio” (described in 5.1.2).

If a balance responsible party balances its own portfolio, it may reduce its imbalance cost. If the imbalance of the portfolio is in the same direction as the system imbalance, balancing costs are indeed reduced by the imbalance reduction. If the balance is totally restored within the portfolio and the BRP has extra flexibility in its portfolio, it may be used to further support the TSO in its upward or downward regulation. On the other side, if the imbalance of the portfolio is in the opposite direction from the system imbalance, the BRP would be adding imbalance in the system if it reduces its own imbalance. The BRP may even use its flexibility to create more portfolio imbalance in order to support the TSO. The only way to do this properly is to let the market decide. Therefore, the BRP should be able to offer its flexible demand and supply on the reserve market.

The current reserve market operation consists roughly of three steps:

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[30] See http://www.tennet.org/english/images/Bedrijfsvoeringsconcept%20UK_tcm43-12801.pdf

1. **Contracting of reserves for frequency response:** The TSO contracts generation capacity for primary, secondary and emergency reserve. Production sites of a certain capacity are obliged to make available a predefined portion of their capacity to the TSO. This offer is done in the form of a bid, using a bid ladder. The gate closure of the reserve market typically is in the order of one hour ahead.
2. **System balancing:** In case of (smaller or bigger) system-wide imbalance, the TSO calls upon the reserves available in the order of their bid prices, in order to restore the instantaneous system balance. There are constraints in requirements for the call time (response time plus time for reserve to be up and running) for primary, secondary and emergency reserve.
3. **Determination of imbalance costs:** Based on the bid prices in the reserve market and the contracted volumes, the TSO determines the actual cost for real-time balancing of the system. These costs are imposed on those BRPs that had deviations from their original energy programs. These charges are referred to as *imbalance costs*.

The BRP offering reserve capacity submits its bid before gate closure of the power exchange market, simultaneous with its energy program. These bids can be revised (both in capacity and price) intra-day, until an hour ahead before implementation. At realization, bids are called on in order of the bid prices. Calls on reserve power always applies for at least one program time unit (PTU; in The Netherlands, one PTU equals 15 minutes).

In order to enable BRPs to offer flexible demand and supply on the reserve market, their bids have to fit into the above market structure. One way is to make a forecast of the flexibility in the portfolio one hour ahead, and base a bid on the forecast. This imposes new uncertainties for the BRP. Therefore, in this scenario we propose an extension on the market structure to allow participation on the reserve market for flexible demand and supply with real-time bids.

This business case scenario thus focuses on the participation of parties, having flexible production and consumption, in ancillary markets during the settlement period. Traditionally, these real-time balancing actions are performed by contracted reserve capacity. The key-idea of this business case is the utilization of real-time flexibility of end-users (prosumers) in balancing a control zone. For each control zone, market parties aggregate these flexible distributed generation and responsive loads in a *virtual power plant* (VPP). The TSO contracts in real-time part of these flexible loads for its real-time balancing actions.

5.1.4. Distribution System Congestion Management

This business case aims at deferral of grid reinforcements and enhancement of network utilization. The need clearly arises in areas with a large amount of distributed generation near one location or in areas evolving into a so-called all-electric society, e.g. by introducing electric heating (heat pumps) or electric mobility. Non-coordinated control of these new devices may lead to a sharp rise in needed capacity on lines and transformers. By coordination of these devices, they can be allocated timeslots for operation that are spread out over time. Furthermore, coordination can increase the simultaneousness of local supply and demand in case local generation is integrated.

Congestion management as a service can be aimed at different beneficiaries. In residential houses, it can be used to get a better match in own production and consumption, thereby decreasing the energy bills (difference between buying and selling prices of electricity and reduction of distribution cost and tax payment). The same holds for large apartment buildings / offices / industrial sites, but there it can also be used to lower the connection capacity cost to the external grid. Distribution System Operators (DSO) may be interested in improvement of the quality of supply in areas with restricted capacity in lines and transformers. Within the SmartHouse/SmartGrid project, the focus will be placed on that latter scenario.

The application of this business case is a low voltage cell with residential houses having flexible demand and supply, e.g. heat pumps, µ-CHP, cooling, storage, etc. The DSO is interested in keeping a stable load profile at the transformer station, avoiding peak loads. Therefore, a substation agent measures the load flow at the transformer station. Whenever the load flow becomes critical, the substation agent creates a market signal that encourages the flexible supply and demand to react accordingly. The market signals and the interaction of the flexible supply and demand with the congestion management system could be, for instance, based on the PowerMatcher protocol (or on similar systems allowing real-time control of flexible loads and generators).

5.1.5. Variable Tariff-Based Load and Generation Shifting

The overall load patterns of electricity consumption are quite well predictable. Characteristic peaks occur at some time intervals (e.g. at noon or at 19:00 in mid-European winter days) and other time intervals are characterized by low consumption, especially during night-time. Also, the availability of renewable energy resources can be predicted with certain accuracy, giving an indication of probable situations in the electricity system for the next day. In well-functioning and liquid markets, the expectations of all market participants about the generation and consumption situation of the next day are well reflected in day-ahead power exchange prices, e.g. on the EEX or. If these wholesale prices are passed over to the end-users (directly or in a modified way), the end-users have incentives to shift loads from high-price times to times of lower prices, which would be beneficial for the retailer and for the overall system.

The key idea of the business case is, thus, to provide the customer with a variable price profile on the day before power delivery. This profile, calculated by the retailer, should be fixed once it has been communicated to the customer, so that the latter can rely on it for his further planning of generation and consumption. The price profile can look different for each day, however, to reflect market conditions that also vary from day to day. These variations will likely increase with increasing generation from fluctuating sources like wind and solar energy.

The price profiles could be based on the wholesale prices that the retailer faces when procuring the energy amounts he sells to the customer. The exact relation between the spot market prices and the variable tariff profiles sent to the smart customer can be determined flexibly. The possibilities range from a direct adoption of the spot-prices (plus grid costs, taxes etc.) to more complex contractual relations specifying maximum price and average price levels of the customer. Moreover, in order to make the flexible tariff model more acceptable for the end-user, a “maximum average cost per kWh” could be guaranteed by the retailer, protecting the customer from unintended very high energy bills. It has to be noted, however, that each guarantee for prices decreases the customer’s financial incentive to shift his consumption and generation in the desired way, thus weakening the demand response.

At the customer’s premise, an energy management system should receive the price signal and determine the optimal timing for the energy consumption of those appliances that can be shifted in time (e.g. washing machines or dishwashers) or that have a storage characteristic (such as fridges or deep-freezers). The same applies for generation units, such as μ-CHP plants – these are scheduled to run at those time intervals when prices are highest. The automated energy management frees the customer from the burden to monitor prices every day in order to save money, and it guarantees that possible load and generation shifts occur in an optimal way.

It may be part of the business model that the retailer receives feedback from the customers after the publication of the price curve and during the day of delivery on their automatically planned / predicted load and generation profiles. So the retailer can optimize his portfolio by trading on intraday electricity markets. It is also possible, however, to rely solely on a prediction model of customer behavior. As a further option, it would be possible that in exchange for an additional financial incentive, customers might be willing to accept adaptations of the price profile during the day of delivery reflecting changes in the retailer portfolio that come up during the day and also to reduce imbalance in his portfolio.

The main value driver from the customers’ perspective is to receive a tariff and a technology which reduce their energy bills. The value driver from the retailer’s perspective is the opportunity to attract new customers and reduce his costs when buying from wholesale power markets.

5.1.6. Energy Usage Monitoring and Optimization Services for End-Consumers

In her „Action Plan for Energy Efficiency", the European Commission estimates the EU-wide energy savings potential of households at around 27% (European Commission 2006). As one important measure for realizing this potential, the action plan states that awareness must be increased in order to stimulate behavioral changes. A study for the German Ministry of Economic Affairs [BMWi 2006] estimates the potential for energy savings through a timely display of energy consumption at a minimum of 9.5 TWh per year (this corresponds to 1.5% of the total energy consumption in Germany in 2006). Personalized and well targeted advice on how to save energy can help further exploit the savings potential.

When detailed metering data is collected on a large scale, valuable information can be extracted from the data pool, which can help end-consumers to achieve the desired reduction in energy consumption. For example, through comparing one's own consumption pattern with average load profiles of comparable households, an end-consumer can become better aware of his energy usage. Or, if the place of energy consumption is made visible in a comprehensible manner, the end-consumer is able to find out how much energy is spent by which appliances, and can identify the greatest potential for a reduction of energy consumption. A portal or display that combines information about present and past consumption, comparisons to average consumption patterns, and precise suggestions how to further lower consumption which are tailored personally to the customer is probably the most effective way of realizing the possible increase in households' energy efficiency. It should therefore be tested within the SmartHouse/SmartGrid project.

The business concept of services that comprise average consumption patterns could rely on the principle of reciprocity: those customers who contribute to the data set by allowing metering data to be read by the service provider can also access average data. This concept gives an incentive for the end-users to reveal their data, under the condition that it is not accessible by unauthorized parties.

The additional value to the customer provided by the described information services can either be remunerated through additional fees or through enhanced customer loyalty. A combination of both is also conceivable. If neither positive impacts from increased customer loyalty, nor a customer's willingness to pay for the information service are given, this business case risks being not viable. A retailer usually makes more profit if he sells more products, and if the energy consumption feedback leads to lower energy consumption, sales volumes would decrease for the retailer. Either the energy feedback has a value in itself for the customer (this valuation could also be exploited through higher average tariffs or through advertisement), or other measures, for example through subsidies or tax relief, have to compensate for the losses in sales volumes to make this a viable business case.

5.1.7. Distribution Grid Cell Islanding in Case of Higher-System Instability

The key idea of this business case is to allow the operation of a grid cell in island mode in case of higher-system instability in a market environment. This business cases considers that the islanding procedure is performed automatically. The scenario has two main steps: the first step takes place before the event that may occur and the second step is the steady islanded operation.

During the first step, the system should monitor both the available distributed generation (DG) units and the loads, and should forecast the consumption as well the available power and energy in the next hours. A load shedding schedule should be created based on to the criticality of the consumption loads and on the customers' willingness to pay for running the appliance during the island mode.

In the first minutes after the event, the DSO allows the operation according to the criticality. If there is enough power to the islanded grid, no load shedding will take place. When balance and stability has been ensured the system decides how to manage the energy within the network.

As mentioned before, the transition to the island mode is automatic and neither end-users nor the aggregator interferes with it. The system manages the energy generation and consumption within the island system and it is assumed that all nodes within the islanded grid participate in the system.

Grid cell islanding is of value to the DSO. If instabilities occur in the distribution grid, it is the DSO's task to restore stability as quickly as possible and with the lowest possible number of affected customers. Through islanding, the DSO can reduce the number of connected customers that are negatively affected by the higher-system instability. Islanding also helps the DSO to quickly restore system stability within his grid area. The service of grid-cell islanding can be provided by a commercial aggregator who installs the necessary control equipment in contracted households and then performs the islanding upon request by the DSO in case of a higher-system instability.

5.1.8. Black-Start Support from Smart Houses

The key idea of this business case is to support the black-start operation of the main grid. It considers that after a black-out, the local grid is also out of operation and the main goal is to start up quickly in island mode and then to reconnect with the upstream network in order to provide energy to the system.

The scenario has four main steps: the first step is before the event that may occur, the second step is just after the event, the third step is the steady islanded operation and the final step is the reconnection to the main grid.

The first two steps of the black-start support resemble the operation as described for the grid cell islanding case (see Section 5.1.7). When the system is in a safe state, it will try to reconnect in order to provide power to the grid; the goal is to provide as much energy and power as possible.

Black-start support is of value both to the DSO and the consumer. If a black-out occurs in the DSO's grid area, it is his responsibility to restore system stability as quickly as possible. Flexible demand helps him to perform this task. Black-start support could be provided by a commercial aggregator who installs the necessary control equipment in contracted households and then performs black-start support upon request by the DSO in case of a black-out. This service could be coupled with the grid cell islanding service, and could be provided by the same aggregator. Similarly to the previous business case depends on the market structure and the benefit depends on who is responsible to pay for the possible load shedding and how much the customers are willing to pay for quick power restoration.

5.1.9. Integration of Forecasting Techniques and Tools for Convenient Participation in a Common Energy Market Platform

The volatility of the production level of distributed energy resources (DER) makes forecasting a necessary tool for market participation. The actor with the lowest forecasting error will have the most efficient market participation. Moreover, the usage of intelligent management tools for handling the information about the uncertainties of wind generation will improve the operational costs, fuel savings and CO_2 savings regarding to the present decentralized energy management technology. However any good forecasting tool usually requires accurate data collection.

Currently, wind energy represents an important percentage in the electricity generation of several European countries, such as Germany, Denmark, Spain, Portugal or some Greek islands. The high amounts of wind generation in autonomous or interconnected electrical systems cause several difficulties in the operation and management of a power system. This is mainly due to the intermittent nature of the wind resource, which acts as a limiting factor for wind power integration.

This business case provides benefit for both the consumer and the aggregator. The aggregator has the ability to participate accurately in the wholesale market and gain by reducing the uncertainties. The consumer benefits from lower prices. However, this business case requires the participation of the consumers, since an accurate forecast requires online monitoring of the DER and not simply reading from the smart meter.

Forecasts are needed by following actors of the energy market:

- Energy supplier (balancing responsible party)
  - Customer load forecast
- Energy trader
  - Energy price forecast
- Distribution system operator (DSO)
  - Distribution grid load forecast including intermittent sources
- Transmission system operator (TSO)
  - Transmission grid load forecast including intermittent sources

The benefits of high quality forecasts are:

- Energy supplier (balancing responsible party)
  - Reduced balancing power costs
- Energy trader
  - Reduced energy trading costs through optimized energy retail portfolio
- Distribution system operator (DSO)
  - Reduced network losses through optimal power flow
  - Reduced balancing power costs (e.g. DSO is BRP for loss energy)
  - Optimized network operation
- Transmission system operator (TSO)
  - Reduced network losses trough optimal power flow
  - Reduced reserve capacity auction costs
  - Optimized network operation

The data collection for all these different forecasts is very similar (e.g. every load and price prediction is influenced by wind generation, outdoor temperature prediction, etc.). Every actor needs data from according data collection service providers.

So the business case “Integration of Forecasting Techniques and Tools for Convenient Participation in a Common Energy Market Platform” has two main parts. The first part is the data collection which is the most critical part that may lead to a correct forecast. Data collection is part of the business model since data typically is not freely available and sometimes confidential. The second part is the data evaluation and processing, e.g. for extracting a wind power prediction valid for a certain region. The third part is the distribution of results to the different customers that may also be competitors. It can be expected that the more fluctuating generation is to be integrated into grid, the higher the importance of forecasting services will be. Because of vital interest many actors of the energy market even already today use the forecasts of more than one service provider to improve the quality of their own forecasts.

5.2. Common Preconditions for Realizing the Business Cases

In order to realize the business cases specified in this document, some preconditions have to be met. In the SmartHouse/SmartGrid project, we considered them as given and implemented them in the field trials. The two most important ones are detailed in the following sections.

5.2.1. Advanced Metering and Information Provisioning

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 (see also deliverable D1.2). AMI is empowering the next generation of electricity network as envisioned by, e.g., [ETP SG 2008, Block et al. 2008].

Smart meters will be able to react almost in real time, provide fine-grained energy production or consumption info and adapt their behavior proactively. In the future, the smart meters could become able to cooperate, and their services could be interacting with various systems not only for billing, but for other value added services as well [Karnouskos/Terzidis 2007]. They might take over some roles of the concepts that are envisioned in the SmartHouse/SmartGrid approaches, i.e. the PowerMatcher, BEMI or MAGIC systems: they might not only be able to provide (near) real-time data, but also process them and take decisions based on their capabilities and collaboration with external services.

For the SH/SG approaches to work, we assume that households are equipped with electronic meters that are at least able to communicate their meter readings remotely, both for fixed intervals (usually 15 minutes) and one demand. The EU mandated 80% of all electricity meters to be "smart" in that way by 2020.[31] Therefore, we assume large rollouts to take place in 2012, similar to those that have already been started or accomplished in Italy, Sweden, Finland and, soon, France and Spain. The actual advancement of smart metering in Europe is summarized in Figure 22.

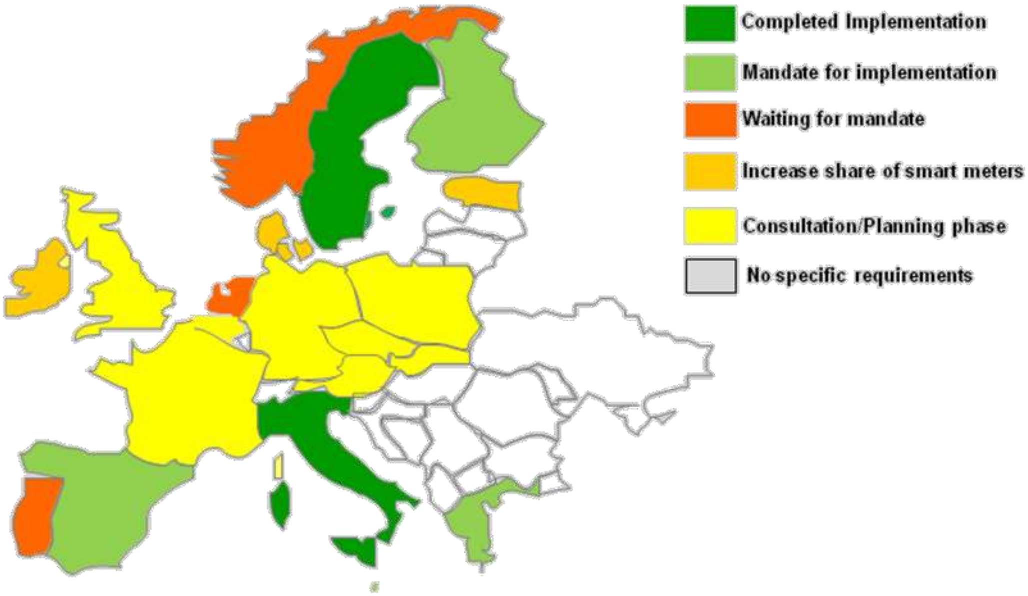

Figure 22: Smart metering deployment in Europe[32]

As defined in D1.1, we assume that the measurements that these smart meters can provide have a granularity of 15 minutes or finer, and that the meter also allows the metering data to be displayed on an external device in real-time. The real-time metering data could, for example, be displayed on a monitor that is installed in a part of the house that the inhabitants visit frequently (in opposition to the places where meters are usually installed nowadays), or it could be imported via a web browser-based customer portal. In

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[31] EU-member countries are required to prove a positive business case for smart metering by 2012. Only if it turns out that smart metering is not economically viable, the 80% goal will be withdrawn.

[32] IDC Energy Insights, 2010

all three field trials, this infrastructure had been provided and all trial participants had access to fine grained metering data through a web portal. This helps to provide historical information about the consumed energy and/or the produced energy within the smart houses and the historical price and cost information. It allows the customer to adapt his behavior to the current situation in the power grid.

It is still unresolved whether all energy-consuming appliances should be integrated into the local energy management within the smart house. A quite realistic vision is that only some appropriate appliances are connected to the smart energy management system. These will be of the type Fixed Program Shift (FPS) or State-of-Charge (SOC), or dimmable devices (Price Power Control – PPC, cp. Deliverable D1.1 for a description of these three types of device characteristics). Those appliances that the customer will always want to consume instantly (like, e.g., entertainment, lighting or cooking) will probably be controlled solely by the customer, just like today. An energy information portal which delivers all price and consumption data to the end customer can then give the information necessary for deciding about the operation of devices that are not integrated into the energy management. The customer is made aware of the current price, so that he can manually optimize the timing of his energy consuming activities.

5.2.2. Communication Infrastructure and Smart Appliances

The business cases 1-5 and 7-8 described above use the demand and supply flexibility that smart houses can offer. This requires that houses are equipped with smart appliances that either communicate with some sort of smart house gateway or are represented by a software agent that takes over the role of translating user preferences into parameters that can be processed by some overall optimization procedure. Until today, these smart appliances are hardly available. In some research projects first companies like Miele and Liebherr are developing prototypes of “smart grid ready” devices, but these are not yet commercially available. In the project field trials, the work-around of this deficit was to control the sockets that appliances are connected to. This is not viable in the future, because it severely limits the scope for smart appliance operation – for example, many modern washing machines do not automatically start operation when (re-) connected to power, fridge lights don’t work when disconnected from power etc. As end-users don’t want to loose too much comfort in using their appliances, mass-scale adoption can only be expected when household appliances are capable of interacting with smart grid applications in a “plug and play” manner.

The technical realization of a gateway (e.g. BEMI) and of software agents (e.g. PowerMatcher or MAGIC agents) designed for this purpose was subject to developments within this project. A common requirement here is also that the communication between the smart house and the offering part (energy retailer, aggregator or DSO) is provided, e.g. via DSL or powerline communication. In two of the three trials, an un-interrupted DSL connection (usually with flat-rate tariff) was required for trial participants to be allowed to participate. Data transfer between the grid/supplier side and the household was managed via this DSL line. Besides, in-house communication between the gateway and the appliances has to be assured. This implies that the appliances that offer flexibility are equipped with a communication device that is compatible with the smart house gateway. A soft requirement in this domain is also that the customer is willing to deliver the flexibility and that his appliances are equipped with the necessary advanced control functions.

5.3. Functional Requirements

5.3.1. Bi-Directional (Real-Time) Information Exchange

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 4.1.5. This leads to challenges for the current vendors of today's trade systems, who are usually not familiar with real-time software engineering.

5.3.2. Optimized Coordination of Demand and Supply

As the SmartHouse/SmartGrid approaches aim at raising the integration ceiling for renewable energy production and better utilizing the existing electricity infrastructure, there needs to be some coordination of demand and supply that aggregates information coming from the different entities of the decentralized system. The coordination could be done by giving some control to flexible consumption or generation to one dedicated partner (similar to the role of the transmission system operator today, who has control over a specified number of flexible units that are kept on a stand-by state for this purpose) or it could also be done using market mechanisms (compare Section 4.1.5).

In each case, the coordination mechanism should make sure that for a specified grid area (this can go down to the level of one grid cell or up to the level of a whole balancing zone or higher), generation is provided in the most cost-effective manner and supply and demand is balanced at every time. The task of optimization and balancing could be provided by different market players, each contributing their parts. For example, an energy retailer could provide flexible tariffs that give incentives to its customers to shift loads from high price to low price periods, and the grid operator procures balancing power for mapping demand and supply. Or a virtual power plant operator could keep a grid cell stable through controlling – directly or indirectly – the flexible loads and generators in a way that the inflexible demand can be met and the inflexible generation can be accommodated.

5.3.3. Decentralized Elicitation of Preferences

The operation of the electricity system is such a huge optimization problem that 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 **Error! Reference source not found.** 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.

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.

5.3.4. Flexible Billing for Incentive Designs

Along with the fine-grained metering, the energy amounts actually consumed and produced in these time intervals have to be billed to the customer accordingly. Thus, the customer benefits from consuming (generating) in low-price (high-price) times and has an incentive to avoid consuming (generating) in high-price (low-price) times. The billing system has to be able to calculate the due amount based on the smallest metering intervals for each customer. The invoice should give the customer a qualified feed-back about his consumption and generation so that the incentive to behave in a way that is beneficial for the overall system remains active.

To calculate the consumption costs for each customer, a generic billing algorithm was developed in the project that can cater for a wide range of metering scenarios. While metering intervals are assumed to be 15 minutes, this may change in the future to be completely arbitrary. The electricity prices may also change at dynamic intervals, as is the case with the PowerMatcher. As such, the goal of the developed billing algorithm is to calculate the costs of a customer's electricity usage over an arbitrary time frame. As inputs, the algorithm requires the meter readings of the customer, the electricity prices, and the time frame over which to calculate the costs (e.g. last month). The costs are then calculated by correlating consumption (kWh) with price (cents/kWh) for the particular meter.

The strategy employed by the algorithm is to break down the time frame over which the costs have to be calculated into small intervals, and then calculate the cost for each interval. This means that every time there is a change in the consumption or the price, the cost until that change is calculated. For example, if there are three price changes in one consumption interval, there will be a different costs associated with each price change. Therefore, the costs are calculated as a weighted average over the duration of each price change in proportion to the duration of the consumption interval. The details of the billing algorithm are described in the project deliverable D4.3.

5.4. Non-Functional Requirements

There are a lot of non-functional requirements related to every modern ICT system. In order to realize the envisioned innovative solutions and services for the SmartHouse/SmartGrid vision, key challenges will need to be adequately tackled. They are listed in Table 4, and rated according to their importance to SH/SG approaches. As the topics of privacy and security are discussed frequently in public debates about the smart grid, these two non-functional requirements are described in more detail in the remainder of this section.

Requirements (continued)	**Relevance**		
	High	**Medium**	**Low**
Privacy	X		
Portability			X
Quality	X		
Recovery		X	
Reliability	X		
Resource constraints		X	
Robustness	X		
Scalability	X		
Security	X		
Compatibility		X	
Stability	X		
Safety		X	
Supportability		X	
Testability	X		
Usability		X	

Requirements	**Relevance**

	High	**Medium**	**Low**
Availability	X		
Capacity, current and forecast	X		
Compliance		X	
Dependency on other parties		X	
Deployment		X	
Documentation		X	
Disaster recovery	X		
Efficiency		X	
Effectiveness		X	
Extensibility			X
Failure management		X	
Interoperability	X		
Maintainability		X	
Network topology	X		
Operability	X		
Performance	X		
Price		X	
Privacy	X		
Requirements (continued)	**Relevance**		
	High	**Medium**	**Low**
Privacy	X		
Portability			X
Quality	X		
Recovery		X	
Reliability	X		
Resource constraints		X	
Robustness	X		
Scalability	X		
Security	X		
Compatibility		X	
Stability	X		
Safety		X	
Supportability		X	
Testability	X		
Usability		X	

Table 4: Overview of non-functional requirements and their relevance for SH/SG systems[33]

Smart grid solutions require 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. New paradigms in the implementation of energy trade will cause significant implications for the involved systems' security:

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[33] Adapted from http://en.wikipedia.org/wiki/Non-functional_requirement

The most apparent change is that communication between customers and suppliers of energy will become bi-directional. 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 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.

Decentralized coordination approaches 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 previously mentioned more frequent and bi-directional 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 [Sultanem 1991] of residents and can be subject to national data privacy laws. It can even be used to deduce the individual use of appliances [Bauer et al. 2009].

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 [McGraw 2010] as otherwise, software insecurities could expose the systems. For instance, [Davis 2009] documented 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 [CISCO 2009]. 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).

6. SmartHouse/SmartGrid Architecture and Experiences

The SmartHouse/SmartGrid architecture has to account for the heterogeneity of concepts developed and tested within the project. One major overarching paradigm that has to be reflected is the distributed control paradigm (see Section 6.1.1). Following this, there needs to be some distributed decision making at the house level, which is facilitated through an appropriate in-house architecture (see Section 6.1.2), in combination with global coordination (Section 6.1.3). The latter, in turn, facilitates a business case of some involved enterprise (Section 6.1.4). Here, we will also highlight some prominent lessons learned so far in Section 6.2.

6.1. Amalgamated Service Architecture

In the SmartHouse/SmartGrid projects, three different technologies for managing demand and supply in a way to realize the goals of an energy efficient, flexible and sustainable smart grid are developed. Table 5 summarizes the main characteristics of the three technologies PowerMatcher, BEMI and Magic.

PowerMatcher	**BEMI**	**Magic**
Basic concepts		
• Decentralized decision making about consumption and production • Decision-making based on centralized market equilibrium of all bids • Real-time mapping of demand and supply • Automated control of production and consumption units • Scalable architecture	• Decentralized decision making about consumption and production • Decision-making based on centralized tariff decision • Mapping demand to available supply • Automated control of consumption units • User-information for manual control of consumption behaviour	• Decentralized decision making about consumption and production • Decision-making based on centralized negotiation of requests • Mapping of demand and supply • Automated control of production and consumption units
Methodology		
• Market-based concept for demand and supply management • General equilibrium theory • Market is distributed in a tree structure • Participants: devices, concentrators, objective agents, auctioneer • Device agents submit bids / demand and supply functions • Auctioneer determines prices • Round-based market place	• BEMI allows to decide decentrally based on tariff information • Decision consists of local information about devices and central information about variable prices • Pool-BEMI sends price profiles • "Avalanching" can be avoided by giving different price profiles to different customer gouprs • Day-ahead announcement of price profiles	• MAS-based using JADE (negotiation-based) • Grid announces SP/BP • MG tries to agree on "better" prices • Maximum of internal benefit • Based on symmetric assignment problem • Agents use reinforcement learning • Adapted Q-Learning • Three states (in|out|no exchange) • Number of involved agents differs with the action to take

Table 5: Overview of the SmartHouse/SmartGrid technologies

Due do the difference between the technologies, SmartHouse/SmartGrid does not have a common architecture in the classical notion, but an amalgamation of heterogeneous approaches that are "glued" together with SOA. This is compatible with the future smart grid vision as we do not expect that a single architecture will prevail; rather several heterogeneous approaches will be applied but all of them will exchange information at higher level via common standardized approaches such as those enabled by web services (WS-* standards).

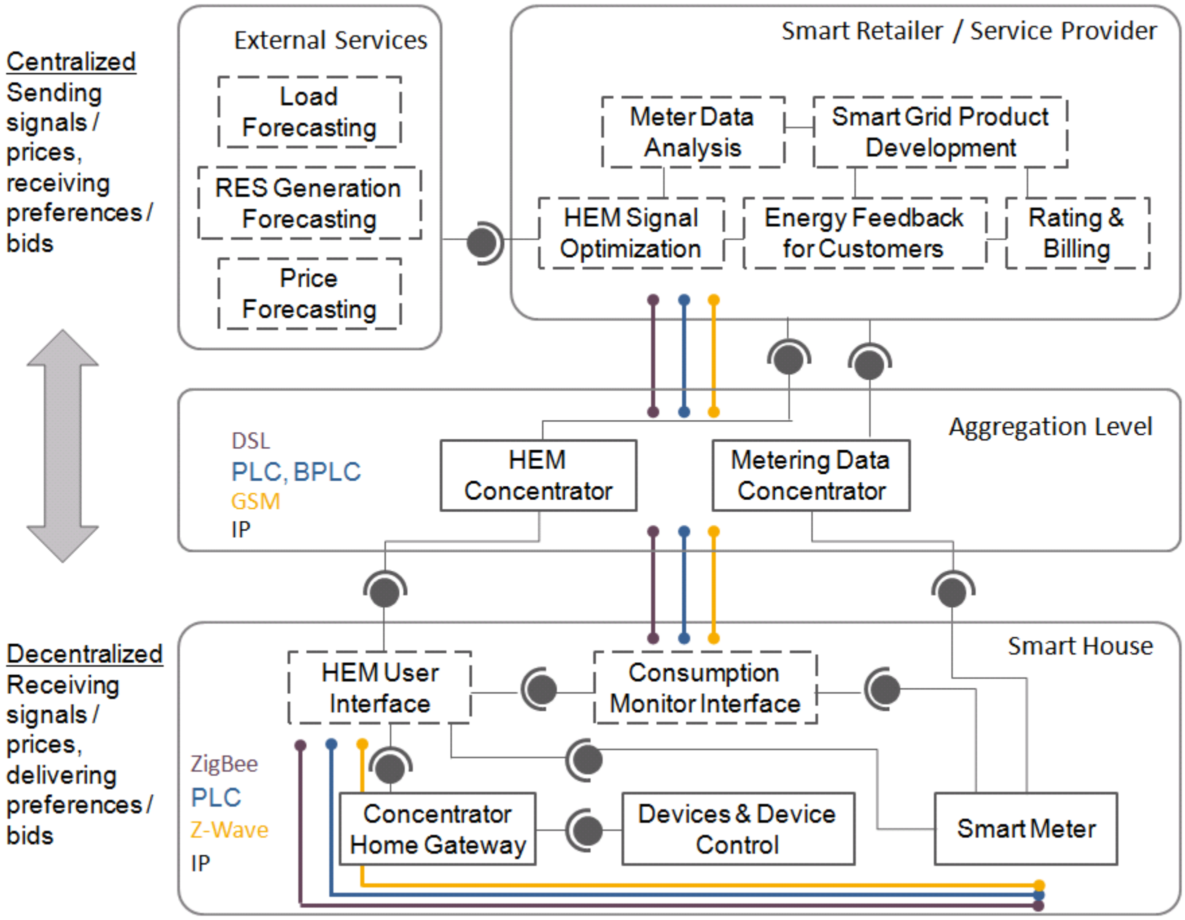

Figure 23: Architecture of loose coupling via services

6.1.1. Distributed Control Paradigm

There are some important commonalities between the technologies developed within SmartHouse/SmartGrid. As already depicted in Table 5 in the row "basic concepts", it can be recognized that the common idea of the SmartHouse/SmartGrid implementation follows a unified approach: PowerMatcher, BEMI as well as Magic manage demand and supply on the basis of a centralized optimization tool that works with decentralized decision making. This is highly important for the acceptability of these technologies – each participant keeps full control over his devices, but has incentives to align the device operation with the global status of the overall system.

Each of the three technologies is based on the concept to map the consumption demand to the producible or produced energy. On the one hand, the consumed energy amount needs to be adjusted in an appropriate way. This adjustment of the energy amount to be consumed is possible by deploying several features like automatically switching on and off consuming devices or manually influencing the consumer's behavior. These features are part of all the three architectures especially the automated switching of the controllable devices in the households. The control of the shiftable production of energy is in a similar way possible by means of automated on and off switching features for e.g. CHP producers.

Each of the concepts includes a central negotiation or calculation mechanism that tries to map the producible energy to the consumable energy for all sources (smart houses and production sites) within the enclosed smart grid. External production sites producing and providing a certain amount of energy can be included in the negotiation process as a fixed and non-controllable amount of energy. Therefore, the architecture of all three set-ups contains some central coordination mechanism.

The way how the three coordination mechanisms are designed is similar from a high-level perspective, but different in the details. Each tool either collects information or forecasts the desired amounts of energy to be consumed or produced from all participating smart houses and production sites. Each tool is able to understand besides the desired energy amounts some indicators that state under which conditions the energy will be consumed or produced. One condition is used for all of the three tools: It is a piece of information about the desired price, if energy is shiftable. After having collected all offers and requests the tool analyses together how the equilibrium can be reached under the sent conditions.

One major difference between the negotiation procedures is the time interval for the repetition of the negotiations and therefore for the consideration of unforeseeable changes. The PowerMatcher and also the Magic system can work in (near) real-time. The advantage is that for unforeseeable demand or production requests a short reaction time can be expected to map the complementary production or demand requests. The BEMI technology, in contrast, works on a time scale of a day, where day–ahead considerations of production and consumption patterns are done in order to define the price levels that act as decision guiding signals.

Finally, the field trials will demonstrate if a lower repetition of equilibrium calculations is sufficient. The near real-time negotiation causes a high degree of scalability and performance requirements. The PowerMatcher tool does the real-time negotiation using a multi-level approach realized by the use of agents clustering several smart houses or concentrator levels stepwise. For a lower number of smart houses, the concept of real-time could scale easily, but for a higher number of smart houses the concept has to be proved.

Decentralized decisions about consumption and production are made by all of the three field trials. This fact is the main common part of the three architectures. The control of switching on or off of a certain producing or consuming device is always done within the smart house itself. Even when for the smart house a central control is established, the decision remains within the house. Of course the decision is guided by a centralized determined and provided signal (e.g. virtual price signal or a real-time tariff / price structure or direct control signals).

6.1.2. In-House Architecture

The project deliverable D1.2 provides an overview of the in-house technology required. In general, the in-house architecture consists of:

- Intelligent nodes/agents that perform communication and control operations over these communication systems. In some cases, these nodes just perform basic control functions such as temperature surveillance or switching commands from the home automation systems, in other cases (such as the PowerMatcher concept), each node is a real intelligent agent.
- A dedicated communication gateway to the outside world, which exists in most cases. In concepts such as BEMI, the communication gateway is at the same time the in-house manager, in other concepts it is just a communication gateway without higher control capabilities than other agents in the house.
- Several devices operated by the customer and measurement nodes. In general, the meter can be considered a measurement node though having a special role for most business cases.
- A user interface

It is a goal of the SmartHouse/SmartGrid vision to enable automatic identification of home appliances. To make this possible, several services for registration, management and access of devices and other hardware/software resources available in the house have to be defined. Also, standardized data representations of household appliances relevant to smart grids have to be developed. For each in-house communication technology it must be determined individually how these data models can be used and implemented. It is described in deliverable D 2.1 how these models are transmitted and used by web services (for home automation and internal services of embedded systems, web services might – as of today – not be well suited; for this reason, the field implementations use various subsets of the services and data models described here, based on technologies such as Java, OSGi and the .NET framework).

The main goals for the design of the in-house architecture are:

- To provide an environment for applications in the area of energy management and energy efficiency at customers' sites in smart distribution grids
- To allow for access to devices and other hardware functionalities that are connected to the system via standardized data models or device service models,
- To allow for automated registration of new devices based on standardized data models and device services
- To make data provided from outside the communication gateway that might be relevant to various applications (such as the price of electricity) accessible based on standardized data models,
- To define standardized software services of the communication gateway middleware ("framework") for using these data models and device services
- To provide standardized software services for functionality that will be needed for many applications: the user web interface, persistent storage of certain types of data and logging.

From these goals, several architectural elements (Applications, Resources, Communication drivers and API Services) of the framework can be identified (see Figure 24):

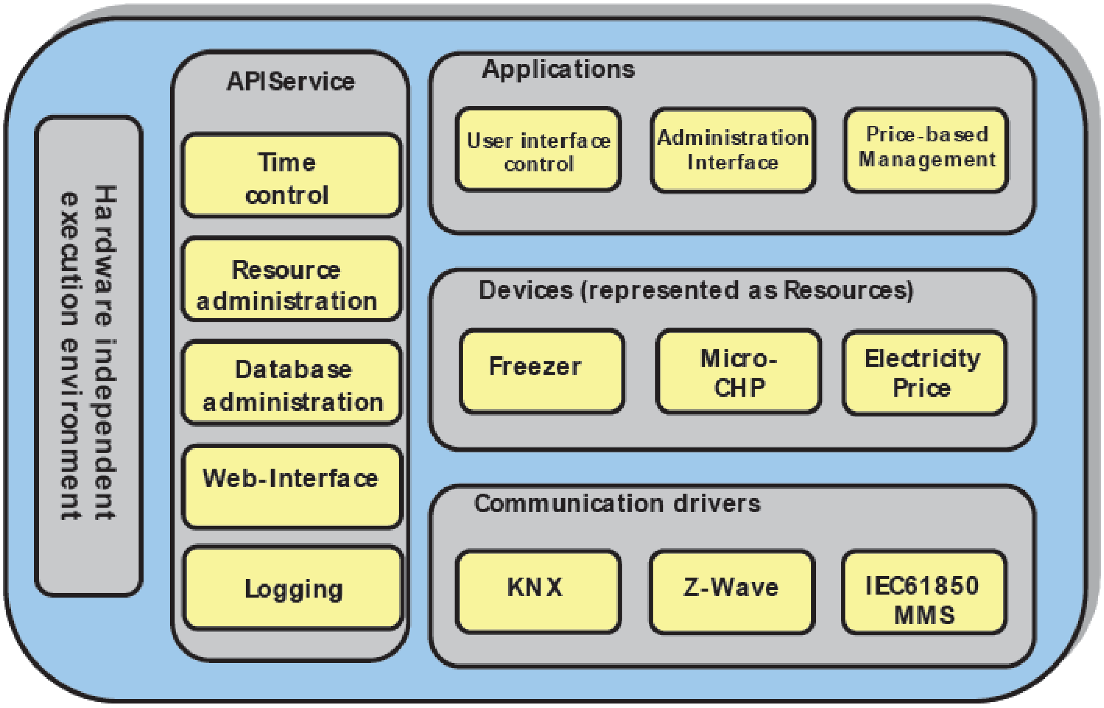

Figure 24: Communication gateway middleware – schematic overview

In order to define and develop a standard for the in-house services, Fraunhofer IWES has started the Open Gateway for Energy Management Alliance (OGEMA) in September 2009. The scope of this alliance is to provide an open software framework for energy management in the building sector, including private buildings and households. This framework is to be run on a central building gateway which serves as interface between the smart house and the smart grid, allowing for integration of parallel running applications from different manufacturers in the area of energy management and energy efficiency. The development of a reference implementation for this framework is also goal of OGEMA and is currently ongoing as part of IWES SmartHouse/SmartGrid activity. The field trial B within project SmartHouse/SmartGrid is currently in fact the first test of the newly developed framework in real-field at customer's premises.

In-House Architecture Experiences

The standardization proposal of the OGEMA alliance is in the core of the in-house architecture considerations, because it is tested at the largest scale within SmartHouse/SmartGrid (with 100 customers in contrast to 25 in trial A and ten in trial C). Therefore, special emphasis is put on the architectural experiences of field trial B here. The extensive overview of all experiences from the three trials follows in the final deliverables at the end of the SmartHouse/SmartGrid project.

The communication gateway hardware for field trial B comprises:

- Vortex x86 1 GHz CPU
- 1GB solid-state NANDrive
- 256 MB RAM
- Zenwalk Linux operating system
- 2xUSB, 2xLAN, 1xRS232
- A touchscreen display and four LEDs mounted into the gateways housing

From operation experience gained from the field test B preparations and installations, this hardware choice was adequate. The computing performance of the CPU is sufficient and the system provides enough memory resources to easily support the operation of the OGEMA framework and applications. Thus, up to now there was only little effort needed on the software side for performance optimizations and giving the system an acceptable response time during user interaction. However, many users tend to operate the system using the web interface instead of the mini display, which is rather relevant for displaying the current electricity price than to display the device operation schedules. Since the mini display is also a substantial cost factor, it has been decided to use hardware without display in the next version; instead, there will probably be an LED bar graph element for indicating the electricity price currently valid. Also, a reset functionality for the gateway which enables the system to be reset to delivery status has been identified to be very convenient. Such a function should work independently from the OGEMA framework. Thus, the next hardware version will feature a reset button or similar reset functionality.

During installations, it has also been found that the specific on-site hardware layout especially depends on the ICT components already existing at the customer site. For example, many customers already own a private network into which the gateway hardware has to be integrated. Thus, it is placed near the customer's home PC in many cases. If the gateway – as is the case in field trial B – uses radio-frequency based in-house communication to nodes and devices, there are also cases where another place has to be chosen in order to get the controlled devices within radio range. In these cases, it may turn out that connecting the gateway to the rest of the network by WLAN is needed. This is easily possible if WLAN is already used within the customer's private network, but the decision to do so can typically only be taken during the installation. From this it can be seen that the gateway hardware must be prepared to fit into an existing installation with much flexibility. Also, much customer interaction and flexibility is asked from the installation teams. This is all possible with the hardware choice taken, but it is also a reason for installation procedures taking up to four hours in non-standard cases in field test B.

In field trial B, intelligent nodes that switch and supervise electric appliances (RSI Boxes) are used. Supervision functions are e.g. detection of a communication loss to the gateway or supervision of appliance status, e.g. the temperature of a freezer. If any abnormal operation is detected, the RSI Boxes switch on the appliance without explicit command from the gateway. In the field test, this have proven to be of vital importance. In some cases, problems with the Z-Wave radio communication used in field trial B have already been reported, which, with the current system implementation, lead to increased device switch-on. This is an intended behavior which is to avoid unsecure operation. However, the specific reasons for the communication problems are not yet clear since it is not easy to analyze this without doing extensive range tests at the customer’s specific sites. Within laboratory environment, metal reinforced drywalls as well as floors have been found to substantially dampen Zwave radio signals. In a test at a private house, it has been found that sporadic connection losses can occur, which cannot always been identified during the installation phase. The exact placement and alignment of RSI boxes seems to be an important factor for this. Hence, it can be concluded that the next version of the system should better tolerate temporary communication losses. Another problem found is that the used ZWave protocol version does not natively support encryption. Thus, a proprietary encryption algorithm was implemented. This problem will be resolved by the next ZWave version, which is but only announced since more than six months and not ready-to-use. Thus, it has been decided to use ZigBee as an alternative radio communication option in the next version which enables native encryption in the first place.

Using the OGEMA framework for implementing the energy management applications has proven to be an adequate choice for ensuring extendibility and modularization. Thanks to this, a new communication driver for the next-version in house communication can now be developed by third parties. Also, the OGEMA approach is being more and more recognized in the energy/building management and standardization sector. However, these advantages are taking considerable development time and it is difficult to communicate the OGEMA approach to the customers actually using the system, since they are not involved in middleware design. This is however a problem with any middleware since the customer does barely notice its existence or complexity if the system is programmed properly.

Operation experiences, especially with implementing the communication system, have also already led to further developments in the OGEMA standard which will be used in the next version. It will feature specific interfaces for networks like ZWave or ZigBee, which the customer can extend by new network nodes using plug-and-play features (“so called user-controlled self learning communication system”).

Reports from the users regarding the software show that some users wish special modifications or layouts of the systems web interface. This suggests introduction of web interface “skins”, as possible with modern mobile telephones or even PC operating systems. Such skins could be provided as download, but are not yet planned for the next version of the system. Also, it has been found that the complex system functions regarding the management of devices are quite demanding for the customer in terms of technical system understanding. Even if a comprehensive customer handbook is provided, it can be expected that users will be in need of remote support during the first days and few weeks of operation. This also of course implies even more technical know-how on the hotline’s side, which is currently difficult to provide given the little operation experience. In this regard, the energy management system is similar to a very complex hardware or software system with the additional problem that this system affects components throughout the customers household and is used by customers with very different pre-knowledge. At the best, introducing energy management systems can be compared with introducing mobile phones or PCs, which each represent technical revolutions on their own. It is yet too early to deduce any conclusions on the question if the man-machine interface currently provided is adequate.

6.1.3. Coordination Algorithms

As for the coordination approaches in SmartHouse/SmartGrid, different approaches have been followed:

- PM In this concept, a large number of agents are competitively negotiating and trading on an electronic market with the purpose to optimally achieve their local control action goals. In the market-based optimization, the optimal solution is found by running an electronic equilibrium market and communicating the resulting market price back to the local control agents.
- The Bidirectional Energy Management Interface BEMI uses an energy management approach that is organized in a decentralized way and avoids a central control of the individual loads and DER. In this approach, every decentralized market participant operates a bi-directional energy management interface which optimizes the local power consumption and generation automatically, depending on local as well as central information like e.g. variable tariffs.
- The Magic system provides a different approach that enables the coordination of the actors. The system provides an architecture that supports complex interactions between the agents based on an advanced agent communication language. The system is implemented upon the JADE[34] platform and also provides part of the system organization, since the concept of coordination between the agents imports significant complexity to the system.

All three coordination approaches have been described in more detail in deliverable D2.2. Summarized shortly, one could say that the PowerMatcher and the BEMI approaches are primarily designed for “normal” operation, whereas the strength of the Magic approach is in the reaction to critical and emergency system states. However, the agent negotiation algorithms from Magic could also be used in normal situations for cost minimization, and the PowerMatcher could also contribute to managing critical grid situations, because it balances local demand and supply in real-time. The BEMI coordination focuses on day-ahead planning, which primarily helps to optimize trading positions for an energy supplier, but as the BEMI gateway can already communicate with all connected household appliances, it can also be enhanced with further functionality for facilitating more business cases in the smart grid. Further developments of all three technologies will draw from the experiences gained with each of the coordination approaches.

6.1.4. Enterprise Integration

The general technical infrastructure needed for all three technologies developed within SmartHouse/SmartGrid, i.e. PowerMatcher, BEMI and Magic, is one (or more) control units within the house and one central optimization unit at the enterprise level. The in-house control units are usually distributed over lightweight control at the device (i.e. one device agent at the lowest level of the architecture or one controllable switch) and one home gateway that concentrates the information within the house and that may optimize the device operation for the whole household, For PowerMatcher, the gateway can be interpreted as the concentrator that aggregates the bids and submits a summarized demand function; for BEMI, the gateway does the optimization and actively switches the connected devices; for Magic the gateway can be interpreted as the highest level of the multi-agent system which includes all the services necessary for achieving the system’s goal.

The enterprise level system communicates with the home gateway in order to transmit information about the current system status. This can be done in form of a real-time (PowerMatcher) or day-ahead (BEMI) price or a notification about a grid event (Magic). This combination of decentralized and centralized collaboration is visualized in Figure 25.

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[34] JADE stands for Java Agent Development Framework, http://jade.tilab.com/

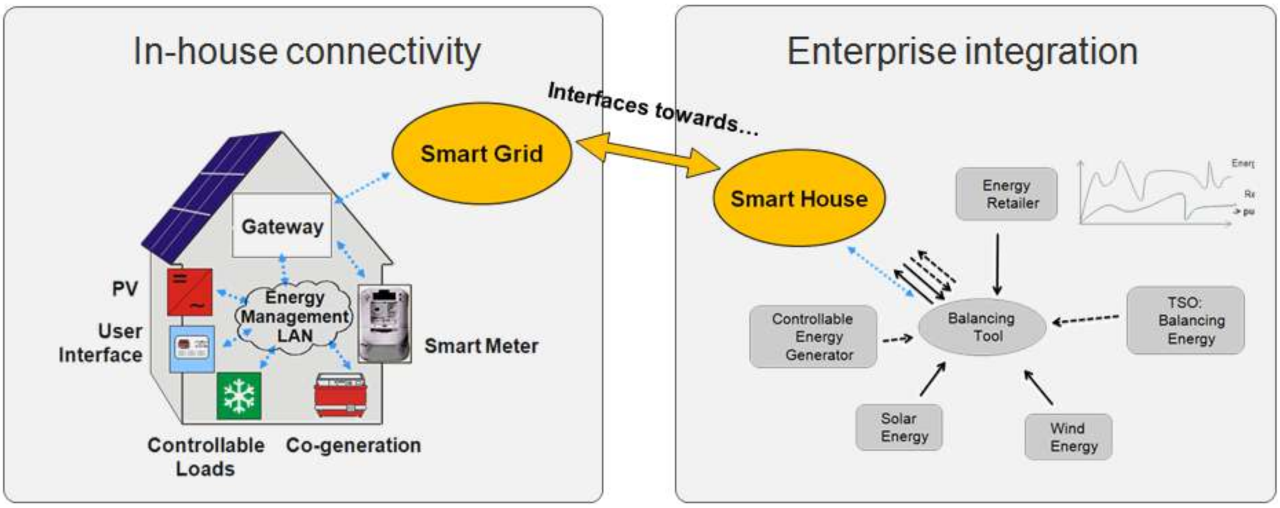

Figure 25: Connection between the in-house architecture and its integration within enterprise processes

It has to be mentioned that usually only one of the business cases described in Section 5.1 can be implemented at a time by the enterprise. Usually, the aggregated flexibility in energy consumption and generation by a cluster of households can either be used for minimizing procurement costs of the energy supplier or for participating in the balancing market or for balancing the portfolio of a BRP or for other business cases that build upon the given flexibility. For example, once an enterprise has bundled the households' flexibility and sold it for balancing purposes, these households are bound to delivering balancing energy in case it is needed, and do no longer have the full flexibility any more to pick the cheapest time slots for running their appliances. Therefore, the proper choice of the business case that should be supported has to be the first step.[35]

Moreover, the business cases that can be implemented by any enterprise depend on the market role that this enterprise has in the energy market. As summarized in Figure 26, each enterprise (and also each further player in the overall system) has a different involvement in the smart grid. Therefore, the functionalities that each of the enterprises require, and the tasks each of them carries out are different. These have are summarized in the following for an energy retailer, a DSO and a commercial aggregator.

- **Energy retailer** – The energy retailer plays a central role for successfully establishing a smart grid, because he is responsible for the delivery of energy to the contracted delivery points. He has to choose one balancing tool (PowerMatcher, BEMI or Magic, in this case) that helps him to balance all available electricity resources with the electricity demand. Other functions he has to carry out are:
    - **Metered data analysis –** The retailer needs to get all detailed metered data (profiles) about the energy delivered or generated at a certain point of delivery. Therefore, he would need efficient tools for collect, storing and processing the metering data. Retailers can then perform interval-based profitability analytics and create individual incentives for special customer groups.
    - **Accurate forecasting and balancing –** The energy retailer utilizes tools that help him to balance his portfolio, based on forecasting techniques and his own historical data. If derivations from these forecasts occur, the balancing tool operated by the retailer can help him to use the demand flexibility to balance them out.
    - **Definition of energy products or tariffs** – SH/SG approaches lead to more complex products in terms of price intervals or price rules that can be defined according to the availability of detailed

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[35] In order to facilitate this step, investment analyses for possible business cases that can be implemented with the three SmartHouse/SmartGrid technologies have been carried out as part of the project and will be provided in deliverable D4.3. A short version of the analysis is also available in a conference paper [Jötten et al. 2011].

  metered data. In order to keep tariffs simple, retailers could also use time of use tariffs (cp. Section 4.1.2).
  - **Energy usage monitoring and feedback** – The data collected from a smart meter should be automatically analyzed and put into a customer portal or report (coming with the monthly bill) for the consumer. The customer feedback should also provide transparency about the operation decisions that an automated home energy management system, such as the PowerMatcher, BEMI or Magic system, has taken. The user should be able to see at what times his flexible loads have actually run and what cost savings could be realized by this optimized operation.
  - **Billing** – Billing functionalities like ToU billing, profile-based or real-time pricing billing, best billing (billing calculation based on different price schemes with a comparison afterwards to choose and bill the cheapest option to the customer, as implemented, e.g., in field trial B), or fixed fee billing are possible options to be used in the SH/SG context. It is decisive that the bill transparently reflects the customer's reaction to any incentives provided for load shifting, so that the customer develops trust in the technology and the incentives can produce the desired behaviour.

- **DSO** – The distribution companies play an important role in the development and establishment of smart grids. Their main contribution to the smart grid is the distribution grid itself. In liberalized markets, DSOs do not participate in the business of the energy supply, but concentrate on the development and maintenance of the distribution grid. A smart grid needs to deal technically with higher loads during times when a lot of energy is generated (and consumed). In case of a large-scale adoption of electric vehicles, this task will become more demanding, as peak consumption might rise sharply, if no simultaneous measures for avoiding peak loads and spreading shoulder loads are taken. This would imply a more expensive grid infrastructure and an investment into the grid construction. Hence, the DSOs interest is to avoid an extensive usage of the grid in peak times. Load shifting of energy usage and generation to an equalized degree of grid utilization is the best choice to use the grid most efficiently. Roughly spoken, the capacity of the grid is the indicator that defines the maximum energy load during peak times that can be managed by the grid. For this reason, the DSO could base the prices for grid usage on the capacity that is needed in peak times. In a smart grid with a high share of distributed generation, another new phenomenon can occur at the distribution level. Traditionally, the distribution grid has been designed to transport electricity from the higher voltage level over low voltage lines to the end-consumer. As the many smaller decentralized units feed in their electricity on the medium and even low voltage level (e.g. photovoltaic panels, small combined heat and power plants), the load flow can also change its direction. So there will be times at which load is flowing from the lower to the higher voltage level. Here again, the DSO can either extend his infrastructure so as to meet these new technical requirements, or he can use the optimization capabilities within a smart grid in order to encourage a local use of the locally generated energy, thus avoiding load flow reversals.
  - **Define the grid-usage tariff or bonus scheme –** If the DSO uses the smart houses' flexibility, he can either incentivise the desired behaviour through variable grid usage fees or special bonuses. The former method is quite uncommon in Europe – today, grid usage tariffs are usually based on the consumption that is transferred through the grid, regardless of any scarcity situations.
  - **Installation of smart meters –** If we assume that metering will still be performed by the distribution companies (which is still the case in most European countries), DSOs will remain the owner of the meters and are the party that has to invest into the smart metering hardware.

- **Aggregator** – A commercial aggregator can contract a set of smart houses who stay with their current retailer but who offer to shift certain loads when needed for system stability or efficiency. The flexibility of all contracted households can then be used for offering reserve capacity on the balancing procurement markets. For example, this aggregator could realize the business case to offer (secondary) reserve capacity to a TSO (cp. Section 5.1.3) via the balancing power markets. In this case, the aggregator has to define the bonus scheme that makes smart houses participate in the balancing, take care of correctly remunerating the flexibility that was actually provided by the smart houses, and participate in the balancing power market for generating the necessary income to make the business economically viable.

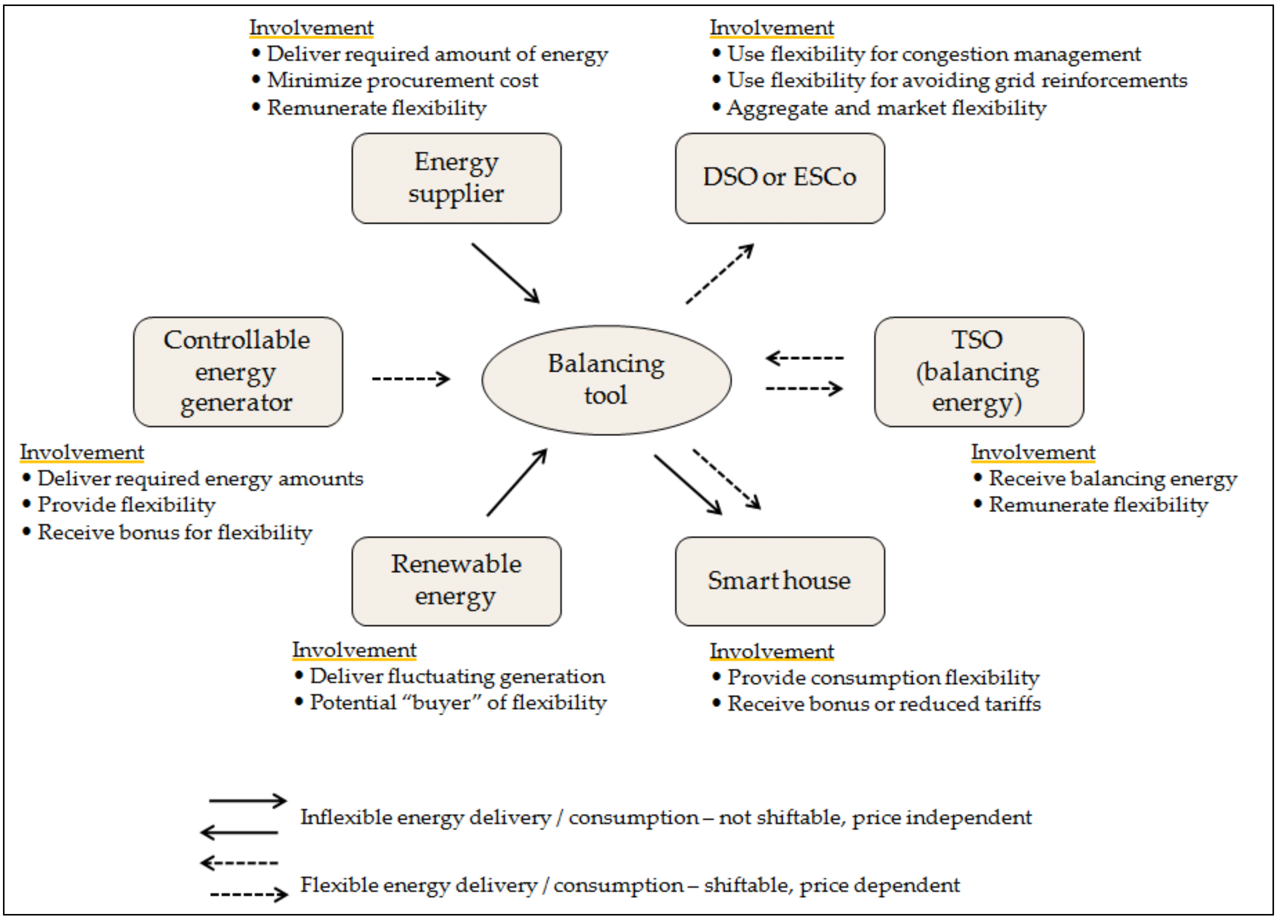

Figure 26: Enterprise integration via a balancing tool

For the enterprise integration part of the developed technologies, a demo prototype has been implemented, which is schematized in Figure 27. The "enterprise portal" offers functionality that supports all described business cases. It is designed in a way that an enterprise can pick the relevant functionality in order to run the SH/SG technologies, and that common functionality which is needed for all technologies is offered in a uniform way. A screenshot of one of the pages of the enterprise portal is given in Figure 28.

The implementation shows the application kernel described below, the data layer, consisting of the database connector (using standard Java Hibernate technology and providing an EJB interface to do data extraction from the database), the external data sources connectors through which links to relevant system information (e.g. wholesale market data, weather services etc.) can be established and additional services on top of the applications, such as a customer portal for metering data or a pdf service that creates the monthly bill on demand.

The external data source connectors allow access to more than one data sources at the same time, for example for using several different weather forecasting services or comparing prices from different wholesale power markets. The connectors have a well-defined interface and factory class that gives back the right implementation of the connector depending on the data that the enterprise portal seeks to access.

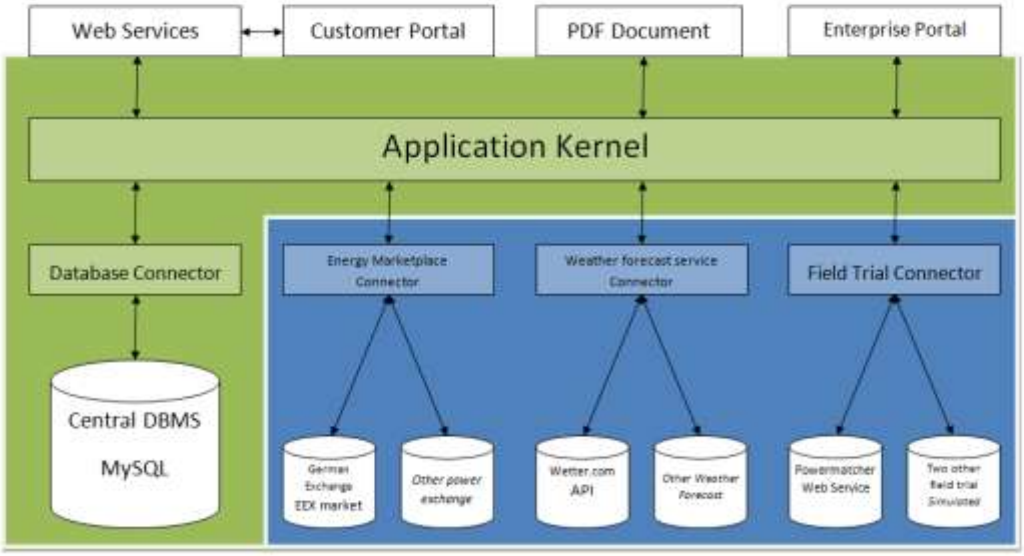

Figure 27: Service infrastructure implementation for SH/SG enterprise integration

The application kernel offers different kinds of services that an energy company needs for implementing SmartHouse/SmartGrid processes as part of their energy business. Some of the services are based on data from the database, and some are based on external data. They include the following functionality:

- **Appliance service** – The bean provides all functions to manage the appliances.
- **Cluster service** – The bean provides all functions to manage the clusters. It provides also function to calculate the consumption of the whole cluster
- **Costs service** – The bean provides all functions to manage the costs. It can also calculate the detailed and aggregate costs for a meter. These data are used to create the bill for each customer.
- **Member service** – The bean provides all functions to manage the members of a SH/SG cluster.
- **Meter reading service** – The bean provides all functions to manage the meter readings. It provides the data that enable to calculate the costs and the consumptions.
- **Meter service** – The bean provides all functions to manage the meters. It provides also function to calculate the meter for a given period.
- **Price service** – The bean provides all functions to manage the prices and the price items. It provides the data that enable to calculate the costs.
- **VPP setpoint service** – This service is relevant for the management of a PowerMatcher cluster. It uses the connector to field trial A. It enables to send new setpoints, to create some scheduled ones and to simulate the price if changing the current setpoint. This bean provides also simple messaging capabilities to inform all registered listener in case of changing in the VPP setpoint list.
- **Customer service** – The customer is in data object based on the member. It has the same attribute but add an address to the member. Each customer has one more meter and a set of appliances like the member. This bean calculates also the aggregated consumption of a customer and the total shifting capability of all its appliances.
- **Power exchange service** – This service provides all the function for getting the data of the electricity market. Depending on the cluster for which the data are requested, the right market place is selected and the request send (through the right connector) to the corresponding data source.

Figure 28: Snapshot of the SH/SG enterprise portal

6.1.5. Metering Infrastructure

In the SmartHouse/SmartGrid project, experiments have been carried out with a prototyped metering platform. In this experimentation, it was discovered that a large portion of time is spent on internal processing of meter reading submission requests inside the application server itself. For example, the total request/response time for a one socket connection, for a single meter reading submission, was approximately four times longer than the time required to insert the metering data into the database. This difference was the first sign that the application server load should be balanced over multiple nodes. As such, further performance enhancements should be focused on reducing the request processing time. For instance, using a meter data concentrator to collect meter readings and submit them in bulk to the main server. This way, the request processing time per meter reading can be reduced, yielding higher efficiency. However, even more aggressive performance-related strategies might provide better results, such as usage of in-memory databases or strategic (on-demand or periodic) committing to the database.

The experiments consisted of a client pushing a high amount of requests with generated metering data; as such, the communication throughput is limited by the TCP receive window (receive buffer) on the server side. The server side reaches its buffer limits (TCP window size) followed by the TCP window scaling (RFC 1323), that is, to increase the TCP receive buffer size above its current value. The client will continue to generate data, but it will be kept in the output buffer until the server updates its window size to an equal (or greater) value of the message size to be sent. These steps will be repeated continuously until all data is transmitted. Although the increase of the TCP window on the server side helps to not exceed the capacity of the receiver's buffer, if receiver if overloaded, requests start to be rejected. This phenomenon is known as the TCP ZeroWindow. Due the fact that the client generates far more requests than the server can handle, this phenomenon occurs.

For an overall architecture, not only performance of the metering platform, but the performance of a concentrator is important for the scalability issues [Karnouskos, 2011]. The concentrator is the interface between many low-speed, heterogeneous, usually asynchronous, channels and one or more high-speed, usually synchronous, channels. It acts as an interface between the smart meters and the enterprise. It is also responsible for aggregating the meter reading data and submitting it to the metering server. Figure 29 shows how the metering data is gathered from (various sources) at strategically positioned concentrators.

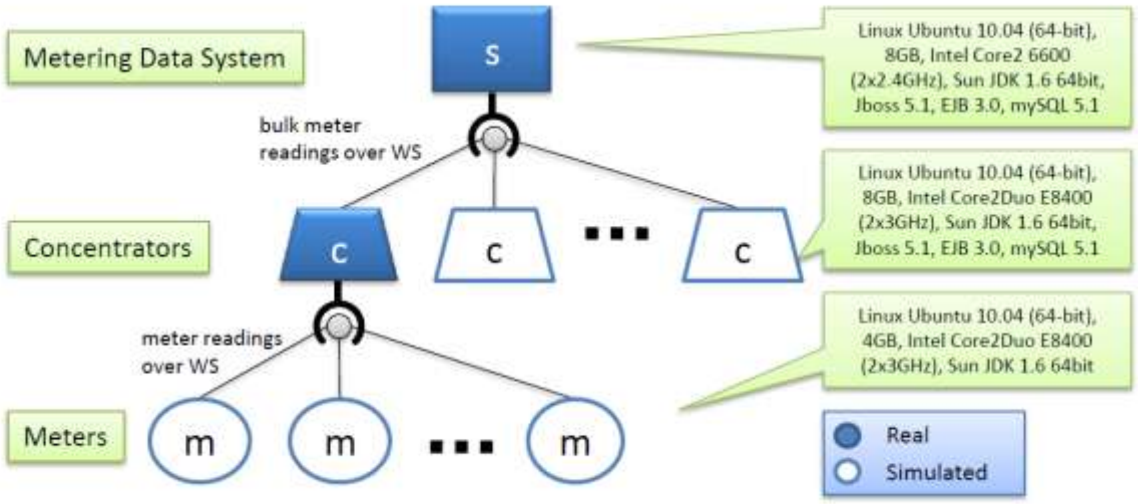

Figure 29: Mass test with concentrator / smart meter performance considerations

It has been investigated how higher performance can be achieved, focusing on the architectural aspects and not on optimizing the software as such. It included concentrators which would act as meter data collection points and attempted to find out what the benefits were. Thus, multiple experiments were conducted.

According to current smart grid industry practices, each meter under a concentrator is sending its current reading every 15 minutes. In one of the experiments carried out in the SH/SG project, each concentrator had receiving rate of meter readings at 60 meter readings/second. With this level of granularity, a total of 54,000 meters would be connected to the concentrator. The results show that, for the tested (off-the-shelf hardware and software) configuration, the MDS (Metering Data System) performance peaks around at 66 concentrators. These results showed that at meter reading submission intervals of 15 minutes, roughly 3.5 million meters that can be incorporated within this configuration (as depicted in Table 6).

Interval	Max. meters / concentrator	Max. meters / MDS
1 min	30,000	240,000
5 min	150,000	1,200,000
15 min	450,000	3,600,000

Table 6: Maximum number of meters per concentrator and MDS

If the granularity of the readings were further reduced to five minute intervals, some 1.18 million meters can be handled by the test-bed server within the proposed architecture. Since the global meter reading processing rate is limited by the MDS, utilizing a higher capacity of the concentrators will result in fewer concentrators being needed. This will obviously help to keep costs down, as fewer concentrators will be needed to be deployed, managed and maintained. The correlation between the time resolutions, maximum meters per concentrator and maximum number of meters per MDS is depicted in the Table 7. Following this line of thought, Table 7 depicts also various configuration settings that can be used as a thumb rule when setting up an AMI.

In the realized experiments, these performances were measured with a high bandwidth, single hop and unconstrained network. This, however, is not a reasonable expectation for a real world scenario, at least for the mid-term. As such, the performance must be further scrutinized under far harsher network conditions that are more reflective of reality. This is important especially between the concentrator and the smart meter where a variety of heterogeneous networks is expected (e.g. residential ADSL connection, power line communications or even through existing wireless mobile phone networks).

Interval	# MDS	# Concentrators	# Meters
1 min	1	[20…66]	[72,000… 237,600]
	2	[40…132]	[144,000… 475,200]
	3	[60…198]	[216,000… 712,800]
5 min	1	[20…66]	[360,000… 1,188,000]
	2	[40…132]	[720,000… 2,376,000]
	3	[60…198]	[1,080,000… 3,564,000]
15 min	1	[20…66]	[1,080,000… 3,564,000]
	2	[40…132]	[2,160,000… 7,128,000]
	3	[60…198]	[3,240,000… 10,692,000]

Table 7: Maximum number of meters for a range of concentrators[36]

It is clear that the results presented are bound to the actual implementation tools and their limitations. No effort has been invested to tune them for high performance. Besides, in all experiments security and privacy issues have not been addressed. Integrating any solution there will a significant impact on all layers. Experimenting with WS-Security, secure channels (HTTPS) or encrypted meter readings, will give an insight to the magnitude of impact. Additionally the use of latest hardware (not dedicated though) such as Intel processors of the i5/i7 generation which have native AES support may assist in minimizing the impact of security. Without doubt further tuning of hardware and software may further enhance the overall performance. However, this should be investigated in future work.

6.2. Experiences and Implications

6.2.1. User Acceptance

The availability of information, e.g. through an in-door gateway equipped with a display is a significant part of the system since it gives the chance to the inhabitants to actively participate in the whole process. The interaction with the habitants revealed that the knowledge of the current cost and consumption makes them more conscious regarding energy savings and as a consequence, solutions like the one proposed by SmartHouse/SmartGrid are more acceptable. Furthermore, the existence of the web portal is also significant, although in Meltemi, it was not widely used (Meltemi is a holiday camp and most of the people do not spend time on Internet). On the other hand, costs are a problem here and a display on the device is usually not very handy to use, as the BEMI experience show. The need of attractive web portals that can be accessed by the user through their PCs or smart phones becomes obvious, and the additional value of displays provided at the gateway software seems to be not high enough to justify the additional investment.

6.2.2. Cost-Sensitive Design

Regarding the energy efficiency and the business cases, the major lesson learned is related to the cost. The capability to provide ancillary services (black start, load shedding etc) was evaluated not only based on technical criterions, but also regarding the cost. In Greece, currently the cost of energy per kWh is very low and not cost reflective (although this situation is changing currently). This means that the ancillary services in low voltage consumers are not cost effective in Greece. However, future estimation about the cost of energy reveals that these applications may be interesting.

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[36] Example; accepting readings at a rate of 60 meter readings/second

Furthermore another lesson learned that also forced the change of some characteristics of the system is the installation cost. It is obvious that the installation cost is a significant part of the system. The system should consider the typical formulation of the electrical system in each house. For example in Greece, the electric meter is always outdoors. Thus, the final architecture and design of the load controller required the installation of some parts inside the main electrical panel (relays and a pulse meter). This turned to be much cheaper than the original design. Moreover, the communication infrastructure is a major part of the system. The initial plan of the installation required the installation of a WiFi network. However, the cost of installing WiFi in an environment full of trees is very expensive, therefore leased aDSL were used.

6.2.3. Involvement of Unbundled Energy Companies

A unique feature of the field test B within SH/SG is that it involves many stakeholders acting profit-oriented in the unbundled market. In this trial, the development process of the back-office functionality has shown that it is a nontrivial task to integrate systems from different partners even if there are common protocols provided. An important lesson from this is that the emergence of these stakeholders from what once were single vertically integrated utilities greatly increases mediation issues when implementing smart grids. Within the project context, this is resolved by project management and common consortium decisions. However, if considering implementation of smart grids in the unbundled market of today, such a consortium would have to be replaced by a trusted cross-partner organization for mediation between conflicting partner interests which otherwise would hinder technical implementation. For example, giving the customer a tariff bonus for incentivizing a load shift for better utilization of the DSO’s grid resources may be of advantage for the DSO, but is unattractive for the energy provider as of today. This is because the introduction of variable tariffs raises cost for establishing new billing procedures, yet does not yield direct income. However, without technical services provided by DSO and energy provider, the smart grid cannot prevail, which is of disadvantage for both.

6.2.4. Reliability and Safety Issues

By introducing systems like the Smart House/Smart Grid concept, comfort of the consumer becomes dependent on complex processes and technology that implements them. Therefore provisions must be in place for guaranteeing comfort when processes or technology fail.

- If communication is interrupted, the nodes depending on it shall fall back to a default mode, providing comfort. Of course this might have a drawback on the optimal or most economical use of the system (graceful degradation).
- Operation of lower level nodes shall not stop if higher level nodes fail. Also here the lower level node shall fall back to a safe mode.
- Measures shall be taken to guarantee availability of critical parts of the system
- Watchdog mechanisms can be implemented to safeguard processes from crashing
- The operator of the system shall be able to monitor the system and should be alerted if critical parts of the system fail.
- The communication is based on the internet technologies and the cyber security concerns are high. The system should ensure that no threat can interfere to the system.

System failures were in the focus of the technology developments and field trials around the Magic system (trial C, carried out in Meltemi). Here, the goal was to investigate the operation during emergency operations such as black start and island operation, which introduce an extra set of fail safe mechanisms:

- The controllers should be equipped with a battery in order to allow the operation during a power outage/failure

- The controllers should have the ability for smart start up. This means that they should have the ability to remember the last state of the system and quickly identify the critical loads as well the existing equipment in the system.

Finally, the systems developed within the Smart House/Smart Grid Concept are dependent on very complex software routing thus bugs are unavoidable. Thus the capability of remote access and programming is important at least for the test sites.

A significant issue was revealed during the installation in Meltemi and this has to do with the safety of the inhabitants and the electrical installation. Since the electrical installations in the test site were very old it was mandatory to replace at least some of the existing panels which definitely increases the installation cost. Furthermore another very interesting issue took place that should be considered in future installations. Some of the inhabitants contact directly the support team of Magic for any problem of their electrical installations. Since the inhabitants are not familiar the electricity issues cannot easily understand that for example a malfunction in the power supply of the refrigerator is not related with operation of the Magic system. This problem will become more complicated in the future within larger installations.

7. Summary and Concluding Remarks

In this deliverable, the main architectural concepts of the SmartHouse/SmartGrid have been described. The general approach is that one control unit or gateway at the level of a smart house is connected to the appliances and devices in the house via an in-house architecture and to one central optimization unit that can be operated at the enterprise level. For larger clusters of connected smart houses, intermediate levels of concentrators can be installed for enabling scalability. Through this, the actual decision making for appliance operation remains at the local level, whereas some global coordination ensures that local generation is best used locally, resource depending renewable generation is better accommodated and the existing infrastructure is operated efficiently, avoiding peak load situations that require expensive reinforcements and extensions.

The in-house control units are usually distributed over lightweight control at the device (i.e. one device agent at the lowest level of the architecture or one controllable switch) and one home gateway that concentrates the information within the house and that may optimize the device operation for the whole household. Three different approaches of overall coordination and device control have been distinguished, i.e. (i) the PowerMatcher technology, where concentrators aggregates market bids coming from single devices and submits a summarized demand function to a global auctioneer, (ii) the Bi-directional Energy Management Interface BEMI, a gateway that does the optimization and actively switches the connected devices based on day-ahead price profiles, and (iii) the Magic system, which consists of a multi-agent system which includes all the services necessary for achieving the system’s goal.

It has to be stated that the SmartHouse/SmartGrid project is still ongoing. By the time that it was planned, the intention was to publish this final architecture document at the project end. As some delays occurred in the field trial implementations, the project had to be extended for six months. Therefore, not all experiences have been gathered yet. However, in terms of the architecture, it can be stated that most of the knowledge generated within this project in terms of the architectural design of smart grid approaches facilitated by the technologies presented here is already available and described in this deliverable.

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