Cellular System Model for Smart Grids Combining Active Distribution Networks and Smart Buildings

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Abstract. With the European Union's political 20-20-20 targets, the structure and control of the overall electricity grid is changing towards a smart grid.

In order to optimizing future grid management, end-users will be integrated into the energy system through incentives and several new energy services. Indeed, end-consumers will become active and independent participants in the energy market by either shifting or lowering their electricity usage as a function of both availability of certain energy sources and energy costs, thereby contributing to the development of environment- friendly energy and improvement of energy efficiency.

Smart grids are also a response to the expected increase in complexity in the control of the low-voltage level, which results from amplified fluctuation of current flows due to the high proportion of decentralized energy generation. As such, smart grids will serve to maintain or even increase supply security in this energy landscape.

At present, energy feed can still be handled by conventional means. However, with the rapid growth of decentralized generation and especially weather-dependent generation, measures must be taken to secure a reliable power supply.

In 2007 the German government initiated the E- Energy programme in order to demonstrate the smart energy supply system of the future – the smart grid[1] - in specific model regions. As one of the six selected model regions, the Model City Mannheim project is currently developing a new ICT infrastructure to boost energy efficiency and receptivity for renewable energy as well as to strengthen grid users' personal responsibility for their energy consumption.

This paper presents the required core elements of a future smart grid.

Keywords: energymanagement, E-Energy, distributed generation, renewable energy, smart grid, active distribution system, ICT, swarm intelligence, distributed automation, agent, system architecture.

1 Objectives of the German E-Energy Funding Programme

The following figure summarizes the objectives described below.

<u>*Environmental compatibility*</u>

The fundamental aim is carbon dioxide emissions reduction and a more conscious use of the limited supply of fossil fuels. A global consensus exists for the pursuit of these overarching goals and has led to the formulation of climate

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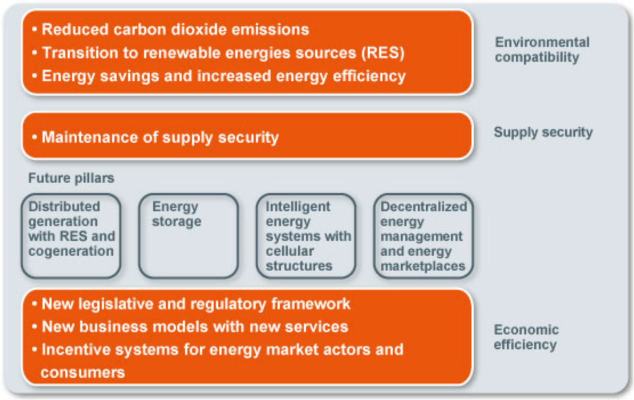

Fig. 1. Objectives and pillars of the future energy system

change-focused policy framework. **The resulting objective is thus the accelerated implementation of energy conversion facilities that make use of renewable energy sources, within the new energy portfolio.** The ERGEG's Position Paper on smart grid and the sources cited there [1, 3-8] provide a summary of these objectives.

The first pillar of future energy management is then, energy conversion through, first, **centralized large- scale generation** in the high-voltage range of the **transmission system**, secondly **distributed generation** in the medium-voltage range of the **distribution system**, and finally **micro-conversion** from local energy sources on areas and buildings on **grid user sites** in the low- voltage range. With regards to distribution grids, the aim is to **augment the ability to integrate the conversion of renewable energy sources and the cogeneration of heat and power**.

The increasing use of renewable energy sources results in **an increased fluctuation in the available energy**. It then becomes necessary to resort to energy storage facilities – in particular **thermal storage** – and develop corresponding business models, in order to integrate both heat and power into the energy system.

Fuel switching away from refined fossil fuel products in the transportation and heat sectors will be a major contributor to the increase in electricity demand, specifically in developed countries. The anticipated widespread introduction of electrically powered vehicles and heat pump technology is expected to increase Germany's annual electricity consumption by about 30 percent (by when?). In the field of **environmental compatibility**, a further target, therefore, is **to conserve energy and to increase energy efficiency across the entire value chain including all participants in the energy market, right down to the grid user.** The planned measures aim to bring about, on one hand, changes in grid user behaviour and, on the other, a reduction of losses during energy transport. The reduction of transport losses can be achieved with incentives for erecting decentralized generation facilities close to the point of consumption and with price incentives for sourcing locally generated heat and electrical energy. A further pillar of future energy management, therefore, is the **decentralized energy management with virtual, local balancing areas**. In decentralized energy management the prosumer is incorporated into the energy market, together with the traditional energy market participants. The aim is to reduce energy consumption through new energy services which disclose **product charateristics including the type of energy conversion and transport distances**. Possibilities for establishing a closer relationship between energy supply and energy service provision will be created, paving the way for many new energy services. In combination with smart grid and smart buildings, the new services induce a holistic approach to building–energy management and facilitate a link with other areas of life. The **grid user is promoted to an active, independently acting participant** in the energy market. The development of the smart grid offers the opportunity of increasing energy efficiency across multiple media (such as electricity, heat and refrigeration/air conditioning).

Supply security

Under these new conditions, the **supply security** must absolutely be maintained. A bidirectional energy flow between transmission system, distribution system and consumer site grids with variable load flows will develop to deal with higher penetration of medium to micro-scale decentralized renewable energy systems in the distribution grid. The inclusion of decentralized installations and consumers' active participation in the control scheme of the low-voltage grid, results in a significantly increased complexity. An excessive level of complexity can lead to loss of controllability in central control stations and centrally controlled balancing areas. This **complexity can be reduced** with individual, intelligently and synergistically behaving structures that are self-organizing but remain connected to the overall system. The current uncontrolled feeding into the decentralized area, therefore, must be overcome through even more decentralized energy management with control loops in cellular structures that supplement the central control measures. The result is a **smart grid with a cellular structure** – an additional pillar of future energy management.

To this end, structures that act independently of each other electrically and in their communication will be created through meshed distribution systems and agents capable of acting autonomously within the **grid cells** (grid moderators) and in **virtual balancing areas** and market areas (market moderators). These structures will act synergistically with other cells, forming an energy organism based on a **distributed and decentralized automation solution**. Smart grids are a response to the increasingly complex control of the low-voltage level resulting from the fluctuating current flows that will occur due to a high proportion of decentralized energy generation Because a cellular approach and decentralized, distributed automation solutions allows the operation of grid sections to be maintained when adjacent sections have failed, they also ensure, or even increase, supply security. The smart grid concept also promote supply security by lowering the dependence on a small number of centralized energy systems and allowing to rely rather on many smaller energy systems in the distribution grid as described above.

Cost-effectiveness

The modernization of the energy system can succeed only if politically and commercially successful market scenarios can be created and implemented. Thus we come to the third of the three energy policy objectives – **cost-effectiveness**. We describe here the specific means to reach cost-effectiveness. Firstly, the necessary **legislative and regulatory** changes must be defined to facilitate the inclusion of the consumer in the smart grid's function with a bidirectional communication between partners in the energy market.

New market scenarios with new business models must be defined **from market roles in the energy sector value chain,** under the conditions of a new kind of energy network with decentralized generation, storage and energy management. This will result in new **products and use cases** as functional components. **Roles and responsibilities** must be defined for this purpose.

A communication between the use cases across the non- discriminating marketplace and between the energy system components within the grid and consumer appliances and installations in the grid user's property, increases the demands on standardized communication. Accordingly, the **standardization** of use case service interfaces, site models and site relationships form a focal point in the development of the smart grid.

The transition to the new energy system requires the participation of all market partners and can not be achieved through a change in one link of the value chain alone. The grid user as well must be motivated to participate in the energy system in a new and unfamiliar way. The objective, then, is to define **incentive systems for grid users**. Especially in the distribution system this may be associated with a change in the regulatory framework.

While the required legislative and regulatory changes are defined mainly from a perspective of environmental compatibility and supply security, the subject of cost-effectiveness focuses rather on business models and **consumer-centric perspective in an atmosphere of increased individual responsibility and personal treatment, especially through incentives, with regards to the provision of energy services**. These two elements are the motivation for the participation in the **energy marketplace**, communication over the **energy Internet** and development of new **energy services** in combination with other areas of life.

2 Business Modelling

We have described so far the objectives pursued through the implementation of the smart grid concept and the essential conditions to allow its development. However, people will invest in a smart grid only if:

1) we succeed in developing future market scenarios with politically and commercially successful business concepts as well as concrete incentive systems to integrate grid users in decentralized energy management;

2) the legislative and regulatory environment required to achieve the objectives and to develop commercially successful business concepts is created, which role is also to fairly allocate the initially very high investment costs across all stakeholders and establish sufficient investment incentives;

3) the standardization process required for a non- discriminating, open electronic market communication between all participants in the future E-Energy market's more complex value network is advanced, whereby standardization of communications affects not only the technical system but also business process communications between the market partners (interconnection of equipment, pants and operating resources in the energy Internet through the virtual energy marketplace with all market partners).

On this basis the mirror committee of the German electrotechnical commission (DKE) for IEC SMB/SG3 Smart Grid [9] defined the term "smart grid" as follows.

*"The term "**smart grid**" covers the networking and control of smart generators, stores, consumers and grid operating resources in energy transmission and distribution systems with the aid of information and communication technology (ICT)."*

The term has also been adopted in the German standardization roadmap [10] as represented in Fig. 2.

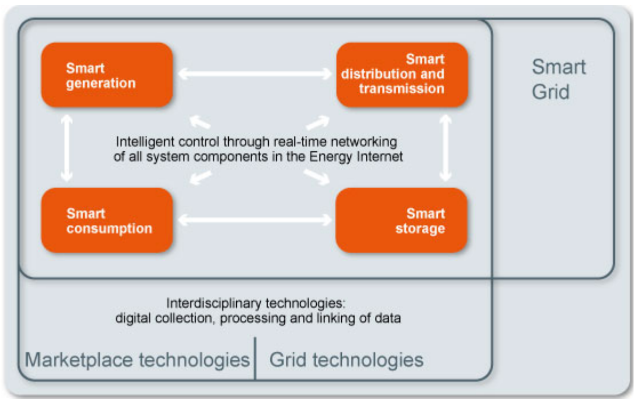

Fig. 2. Smart grid as total intelligent energy system

On this basis, key factors for the ability to describe new market scenarios and business concepts are the use of standardized terminology and definition of unified core models. The following section provides an introduction to standard terminology and Fig. 3 illustrates the defined concepts.

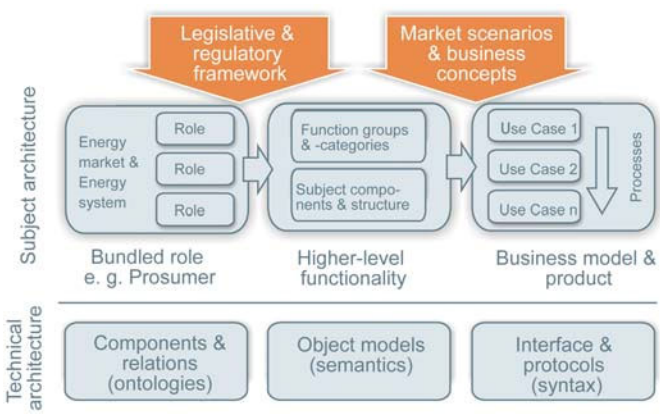

Fig. 3. Modelling of the E-Energy market

➢ Roles

Market roles are assigned to all activities in the smart grid. The roles represent fine-grained instances in the value network, capable of legal transaction.

Roles are, to some extent, nationally or regionally defined by various laws and regulations. With as detailed a classification of theoretical granular roles as possible, an attempt can be made to define solutions, functions, modules and interface descriptions such that basic results remain transferrable on an international or European level. In practice this means that some market roles will be grouped into so-called **bundled roles** (for example prosumer as producer and consumer) or market participants will perform several market roles (for example utility companies).

The following market roles exist already or have been identified in the smart grid with newly arising responsibilities:

- Producer
- Consumer
- Transmission system operator (TSO)
- Distribution system operator (DSO)
- Communications network provider
- Energy supplier (electricity, heat, gas)
- Balance responsible party (BRP)
- Balancing grid coordinator
- Control zone responsible party
- Energy trader
- Energy exchange
- Measuring point operator
- Measuring service provider
- Energy marketplace operator
- Billing and settlement service provider (accounting between unbundled mar ket participants)
- Energy service provider (energy advisor, contractor)

To these market roles that participate directly in the processes, other stakeholders must be added, such as

- manufacturers of smart grid-capable electrical apparatus, plants and operating resources,
- suppliers of information and communication technology incl. software for energy services,
- regulatory institutions,
- political entities.

➢ Actors

An actor is an acting element within a domain. It is sender for a use case or recipient of a reaction from a use case and has an assigned role, for example a natural or a legal entity, a physical device, or a logical device as abstraction of a category of physical devices.

➢ Domains

Domains are system areas with defined boundaries, in which the activities of use cases take place and in which the overall energy system can be coarsely classified by the physical current flow, as, for example, laid out in the NIST or IEC roadmap. To allow a meaningful bundling of use cases, a further breakdown of the overall system may make sense.

The following illustration shows a proposal forwarded by Transmission & Distribution Europe that has been expanded into a more comprehensive domain proposal:

- Power Generation domain with the three subdomains, namely Central Power Generation in large-scale power stations, Distributed Power Generation in the distribution systems, and micro generation on grid user sites (such as photovoltaics or cogeneration units)
- Transmission System domain with the two subdomains Decentralized Transmission System Infrastructure and Central Transmission System Infrastructure
- Distribution System domain with the two subdomains Decentralized Distribution System Infrastructure and Central Distribution System Infrastructure
- Grid User Property domain with the four subdomains Residential Sites, Commercial Sites, Industrial Sites and Vehicles
- Site Devices and Installations domain
- Markets domain with subdomains Energy Wholesale Market, Central Balancing Power Market, Energy Services Marketplace and Decentralized Markets

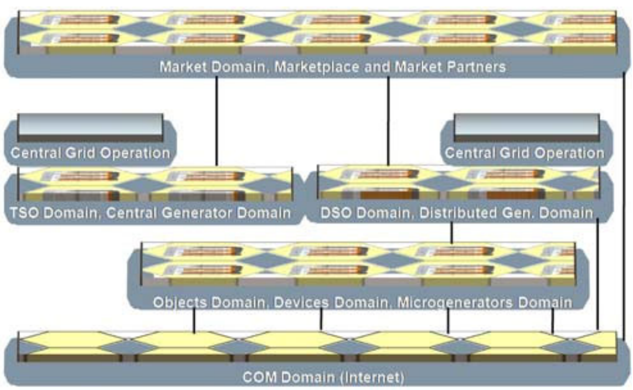

Fig. 4. Domains in the energy system

➢ Use cases

A use case is a structure for bundling activities on a lower classification level from an external viewpoint. The use case is used to represent detailed functional descriptions within a domain independently of the business model or the system architecture. The description of use cases with site models and service interfaces is regarded as the basis for standardization in the smart grid.

- **Use case activity**

A use case activity is an activity within a domain in the energy market with definition of an input through an actor (the sender) and an output through another actor (the recipient).

- **Site semantics, interface syntax and site relationships (ontologies)**

As process function blocks, the use cases communicate through interfaces. To ensure a trouble-free information flow through interfaces, communication models and market roles require unified site semantics, defined relationships between sites (ontologies) and a defined syntax.

- **High-level functions**

High level functions bundle use cases with various actors in order to describe complex sequences across roles and systems and to systemize the many use cases.

- **Processes and products**

Use cases are connected to processes by market roles and are associated with products.

- **Business cases**

Business cases as commercial services arise through the connection of processes with their component parts – the use cases – and the products of a role or bundled role.

3 System Modelling

3.1 Basic Cellular Concept

With the advancing utilization of decentralized renewable energies in the distribution system, a bidirectional energy flow between transmission system, distribution system and grid user properties is developing. Cases of load reversal can already be witnessed today and will, in future, necessitate an active management of decentralized plants. The currently uncontrolled decentralized infeed must be overcome with decentralized energy management. Initial initiatives to this end have been taken with the bundling of distributed generation capacities into virtual power plants. The grid, however, continues to be controlled by central operations from grid control rooms, with the consequence of a significant increase in the complexity of the control system due to the growing number of decentralized components that need to be considered. This also impacts the complexity of the existing balancing area management through supraregional balancing grids on the transmission system level. The developments in E- Energy project *moma* therefore focus especially on new methods of decentralized and automated grid management within the distribution system and on virtual balancing areas that can handle both the local situations and the creation of new product groups related to generation or aimed at specific consumers.

The concept of complexity, the associated approach in moma, the network topology that is based on it and the cell model have been described in [11] and in the associated sources [12,13] and will not be dealt with again here.

3.2 Site-Related Energy Management

An approach is proposed for developing a smart grid in the domains of the transmission system, the distribution system and the site grids in the grid user domain in the form of a cellular grid system. The cells are each fully equipped with smart grid components (generators, consumers, energy storage and grid operating resources), so that they can act as agents with self-optimizing energy balance as a system expanded with ICT interfaces and as core of the local intelligence.

Through local measurements, status information about other cells and external parameters from central distribution grid control systems allow the agents to operate as a part of an overall energy system. This results in an information and energy exchange between the cells. A swarm intelligence pattern emerges at this point, carrying the patterns of self- optimizing and self-healing.

In the moma project, a solution is being developed to link energy system components and site agents within the site domain via the system structure of the bidirectional energy management interface (BEMI) and the Energy Butler's local intelligence, combined with the local intelligence in the grid and market agents of the distribution system cell in which the site is integrated. The developments for the Energy Butler are based on the Fraunhofer IWES papers on the BEMI [14,15,16,17]. The following illustration shows the implementation model within the scope of moma.

The domains described above contain the grid user's site domain, which can be in one of the four categories residential, commercial or industrial sites and vehicles. In the cellular core model of the energy system, it is proposed to include the grid user's site domain in a site grid cell that is part of the system architecture and has an independent flow of both energy and information. As an electrically independent unit, a site grid cell features each of the four energy system components categories: loads, generators, accumulators and grid operating resources. These, in turn, are linked to system services and to communication equipment through an ICT interface with its own information-processing equipment (sensors, switchgear, control equipment). The site grid cell is defined as the smallest electrically independent unit in the sense of its down-regulation and startup capability and therefore has its own network structure.

Because a single site may contain several consumers with different energy management interests and requirements, it is further proposed that the system architecture be further broken down within the site domain viewed as connection site with sub-site cells. In an electrical sense, sub-site cells are non-independent structures in terms of the definition as site cells and distribution grid cells, but are independent structures in an information technology sense because they are equipped with sensor and actuator circuits as well as agent structures for energy management in the sub-site cell. Sub-site cells can correspond, for example, with apartments in apartment buildings and with offices and shops on commercial sites. Site grid cells and sub-site cells contain energy system components and an ICT interface in the form of a bidirectional energy management interface (BEMI).

In Model City Mannheim this approach is being implemented through

- consumer metering equipment in the site grid cell with field communication between the metering devices of all supply partners;
- a meter gateway for communication with the metering equipment, with the sub-site cell and with the distribution system cell

- a BEMI computer (Energy Butler) acting as central ICT interface component, which maps the site's agent structure;
- devices and installations as energy system components of all four categories
- ICT interfaces at the consumers and generators (appliance and power plants) with information- processing modules (sensors, actuators, control devices) as so-called sub-BEMIs
- a user control and display unit
- site-integrated communications between these components in the form of a private network, an automation network or an energy management LAN
- communication between the grid user's private network and the Internet and a protected, IP-based broadband communication with the DSO's communication network, whereby broadband power line is used for IP communications in moma.

To ensure data privacy, the communication between the meter gateway and the Energy Butler with the distribution system cell containing the site ensures the interaction of these two gateways in site grid cell and sub-site cell, so that data from consumer metering devices that is supplied only for on-site services is not sent to other market partners. If a suitable safety bridge is set up between Energy Butler and meter gateway, direct on-site communications can also be set up. To this end, approaches to defining a common smart meter gateway with common hardware for both cell areas also exist. A clear security and role concept for the smart meter gateway is crucial especially in buildings with several apartments and offices.

To introduce decentralized energy management as a widely accepted solution, a standardized communication method is needed for interfacing automation and consumer metering devices in grid user property with devices and plants from many different manufacturers. Energy system components (devices and plants) of all four categories are therefore regarded as domains in their own right within the energy system.

This section briefly outlines the remaining cell types in Figure 5. The site grid cell is integrated in a distribution system cell, which contains agent structures for grid and market support. The distribution system cells, in turn, are components of a system cell, which contains an integration platform that connects the grid cells to the overall grid control room – including the grid control station – and to the transmission system. Through the energy marketplace it also connects the system cells' local market mechanisms with the partners on the energy market (suppliers, traders, wholesale and balancing power market, energy and metering service providers). Communications of the overall system is IP-based. The result of this interconnection of energy system components in the grid cells with the energy market partners is the so-called Energy Internet.

In the German standardization roadmap document, the two focus groups Inhouse Automation and Distribution System Automation have been set up with the aim of advancing the standardization process for the function principle of the site domain, the devices and plants domain and the distribution system domain. Under the umbrella of E-Energy and moma, initial standardizable solution approaches have been presented for the definition of a hardware-independent site agent execution layer for site agents (for example BEMI computers), for controlling the energy system components with OGEMA [18], and for communications between the energy system

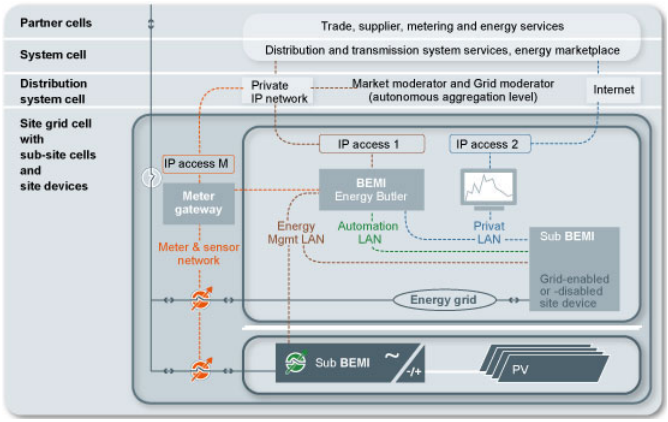

Fig. 5. Arrangement of the site domain within the cellular model

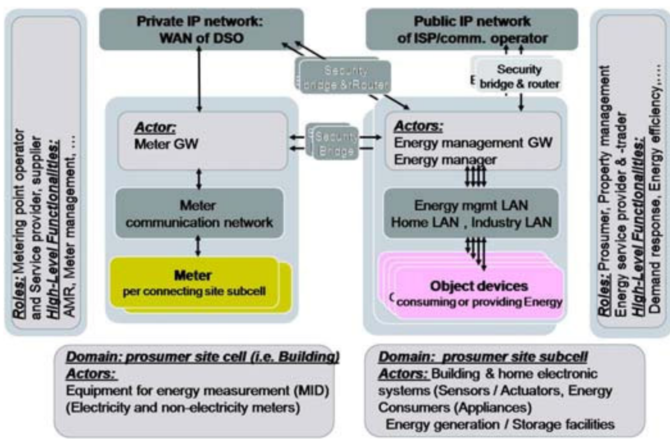

Fig. 6. Object domain of the grid user in the cellular model

components for the object's energy management LAN shown in Figure 5. To facilitate a description of these approaches, generalized terms are to be introduced. Figure 6 illustrates their assignment to the activity domains, market roles and function examples.

Figure 6 illustrates the relationships between the following:

- the consumer metering devices and associated communication paths to the metering equipment
- the meter gateway as communication component between the consumer meters in the site grid cell and the distribution system cell and the energy management gateway
- the energy management gateway (EMG) as generalization of the BEMI computer platform
- the energy manager, which performs the energy functions and generalizes the services of the BEMI computer

- the energy management LAN in the sub-site cells, which connects the energy management with several site devices
- the energy system components (site devices) to be controlled across the site's entire control loop.

Between the meter gateway and several EMGs in the sub-site cell the issue of data protection and data security is visualized by means of the security bridge and by the IP-based communication with the public Internet and the distribution system's private, protected communications network. The illustration further shows the domains, in which the components are listed as actors in the energy system. Market roles and use cases or function groups acting in the domains are shown here only by way of example.

The EMG is defined as a physical device consisting of computer system hardware, an operating system, a virtual runtime machine, a hardware-independent programming platform and an application and communication framework for mapping communication stacks, resource description and basic functions. For the Energy Butler, the EMG is a hardware and firmware system platform, bundled with an application and communication framework that facilitates operation of an energy manager software application.

The energy manager is implemented as a software solution consisting of device-specific energy services that access the EMG's application and communication framework. It further consists of energy automation services, which use the device-specific services and device resources for in-house communication and which act as interface to the active distribution system. It represents a smart agent structure as grid user agent in the site grid cell or in the sub-site cell. Its functions are to automate energy management, maximize energy efficiency, reduce energy costs and determine price, source, type and use of the consumed energy.

The described solution is illustrated in the form of an implementation stack in the figure below.

The OSGi programming framework and the OGEMA application framework run on the underlying hardware of an embedded system. This allows the execution of

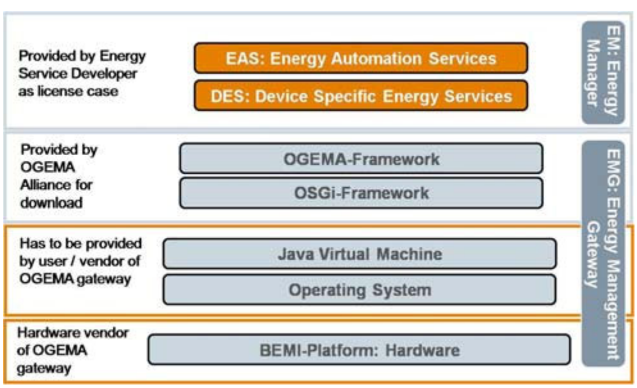

Fig. 7. Energy Butler, implemented as a BEMI computer, generalized as sum of energy management gateway (EMG) and energy manager (EM)

energy functions for delivery products, energy and energy metering services, and interface services to other areas of life on various hardware platforms (smart meter gateways, heater controls, building services automation systems, network routers, Energy Butlers, etc.) As application platform for the OGEMA framework, a technology-specific stack consisting of operating system, Java Virtual Machine and OSGi is currently being proposed, although this approach could also be implemented with other technologies.

3.3 Energy Management in the Distribution System with Decentralized Decision-Making and Site Guidance

As part of a dissertation, the grid user site-centred approachto energy management in Model City Mannheim using the BEMI model has been extended with regional energy management, which operates on a higher level but still uses decentralized decision-making. This is implemented with a component that forms part of the distribution system [19].

Especially in the context of the liberalized market and the unbundling of grid and supplier, the role of energy management has been investigated with various market operating models. Included in this consideration of a combined system of decentralized energy management withdecentralized decision-making but associated, higher-level incentive management through a BEMI pool is the operation of a virtual power station. A simulation program has been developed to investigate the operation of a system consisting of many BEMIs and a higher-level BEMI pool, including its repercussions on grid management. A lab test was also performed to investigate incentive-based voltage-maintenance through influence of the active power in combination with a virtual power station.

The BEMIs are controlled from a higher-level system by means of price forecasts, from which variable price curves for consumption and generation management are plotted. These curves, in turn, form the basis for new load and generation forecasts that yield new energy quantity forecasts for balancing. The operation of a BEMI pool is proposed for a market actor, which is referred to as *energy service provider* in the paper. Through the market processes proposed as influencing factors for active power, the grid's influence on prices therefore becomes a second reference variable. The pool BEMI, then, is the interface between market and grid operator on one hand and the sites' energy system components, which the BEMI system controls, on the other. In the distribution system, the BEMI rules, then, do not develop as a swarm but through a controlled model.

With the system model for connecting energy management in the grid user property through a higher- level instance in the distribution system – which can unite market and grid interests in the BEMI pool – a foundation has been created on which virtual power stations can be included in the market mechanisms of Model City Mannheim. Integration of virtual power stations is realised through virtual balancing areas and products for energy supply in combination with variable pricing to influence consumer behaviour based on generation. This also paves the way for local market mechanisms.

The paper furthermore concludes that the complexity in virtual power stations and in higher-level decentralized energy management systems in large distribution system areas will, in future, increase significantly as the number of energy system components incorporated in market and grid management rises. A central control loop in the distribution system with the described mechanisms will no longer be controllable once a certain degree of complexity is exceeded. As mentioned above for the core model, complexity can be reduced again through the creation of cells with their own control loops and a much lower number of energy system components. A market controlled only through the swarm intelligence of the BEMIs in the site grid cells is not proposed as alternative. Indeed, the energy volumes that can be handled with this approach are still too small. An additional barrier to deployment of the swarm intelligence concept is that the fine-grained grid management's dynamic behaviour can not yet be easily simulated numerically.

The described paper identifies the connection between decentralized energy management and central distribution system operation through the grid control system as a further research requirement. The moma project therefore proposes a connection of central and decentralized grid management in distribution system cells. The number of all four categories of energy system components in each of these distribution system cells is large enough to allow the meaningful operation of a closed control loop. On the other hand, the number of components is small enough to keep the complexity of the decentralized control loop in the distribution system cell at a manageable level. In each of these distribution system cells the link-in mechanism for a virtual power station can be utilized in the sites (BEMIs) through decentralized energy management controlled by a higher-level instance (BEMI pool).

In an extended approach, virtual balancing areas and a new actor, the market agent, facilitate regional market mechanisms. Through the grid agent, metrology, regional reserve generation plants and regional system services facilitate a grid management that is split into regional grid cells. In order to join the overall system consisting of several grid cells to an overall distribution system, an exchange of information and energy between grid cells and a control with outline conditions by the central grid management is implemented. This cellular structure of autonomous but interconnected systems results in a self-optimizing, self-healing network of independent cell agents, which collectively exhibit swarm intelligence. Since only a select few cells can be equipped in this ways in the scope of this project, practical trials are supplemented with comprehensive, in-depth numerical grid simulations of larger grid areas.

The following section describes the initially outlined approach in detail as a possible solution.

3.4 Decentralized but Connected Grid Management in Grid Cells with Grid Agents and the Interaction with Market Agents

The challenge consists in achieving:

- site-related energy management with BEMI systems in the grid user sites;
- energy management with decentralized decision- making in regional energy market structures (market agents for virtual power station functions for generation aggregation and virtual balancing areas) with site guidance through communication of market situations to BEMI pool functions;
- energy management with decentralized decision- making in the distribution system (grid agents in controllable grid cells, whose regional expansion is determined by manageability of complexity) and with site guidance through communication of grid situations to BEMI pool functions;

- connected grid management of all cells of a grid compound as self-optimizing control loops, such that the cells form an overall compound system with self- optimizing control on one hand and guidance through boundary conditions of higher-level market- and grid management structures on the other.

The overall system of grid cells, in which market and grid agents operate, is to be modelled as a swarm of agents that form the overall system of grid cells into a unified energy organism.

In order to facilitate widespread penetration of an energy system with agents acting as smart, decentralized grid and market instances, modelling and simulation work will be necessary to investigate the overall system's behaviour. With this new concept, decisions are made decentrally on the basis of complete control loops in the grid cells with decentralized information about market, grid and environment, and on the basis of external outline conditions in the other grid cells and higher-level management instances. The aim is to achieve self- organizing, smart consumer and generator behaviour in cellular grid structures while minimizing the level of central control. Regarding site-related energy management with control through BEMI pool structures, the Energy Butler, as core of the BEMI systems, receives the listed information for local control of the sites' loads and generators via (i) direct load and generator control, (ii) a market partner or (iii) incentive-based control with decentralized decision-making. The control takes place in such a way that a predictable behaviour of the whole body of BEMI systems is achieved. The individual BEMI systems exhibit defined behavioural patterns, which are influenced by the requirements of the consumers and which autonomously make decisions in their name.

The BEMI is the site-specific node in the distribution system cell at which various interests and tasks of several energy market roles come together. The possible actions are limited by the components actually installed and by existing energy potentials.

The many and varied interests of generator, consumer, supplier, grid operator, energy service provider and other market roles must be matched to each other. To this extent, intensive market communication and a balance between various interests through regulated procedures is also necessary in the unbundled market. Especially the interaction between BEMI pool, in which market and grid roles interact, and the site BEMI systems, which represent the grid users, reflect these conflicting interests. While the system actors with these roles represent their owners' interests, they also consider the interests of other market users through external parameters and incentives.

In a social context, this would be termed social behaviour, although, to technical systems, this term can be applied only in a figurative sense. Nevertheless, the rules by which the actors act must be implemented in such a way that the system becomes self-stabilizing. It would therefore seem to make sense to **allow market and network agents to develop a swarm-intelligence**.

The market roles' various interests come to play in an environment that is formed through a virtual energy market and the physical, electrical energy grid. The actors' freedom of action therefore is defined by the energy exchange market mechanisms and by the technical limitations imposed by the grid. The initial situation is one of large control time constants between forecasting and balancing that form a present-day perspective, reaches a long way into the future to determine target values and the control based on actual values in predominantly central structures. In an effort to obtain better forecasts and reduce deviations in the context of an ever more decentralized and varying generation, control time constants with decentralized control structures would tend to be smaller. The long-term objective is to achieve a real-time capability for this control process and thereby, through ICT networking, to create a system that can, independently and at any time move energy to where it is needed.

As long as the BEMI systems on the grid user sites are being controlled by the BEMI pool in regional structures, it is proposed that the overall grid structure be split into regional, independent control loops, which, equipped with agents, exhibit local intelligence. The overall system of cells should, however, exhibit swarm intelligence through its agents and within the constraints of external and higher-level limitations. Building upon the individual behavioural patterns, a need therefore exists to model and simulate the swarm behaviour of an overall energy system consisting of cells that each contain all required energy system components.

Swarm intelligence is a specific field of artificial intelligence (AI) based on agent technology. It is also referred to as distributed artificial intelligence. G. Beni and J. Wang coined the term in 1989 in the context of robotics research.

Distributed artificial intelligence works on the premise that artificial agents, through cooperation, are capable of higher cognitive activity. Marvin Minsky terms this ‘The Society of mind’. Sunil Nakrani of Oxford University and Craig Tovey of the Georgia Institute of Technology presented an application example at a conference on mathematical models of social insects in 2004. They modelled the calculation of optimum load distribution in a cluster of Internet servers based on bee’s behaviour when gathering nectar.

Communication and specific actions of individuals can result in a social community developing collective intelligence, which is also referred to as group or swarm intelligence. System-theoretical and sociological explanations of this phenomenon have been given.

An organism of this kind does not have a central instance that controls the behaviour of each individual. Instead, the swarm as a whole simply reacts to information in the form of higher-level outline conditions. This presupposes a communication between swarm members (market and grid agents) with each other and an exchange of information with the system environment, i.e. the energy marketplace with associated market partners and the central grid management instances.

There are several reasons why individuals strive to act as part of a swarm. One is that the space within a swarm offers both protection and a greater range of possibilities. Applied to the energy system this means a higher degree of supply security in the overall grid and a greater scope of performance possibilities compared to energy structures consisting only of discrete, autonomous sites. The aim of self-determination can therefore be associated with the aspect of supply security.

The agent swarm identifies overall states within the system but can furthermore ensure regional optimization, since the complexity of regional control structures remains manageable. It also becomes easier to maintain operation of sub-grid areas in the event of a failure of other grid areas, which contributes to supply security.

With this objective in mind, a model is being created as part of the moma project, within which a swarm of market and grid agents can exhibit meaningful behaviour.

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