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Content

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Real-time simulation of Distributed Generators, for testing a Virtual Power Plant software

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Abstract: Virtual Power Plants (VPPs) are designed to monitor and schedule a large number of decentralized producers and consumers via intelligent software. A possible way to test the VPP functionality is to interface its software with simulated producers and consumers under various scenarios. This paper presents the development of the real-time simulation platform “OpSim” and its first application as a testing environment for VPPs. A test case is described, in which the VPP from Bosch Software Innovations is connected to a simulated CHP plant on the OpSim platform. It is shown that the VPP can monitor this plant via a standardized interface “VHPready 3.0”. Time shifts in the signal between VPP and OpSim are observed. Moreover, a future outline is given, for applying real-time simulations as a testing method for VPP software.

1. Introduction

The vast installment of renewable energy sources has led to a significant amount of decentralized power sources in German power grids [1]. Unlike conventional power plants, these distributed generators (DGs) are chiefly located in the distribution grid at medium and low voltages. This poses control challenges for distribution grid operators, who now have to monitor and handle a multitude of small generators. Moreover, single DGs may be too small to bid into energy- and ancillary service markets, creating challenges for DG-operators who aim for optimal profits.
A way to mitigate these problems is by pooling the DGs together with storages and flexible loads (collectively referred to as “units”) to so-called “Virtual Power Plants” (VPPs) [2, 3, 4]. The VPP contains intelligent software, which monitors and schedules the operation of a large number of decentralized units. The pool can be marketed optimally and provide ancillary services, e.g. frequency control [4], similar to an ordinary power plant.
The VPP-software must be thoroughly tested, to ensure an optimal scheduling of its vast pool of units. For example, it should be verified that the VPP can manage a large portfolio and deal with large quantities of status information from each unit in the pool. Such tests could be performed partially offline, with simulated DGs, storages and loads, as simulations have the advantage that various scenarios can be tested before new hardware is connected to the VPP. Yet, to ensure that testing conditions are realistic, the simulations should run in real-time and communicate to the VPP software via the same interface that a real DG, storage or flexible load would use. Hence, an ordinary offline simulator would be insufficient for this task.
In this paper, we introduce a prototype development of a real-time simulation platform “OpSim” [5, 6], for testing aggregation and grid operation strategies. In a first functional test, we use this platform to simulate a DG and connect it via a standardized interface to the VPP of Bosch Software Innovations. Hence, OpSim provides a first functionality to test VPP software. Through this test, we validate (A) if the VPP can monitor the simulated DG and (B) if there are any latencies between simulation and interface.
The paper is structured as follows: first, related research on real-time simulations is reviewed. Second, the OpSim platform is introduced. Third, results of the test run with the VPP from Bosch Software Innovations are evaluated. Finally, future applications and follow-up works are outlined.

2. Related Work

This section reviews existing works, in which real-time simulations are used to test Smart Grid control strategies (each strategy is marked by italic text). In our nomenclature, such strategies could be a VPP, but also e.g. a voltage control algorithm.

- The OFFIS institute released the co-simulation platform “mosaik 2.0”, to combine different simulators and controllers. One application was the combination of a grid simulator *with an agent-based voltage control strategy* [7].
- Faschang et al. introduced a rapid control prototyping platform for networked Smart Grid systems [8]. It comprised of a message bus architecture, to connect *prototype grid controllers (in the example, a controller for tap changers and reactive power in low voltage grids)* to grid simulators. Its purpose was to test the controller under increasingly realistic conditions, up to a field test implementation.
- In [9], a real-time simulation of two medium voltage feeders with nine controllable DGs was established, to evaluate an *online voltage optimization algorithm* for DGs and tap changers. Apart from demonstrating the algorithm’s ability to run in real-time, the grid simulations showed that the algorithm improved the voltage in three exemplar simulations.
- A real-time testbed for *wind park controller soft- and hardware* was developed in [10]. The testbed consisted of detailed turbine, grid and wind field models, which were solved with parallelization methods on multiple computers.
- Georg et al. [11] designed a hybrid architecture to enable a combined simulation of both power systems and communication architectures. Its aim was to validate real-time capabilities of *power system protection and control algorithms*.
- In the Project “SIEM”, a real-time simulation of electric vehicles is developed [12]. In particular, the simulation is used to test a number of *smart charging strategies* on simulated electric vehicles, to evaluate if such strategies relieve loading peaks in the grid.

In various applications, one particular type of controller (e.g. protection, voltage optimizer) is the main focus, though some works aim for an architecture which allows multiple control strategies to be active at the same time. “OpSim” also belongs to this category.
In particular, real power systems are controlled by multiple mechanisms, some being market-driven (e.g. VPP) while others are crucial to maintain the grid within acceptable operating conditions (e.g. technical VPP [13]). Investigating them in a holistic simulation environment is the goal of our project.

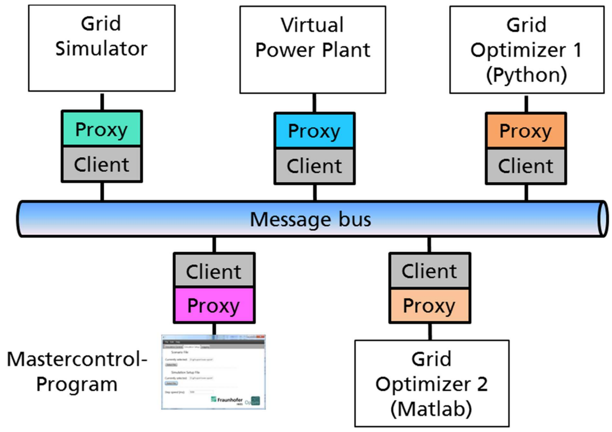

Fig.1:*The OpSim platform for distributed simulations of power systems.*

3. The OpSim platform

OpSim is a platform for real-time simulation of power systems which interacts with multiple control systems, such as voltage optimizers and VPPs. The system architecture is motivated by the concept in [8] and consists of three parts, which will be briefly explained in the next subsections.

3.1. Components

As shown in Figure 1, OpSim connects several distinct components to emulate a power system with multiple control strategies. In this context, the word “component” has two meanings: (A) it can be a simulation (e.g. Opal-RT [14]) to emulate the electric grid with its variety of generators, storages and loads and (B) it can be a controller, which is either a simulation itself (e.g. a control block in Simulink) or a fully developed software (e.g. a VPP). Combining multiple components enables us to model a complex power system, in much more detail than an ordinary grid simulator provides.

3.2. Message bus

Components exchange information via a message bus, which forms the center of the OpSim platform and runs as a server application. Since each component is a different software with its own variables, programming language and interface, the components are not directly connected to the message bus. Rather, a client and proxy (written in Java) govern this interaction.

3.3. Proxy/Client architecture

Each component in OpSim is situated behind a client and a proxy. This architecture is motivated by the concept in [8]. The client is highly generic and handles the (dis)connection, synchronization and information filtering of a component. The proxy on the other hand, is component-specific and serves as "translator" for data between a component and the message bus. Hence, when a new component (e.g. a VPP) is connected, only a new proxy needs to be created, whereas an existing client can be used.

4. Connecting VPP and OpSim

This section demonstrates the first stage of using OpSim as a testing platform for VPP software; a simulated CHP plant model is connected to the VPP of Bosch Software Innovations, via the standardized interface "VHPready 3.0". This section discusses the components of this test, as shown in Fig. 2.

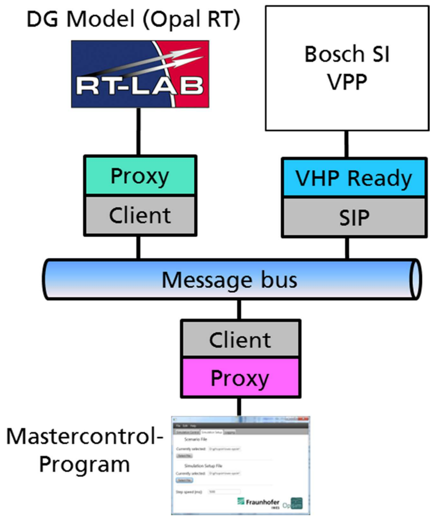

***Fig. 2**: Setup to connect a VPP software to a simulated DG (CHP plant), using the OpSim Platform. Source of Opal-RT image: [14].*

4.1. VPP of Bosch Software Innovations

The VPP from Bosch Software Innovations is designed to support many different scenarios, depending on local and national rules, regulations and constraints. The common requirement is a supervising software that pools/groups the units connected to the VPP. Hence, a modular VPP was designed to enable varying business cases by utilizing a flexible software. The main functions of the Virtual Power Plant Manager are:

- Master data management
- Time series management
- Asset control interfaces
- Forecasting capabilities
- Optimization of varying business cases
- Monitoring of operational business
- Reporting for business and audit requirements

4.2. VHPready and SIP Component

In order to connect the VPP and a simulated CHP plant, OpSim must provide the same communication interface as real CHP plants. The SIP (Standard Interface Preparator) is the link layer for this purpose. It provides different functions for external systems, such as data collection and operating control (e.g. interpreting VPP schedules). In the present setup, an interface has been realized which prepares a VHPready 3.0 server to interact with the simulated CHP plant. VHPready is a popular open industrial standard for the connection of DGs and flexible loads to a VPP [15], based on either IEC 60870-5-104 or IEC 61850-7-420.

4.3. Simple CHP plant model

A CHP plant is modelled in real-time on an Opal-RT simulator [14]. The model is kept very basic, as its main purpose is to test the connection between VPP and OpSim. However, it does provide all variables of VHPready, including 15 minute energy-meters and status information. The dynamic behavior of the model is captured by the following equations:

$$T_{ramp} \frac{dP_{el}(t)}{dt} = P_{set}(t) - P_{el}(t), \quad (1)$$

$$P_{th}(t) = P_{el}(t) \cdot \frac{P_{th,nom}}{P_{el,nom}}, \quad (2)$$

$$\frac{dE_{th}(t)}{dt} = P_{th}(t) - P_{disturbance}(t), \quad (3)$$

$$P_{fuel}(t) = \frac{P_{el}(t)+P_{th}(t)}{\eta_{total}}, \quad (4)$$

in which Eq. (1) describes the dynamic response of the electric power P_{el} of the plant to a power setpoint P_{set}. Equation (2) describes the thermal power output, which is simply scaled with the electric output. Equation (3) describes the energy E_{th} in the thermal storage of the plant, due to thermal production P_{th} and disturbances P_{dist} (=heat consumption, here assumed to be zero) and finally,

Symbol	Meaning	Value	Ref.
T_{ramp}	Response time of CHP	Variable	-
$P_{th,nom}$	Nominal thermal power	97 kW	[16]
$P_{el,nom}$	Nominal electric power	50 kW	[16]
η_{total}	Total plant efficiency	87%	[16]
$E_{th,max}$	Thermal storage size	194 kWh, thermal prod. of 2 hours	[17]

Tab.1: *Main parameters of the CHP plant model.*

Equation (4) describes the fuel (e.g. natural gas) consumption by a total efficiency parameter η_{total}. The parameter values are motivated by a number of references, shown in Table 1.

Finally, the simulation is started and stopped through the "Mastercontrol-Program", which is also connected to the message bus (Fig. 2). Once the simulation has started, the VPP can connect via VHPready and receives real-time measurements from the simulated CHP plant. The entire test setup as shown in Fig. 2 is performed on geographically distinct computers:

- The message bus runs on a server at Fraunhofer IWES in Kassel. The SIP component and VHPready interface run on a distinct server, also at Fraunhofer IWES.
- The Opal-RT System, with the plant model, runs on a host PC and OP-5600 hardware at the University of Kassel.
- The Bosch VPP is being operated in a Bosch data center. The VPP runs on standard AMD- or Intel-based server hardware and Windows or Linux as the operating system.

In the following section, results from a first simulation with OpSim are discussed.

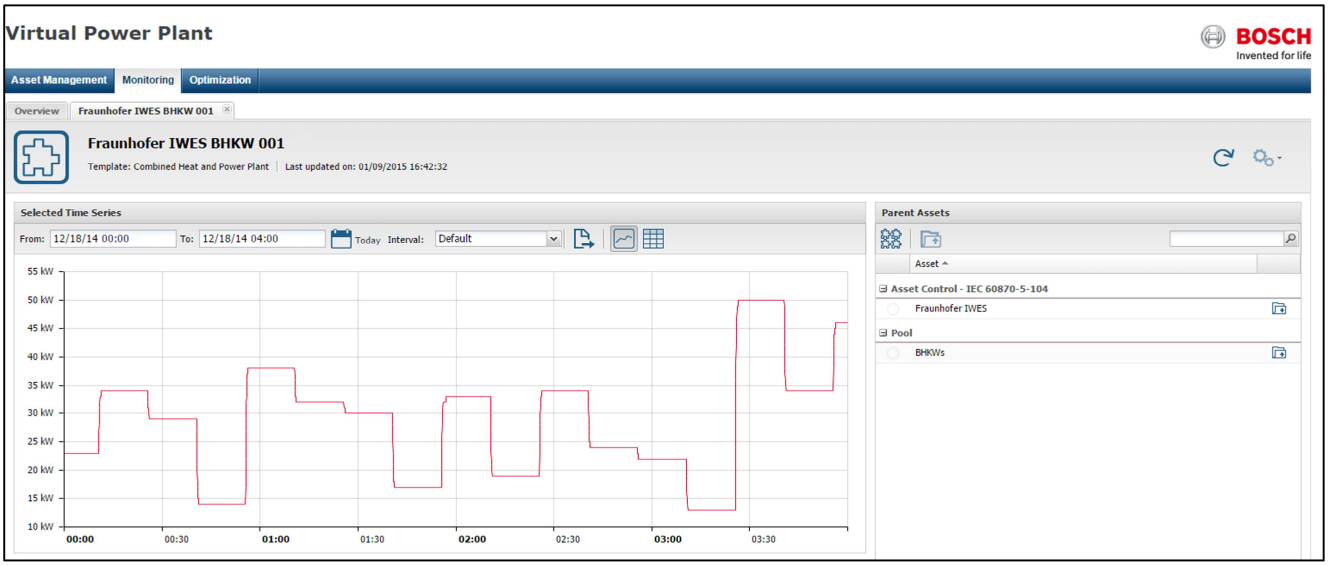

Fig. 3*: Active power measurement of CHP model "IWES BHKW 001" on Bosch SI VPP Interface.*

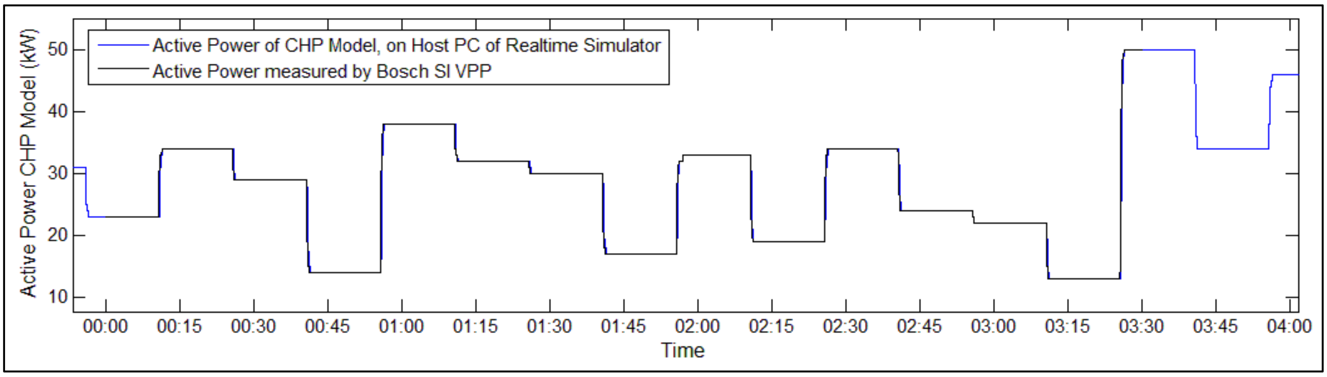

Fig. 4*: Comparison of CHP plant model active power on the host PC of the real-time simulator (blue curve) against the active power measured by the Bosch SI VPP (black curve) on 18 December 2014.*

5. Results

A real-time simulation of OpSim was started on 17 December 2014 around 17:00. Briefly thereafter, the Bosch SI VPP connected to OpSim via VHPready. This test continued until 11:00 on 18 December, during which the CHP plant model was assigned a random active power setpoint every 15 minutes. This assignment was done within the model itself, as the main goals of this test were: (A) to verify if the VPP successfully received the varying output of the CHP plant model and (B) detect if there exist any remaining time lags between the simulation components.

During this 18 hour testing period, the VPP registered the active power from the CHP plant model. Figure 3 shows the monitoring of the VPP on 18 December on a four hour exemplar interval. In addition, Fig. 4 compares the electric power of the CHP plant model, running on the Opal-RT system, to the electric power measured by the VPP. On the scale of hours, the comparison appears quite well and indeed, the VPP measures the simulated CHP plant in OpSim, as if it were a part of the VPP portfolio.

Second, since the simulation is decentralized, the system is built to handle time delays between its components. Indeed, between model and VPP, time shifts have been observed. For the first application of energy marketing, these time shifts were negligible. For future applications with VPP and grid simulations, the time shifts will be investigated further.

6. Discussion and next steps

This paper introduced the ''OpSim'' simulation platform, a novel tool for testing smart grid control strategies on a real-time simulated power system. The discussed application was a test of a Virtual Power Plant software; on OpSim, a model of a CHP plant was simulated in real-time, while the platform offered a standardized interface (VHPready 3.0). To this interface the VPP software by Bosch Software Innovations was connected, to monitor the simulated CHP plant as if it was real hardware.

The first test results appeared promising: on a simulation test interval of 18 hours, the active power of the model was registered by the VPP. A closer investigation of the timing on a four hour exemplar interval showed that between the time stamps of the model and the VPP, there exists a time shift. The origin of this time shift will be investigated further in subsequent works.

6.1. Future applications for VPP tests

On the short term, real-time simulations from OpSim could be used to test the connection between VPP and multiple units on a technical level, e.g. under normal operation conditions or emulated communication failures in the units. Also, a pool of simulated units can be used to test which VPP optimization gives the optimal economic result when scheduling the pool.

On the longer term, the VPP can expand into a Grid Optimization Manager (GOM), which monitors conventional units (e.g. generators, storages, loads), but also grid voltages and transformers, to provide ancillary services for grid operators. For this GOM, OpSim could be a testing environment, to emulate large grid models with a high amount of households, renewables and storages (e.g. electric vehicles). In such an environment, the GOM could be tested under normal operating conditions or during grid faults, for development and training purposes.

6.2. Future applications for grid control

Besides the discussed VPP applications, OpSim will be used as test and simulation platform in other applications, such as grid operation strategies. For example, to test new distribution management systems (DMS) on vast simulated HV/MV/LV grid areas – one could reduce the timing and amount of data exchanged between a grid simulator and DMS, and evaluate if the DMS can still keep the grid within desired technical boundaries. Also, a more sophisticated coordination between distribution- and transmission grid operators, via provision of ancillary services between their grid areas, promises considerable room for improvement.

Acknowledgments

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Stochastic simulation of photovoltaic electricity feed-in considering spatial correlation

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Abstract: The growing generation capacity of electricity from renewable energy sources (RES-E) around the globe has an increasing impact on traditional energy and electricity markets. Well-ahead planned investment decisions as well as short term management of the power plant and storage dispatch and other challenges are highly dependent on the feed-in of RES-E. Therefore a thorough research of RES-E supply and knowledge about methods to generate corresponding model input is crucial when simulating electricity markets.

This work focuses on an approach to generate an arbitrary number of synthetic time series of weather data (solar radiation in this example) on a high spatial and temporal resolution in order to calculate electricity production from photovoltaic power plants. While each time series shall represent its location as realistic as possible, the dependencies between the different location's stochastic processes will be included The method to generate synthetic time series inheriting dependency is developed for the application in energy systems analysis. Key indicators of the calculated RES-E supply time series are emphasized and discussed in a quantitative way in an effort to contribute to the research of RES-E supply and their effects on distributed energy systems and grids.

1. Introduction

The stochastic characterization of solar irradiation and other weather parameters has been studied intensely in literature. The approaches can generally be divided into two categories: Firstly, Markov processes draw a random variable applying a transition matrix which represents the probabilities of future states in dependence of the past realizations. (e.g. [1] and [2]). Secondly, regression based models are based on drawing random variables applying an estimate of the probability distribution functions of the observations. Current and past realizations can be taken into account (e.g. [3] and [4]). Approaches of both methods are well advanced when simulating weather time series at single sites focusing on temporal correlation. They are well suited to generate irradiation profiles for energy systems analysis omitting limitations by a grid infrastructure. Current research considering multiarea simulation of RES-E supply as in [4] is yet limited to a small number of considered sites.

However, with the decentralization of energy systems through electricity generated from renewable energy sources and the rising importance of grid aspects, the consideration of spatial correlation becomes increasingly relevant. Ignoring the spatial dependency of RES-E supply may lead to a serious underestimation of their electricity generation. Therefore, in this work we explore an alternative methodology to generate any required volume of realistic photovoltaic feed-in data inheriting spatial dependency between different locations based on copula theory. This aims at enabling energy systems analysts to base their modelling approaches on a larger set of realistic data and thus reaching more robust and reliable results. In section 2 the principal stochastic simulation processes is described, followed by its application and illustrative results in section 3. It is finished with the main conclusions and indications of needs for further research in section 4.

2. A stochastic process to simulate solar radiation supply: model description

For our analysis we use extracts from historical irradiation data on a European scale with a temporal and spatial resolution of 10 minutes and 20x20km² provided by a numerical weather model. First, we adjust the time series of historical data in a linear way in order to remove deterministic effects which do not need a stochastic characterization for simulation. For this analysis we conducted the following two steps:

Subtraction of periodic and recurrent values: The irradiation from the sun can be forecasted in a perfectly deterministic way for a surface outside the earth's atmosphere The disturbances within the atmosphere result in a reduced level of irradiation to reach the earth's surface

Deploying 24 years of historical irradiation data on a 10 minute resolution, we construct a maximum irradiation curve which represents the maximum possible irradiation to reach the surface at a certain site and time step of the year. Through subtraction of this trend function we eliminate periodic elements of the time series and reduce the time series to information about the underlying stochastic in the atmosphere. Fig. 1 shows how the trend elimination explains large parts of the spatial correlation within the time series.

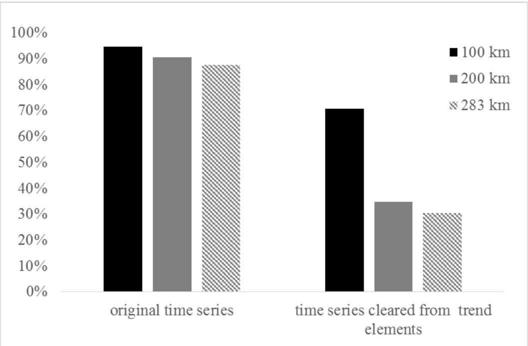

Fig. 1: *Spatial correlation before and after elimination of trend elements (as a function of spatial distance)*

Normalization of the time series: The second step of our adjustment generates a normalized times series with values limited to the range between [0,1] through division by the maximum irradiation curve introduced above. This helps to reduce the heteroscedasticity of the time series that occurs on a diurnal and seasonal (yearly) basis and thus enables us to implement a single irradiation process per site in contrast to modelling every time step of the day separately. The backwards-normalization also guarantees the simulated irradiation for every time step to be within a physically possible range. Both elements of time series adjustment can also reduce large parts for the autocorrelation within the data, especially for a lag of more than a few time steps (compare Fig. 2).

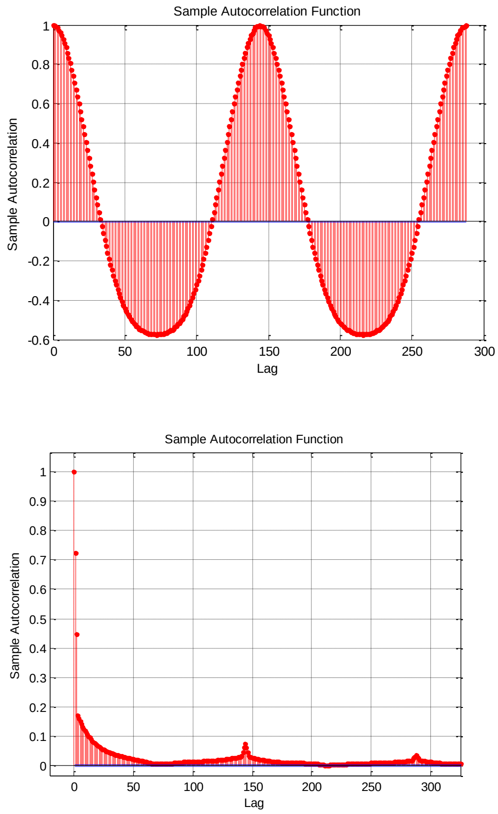

Fig. 2: *Autocorrelation with differing lags for the original time series (above) and the time series cleared from trend elements and after normalization (below)*

Based on work from [5] and [6], an approach is developed to simulate multiple time series representing simultaneous solar irradiation at various sites using copula theory. A copula can basically be described as a tool to draw from an arbitrary number of uniformly distributed random variables taking into account their dependency. Sklar's theorem postulates this idea to join together the one-dimensional cumulative distribution functions (cdf) F_X and F_Y of any random variables X and Y:

$$F_{XY}(x, y) = C(F_X(x), F_Y(y)) \qquad (1)$$

The copula C represents the method to transform any number of independent and one-dimensional random processes to a joint multivariate distributed random process. There exists a variety of different copula designs in literature. In this work, in order to join together the irradiation processes of numerous spatially distributed sites, we apply a Gaussian copula defined as follows:

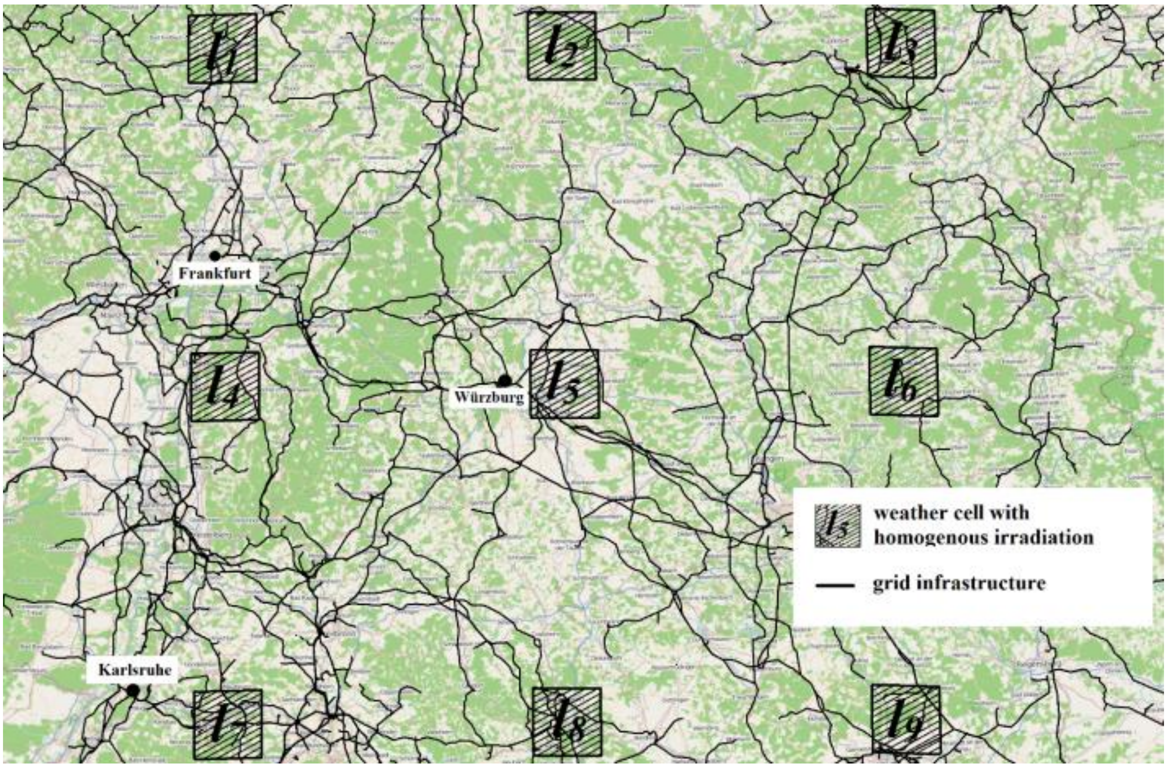

Fig. 3: *Layout of the nine weather cells where the locations of the model PV-plants are assumed to be installd*

$$C(\varepsilon_1, \varepsilon_2, \dots, \varepsilon_n) = \Phi_n(\Phi^{-1}(\varepsilon_1), \Phi^{-1}(\varepsilon_2), \dots, \Phi^{-1}(\varepsilon_n)) \tag{2}$$

The random processes at each of the $n \in \mathbb{N}$ sites are represented by the independent random variables $\varepsilon_1, \varepsilon_2, \dots, \varepsilon_n$ that are uniformly distributed on the interval [0,1] and linked by the Gaussian copula C. Φ represents the standard normal distribution function and Φ_n the n-dimensional multivariate standard normal distribution function. In order to generate synthetic irradiation time series we apply the following steps:

1) Reduce deterministic parts and normalize the time series through the trend adjustment described above.
2) Estimate the matrix of linear correlation under a Gaussian copula from the historical time series.
3) Draw uniformly distributed random numbers for the n modelled sites applying the Gaussian copula.[1]
4) Back-transform the uniformly distributed time series to the original domain of solar irradiation using the inverse cdf.

[1] Step 2 and 3 were performed using the functions copulafit and copularnd from MathWorks Matlab software.

The transformation between the uniform distribution and the empirical distribution is done by standard inverse transformation methods which can be applied to draw random numbers following any desired empirical distribution: May X be a random variable and F_X its invertible cdf with:

$$F_X(x) = P(X \leq x) \tag{3}$$

Then $F_X(X)$ is uniformly distributed: $F_X(X) = U \in [0,1]$ and the inverse empirical cdf $F_X^{-1}(U)$ follows the distribution of X. [5]

3. Application and results with regard to the influence of spatial correlation of different locations on the PV power supply

For modelling the solar power generation, we apply the PV model of [2] which includes an implementation of the physical model of [7]: The (horizontal) global irradiation is transformed into electrical power in dependency of the ambient temperature and technical properties of the PV system (e.g. orientation, module efficiency, etc.). In order to illustrate the effect of spatial correlation on the PV power supply, we generate time series for an illustrative cluster of $n = 9$ locations, located as illustrated in Fig. 3.

The set-up is motivated by the gridded structure of the underlying data which is available on a 20x20km² scale. The sites l_i $(1 \leq i \leq 9)$ are equally spaced by 100km to each other and a location in central Germany was randomly chosen.[2] The denomination of sites is illustrated by the matrix L:

$$L = \begin{bmatrix} l_1 & l_2 & l_3 \\ l_4 & l_5 & l_6 \\ l_7 & l_8 & l_9 \end{bmatrix} \tag{4}$$

Typically, when no correlation is accounted for, a representative irradiation profile for a certain region is used and applied to the accumulated size of all PV systems within the region. In order to compare to this approach, we assume a PV system with a nominal (peak) power of 90MWp and take the simulated irradiation of l_5 as representative profile for the whole cluster (locations 1-9). In comparison, nine separate 10MWp PV systems with the same technical characteristics are allocated to each location and the simulated site-specific irradiation profile is applied. Then, the generation of the different sites is aggregated to one 90MWp system. For both cases, the same ambient temperature profile, representative for the cluster, is used. The simulation runs on 10 minute time steps and covers a full year.

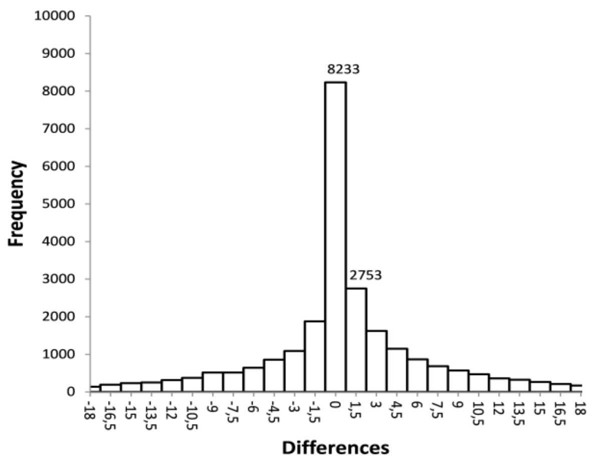

Fig. 4: *Differences of 10min time steps within a year between one 90MWp (l1) and nine aggregated 10MWp PV systems (irradiation values equal zero are excluded)*

[2] The coordinates of the central location l_5 are +49.81° latitude and +10.17° longitude.

The consideration of local correlation results in different electrical PV supplies. Fig. 4 shows the occurrence frequency of the power difference between both cases. For 8233 time steps of the simulation, the difference is lower than ± 0.75MW, for 2753 time steps, the supply of the 90MWp PV system is 0.75-2.25MW higher than the sum of the nine locations. The slight negative skewness of the distribution is reasoned by a higher irradiation of l_5 compared to the average irradiation of the other locations. That indicates the problem of choosing a "representati e" profile for a region
In the extreme case, there is an underestimation of -51MW. Albeit this event occurs only twice per year, there is a crucial impact for capacity and dispatch planning or grid issues when half of the installed power is not supplied. Bearing in mind the installed capacity of photovoltaics in Germany for example which exceeds 30.000 MW, it becomes clear that ignoring spatial correlation between RES-E generation units might cause high risks for the security of supply.

4. Conclusion and outlook

A methodology to simulate spatially correlated irradiation time series based on copula theory was successfully implemented. Enhanced trend adjustments to the time series and the ability to explain large parts of correlation were presented. Furthermore, we show that for simulating global irradiation, the spatial weather dependencies should be taken into account to generate valid PV profiles. Future enhancements of the simulation process can be reached by an integrated approach which simulates a plurality of parameters including spatial and temporal correlations between the various parameters (e.g. temperature, wind and global irradiation). The methodology to generate spatially correlated PV profiles outlined in this paper can be applied to the analysis of decentralized energy systems and grids.

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Agent.HyGrid: A seamless Development Process for agent-based Control Solutions in hybrid Energy Infrastructures

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Abstract: Decisions regarding design, implementation and needed policies for decentralized control solutions of future energy grids require profound investigations that ensure a secure and reliable grid operation. This applies to scientific computational systems serving the development of new control approaches on the one hand, but also for test-bed frameworks being used for the final verification of required functionalities before hard- and software components are deployed in real applications on the other hand. In an ideal case, the developed software artefacts are reused in various on-site systems for different purposes, which would avoid a redundant work overhead. By closing the gap between simulation environments, test-beds and real on-site applications, the *Agent.HyGrid* project intends to demonstrate that such systematic and seamless software development process is practicable. Based on the definition and the unifying concept of so called "Energy Agents", a reference development process is defined. It shall be used as a blueprint for further developments of decentralized, agent-based control solutions.

1. Introduction

The current trends and developments that are driven by information technologies show clearly that our society and thus also energy markets and the energy systems connected therewith will be developed to a globally interconnected and interoperable complex system. Even though this sounds visionary from today's perspective, the current developments in the area of Smart Grids and Smart Markets are clearly indicating this. However, in contrast to the associated vision of a partially distributed and interoperable control of energy supply, today's used or newly developed "smart" control approaches are basically heterogeneous and proprietary and a further spread of these incompatible solutions may cause uncontrollable or unstable grid situations in the future. Moreover, this heterogeneous situation tends to hinder the further systematic and sustainable development, needed to reach the goals that are intended with the energy transition and the ongoing transformation of the energy sector.

The *Agent.HyGrid* project intends to contribute in this context and aims to develop a systematic and well-defined (IT-) development process for distributed computing entities that are called Energy Agents. For this purpose, a holistic and unifying approach is chosen that, based on the energy conservation law, considers energy transformation processes in general. Thus, not only electricity grids will be considered in the project but also energetically hybrid processes.

As part of the project, *Agent.HyGrid* will investigate and determine the necessary characteristics and the applicability of unified Energy Agents that are rooted in different energy networks. For this, the well-known concept of agents or software-agents respectively, originated in computer science, will be transferred systematically into the energy domain while considering special requirements of energy technology and economy. For this purpose, both unifying reference data structures and behaviour models will be developed within the project. Beyond, the application of these Energy Agents in requirement and planning phases, in Multi-Agent based Simulations, test-bed applications, the usage in real-life on-site systems will be investigated and subsequently summarized by a systematic reference development process. In a real test and application scenario of an electrical distribution network, connected with further hybrid energy converting systems like households, combined heat and power (CHPs) or power to gas (P2G) plants, the applicability of proactive Energy Agents will be tested and validated by using additional local and network state predictions. The challenges of this project are manifold and lie in bridging the gap between simulation and real application on the one hand. On the other hand, the generation of the required unifying data- and the operational action models for hybrid energy systems will be challenging tasks. We believe that the proof of a unifying Energy Agent approach as well as the investigation and the definition of a systematic development process for these agent has the capability to sustainably influence and enforce the ongoing transformation process of our energy supply system.

The next section will introduce needed backgrounds and related work. It follows a brief description of our objectives and the necessary approaches in section 3, while section 4 will outline the application scenario. This will be followed by a discussion and a conclusion in the sections 5 and 6.

2. Background & Related Work

Because of the high complexity that is addressed with the *Agent.HyGrid* project, a discussion of related topics requires to consider different aspects of scientific principles as well as the current state of the art. For this, the following section outlines and discusses the topic of Agents and Multi-Agent Systems (MAS). Furthermore it emphasizes some important and project related aspects out of the affected areas. This will be followed by a short discussion of current, agent-based Smart Grid approaches. Furthermore, based on a state of the art implementation, the section will discuss current approaches for automating distribution networks. The section ends with a short introduction and discussion of the Energy Agent.

2.1. Agents and Multi-Agent Systems

From the information technology point of view and in very general terms, an agent, or more precisely, a software agent, can be seen as a computational entity that is situated in an environment and that is capable of autonomous interactions with this environment [1]. Other optional properties and abilities that are further associated with intelligent agents are their capability to communicate (needed for social abilities), a reactive or proactive behaviour and the capability to learn (e.g. [2]).

If the overall system consists of a set of loosely coupled agents that act and cooperate with each other in the same environment, a Multi-Agent System (MAS) is formed. MAS may be implemented to deal with problems whose complexity overstrains the description cardinality and thus the capabilities of monolithic systems. For the practical problem solution agents have to rely on the above mentioned communication capabilities and possibly also on the ability to collaborate, negotiate, delegate responsibility and the ability to trust. These subjects are discussed in detail in literature (cf. e.g. [1]).

The effort to build a MAS can be seen as very high. From software engineering perspective, this requires various modelling and implementation tasks describing the autonomous character of the agents. Based on a selected operating system, a particular software or agent platform and by using object oriented techniques, developer have first to consider different agent behaviours (e.g. with a deliberative characteristic). Further, the possible interactions between agents have to be related to common data structures (e.g. to ontologies), as well as approved protocols, in order to enable error-free communication processes and negotiations based thereon [3].

Large-scale MAS, with several thousands of autonomous entities, require further modelling activities for the grouping of agents. Such groups can be formed and organized in various ways, as for example in a manual and rigid or an automatic and dynamic manner. In this context one approach is the organisation of agents in so-called holonic systems. Here, groups of agents (so-called holons) are hierarchically structured, while one agent acts as representative for this group and organizes interactions between other or parent holons [4]. In recent years this type of agent organisation is frequently used in Smart Grid research applications and corresponds basically to a hierarchical decentralized organisation of complex systems [5].

Further modelling and implementation efforts result from the question what rules of conduct or which laws agents are subjected to. This has to be defined by binding policies that must be accepted and complied with by the agents. But to identify and model such behaviour is, depending on the domain in question, already a complex process. In order to not overstretch this aspect here we refer to [6] for further reading. At this point, however, we would like to state that this is a crucial key aspect for a comprehensive and successful application of agent systems.

Design and implementation of large-scale MAS requires systematic and sophisticated engineering processes that integrate all of the above mentioned aspects and efforts. For this purpose, several approaches for Agent oriented Software Engineering (AOSE) were envisioned and developed in the last years, but they differ in the target architecture of the agents and in the stages that an agent has to go through before it is deployed in an application. The main differences between AOSE methodologies may be found in their domain specific background and their starting points for the software engineering process that may be based on agent technologies, requirement engineering, object-4orientation or knowledge engineering. Further special purpose and general purpose methodologies for agent-based systems have to be distinguished [7]. Without discussing or even comparing all known AOSE methodologies, we just want to name some approaches here, as for example GAIA, Tropos, ADELFE, PASSI, MaSE and Prometheus. Further, we refer to [8] and [9], which provide a good overview as well as a classification and comparison of AOSE methodologies.

The last aspects for modelling and implementation to be mentioned here is of great importance for cyber-physical systems or so-called physical agents. Such agents are delegated to control or support actual technical systems and can be understood as autonomous entities like robots, on-site control systems and other systems, capable of interacting with further agents in a larger context. If they are used this way, agents need to have suitable knowledge about the actual capabilities and the current state of the underlying technical system in order to determine the degrees of freedom for possible further actions. Additionally, knowledge about the actual environment is required in order to react on various situations in this environment and find appropriate solutions for occurring problems or challenges. Therefore, this results in further efforts for the development of a “technical understanding” and a suitable environment model for the agents. In particular this requirement will be addressed with the *Agent.HyGrid* project, outlined in section 3.

2.2. Smart Grids and Agents

The reason that software agents have attracted great interest in the domain of power engineering can be found in the increasing number of individually IT-controlled technical systems (e.g. in households), but also in the increasing number of problems that are caused by uncontrollable or volatile energy producers; e.g. in electrical distribution networks. Consequently, more and more decentralized controlled systems affect the stability and the reliability of our energy supply. Here, the agent paradigm inherently fits and describes the decentralized character of these control solutions on the one hand, but as a task for agents, it is obvious that such decentralized control solutions have to adapt their behaviour and performance in accordance to existing infrastructures and networks.

Literature presents various approaches related to actual technical systems, but also specific Smart Grid concepts. Most of them focus either on: 1. Optimizing the performance and the efficiency of power converting systems, 2. Abnormal conditions and island mode operation, 3. Pooling of energy sources and sinks, 4. Demand Side Management (DSM) or 5. Demand-Response in regard to market aspects.

In the second case of abnormal load or grid conditions it is possible to separate the affected regions from the grid and put them into a so-called ‘islanding mode’, while stabilizing the detached area allows reconnecting. This implies that the area in question is self-controlled and -sustainable in regard to its energy needs. Successful examples of such islanding modes are reported in [10], [11] and [12].

Most of the solutions are envisioned form ‘virtual power-plants’ in which decentralized electrical energy converters are aggregated [13]. Those clusters usually contain a small number of fluctuating production facilities extended by some power generations equipment that is capable of balancing the unsteady nature of their fellow workmates. The advantage of this type of systems is their controllability in a device dependent power range, which makes them comparable to conventional power plants. However, problems in regard to voltage stability may occur due to the dislocated nature of the energy production. An exemplary real-life implementation of such a system is the regenerative model-region Harz [14].

Other projects in the domain of energy management are trying to optimize the demand depending on the availability of energy from renewable energy sources. This technique is called "Demand Side Management”. A further specialization of this control approach is the so-called “Demand Response”. Here, based on time variant electricity rates, incentives are given to use energy-intensive applications in times of low energy prices, which usually correlate with elevated energy availability [15]. Projects like E-DeMa, eTelligence, Smart Watts or the Model city of Mannheim do follow this track [16]. These projects do aim at studying the implementation of smart devices in a large infrastructure, focusing on different aspects of electricity generation, consumption and storage while paying special attention to policies and rules. All these projects have one drawback in common, which they share with the majority of similar projects in the international research community - they focus on the electricity domain only. This limitation does not pay tribute to the fact, that the different energy systems are interconnected. An electricity system has to be regarded in the context of the surrounding supply and distribution infrastructure. Not only the gas-, heat- and water network are important counterweights, featuring volatile processes, affecting each other across domain borders, but also meteorological information have to be taken into account. Examples can be found in the linkage of the electricity grid with the heating demand by e.g. night storage heating or the conversion of spare electrical energy to gas by using Power2Gas.

Besides the expected or reported benefits with the use of decentralized decision making and control processes, there are some further downsides in the context of the ongoing research and discussion: All multi-agent based power control systems in literature known to the authors (e.g. [17] and [18]) do apply proprietary data exchange formats and architectures. This leads to compatibility and comparability issues. Even though a multitude of available standards like IEC61850, the Common Interface Modell (CIM) or the OLE for Process Control Unified Architecture (OPC UA) and proprietary solutions for the different aspects of data exchange and control, none of them is completely suited for the needs of distributed processing and control for future hybrid energy grids.

2.3. Automation in Low Voltage Grids

Due to the switch from centralized to more decentralized and renewable power generation, especially medium and low voltage grids are currently facing new challenges. Seen from the network perspective, new requirements resulting thereof are: 1. Including a large number of decentralized power generation units, 2. Increasing demand of electrical power (e.g. integration of electrical vehicles) and 3. Installation and utilization of electrical storage units [19].

However the current low voltage grids have not been designed to meet these requirements. As pointed out the typical power flow was characterized by a centralized energy distribution in the past. According to this the maximum load in low voltage grids always appeared near the transformer substation. As a result of the current transformation critical situations like a complete inversion of power flow appear much more often, which results into two major problems for low voltage grids:

- Deviations of the permitted voltage range (±10% of the rated voltage according to DIN EN 50160)
- Local inner overloads of the grid equipment, especially of the power cables [20]

Even if the described problems only appear for a few hours per year and especially in situations where the power flows are inverted by a high infeed of decentralized generation units while the local consumption is minimal, the described situations are thoroughly dangerous regarding a regular operation state of the grid. To overcome these problems there are two solutions in principle: Massive investment in additional low voltage equipment, e.g. new cables and transformers, or moderate investment in selective installations of local, stand-alone control intelligence. Beside the fact that an investments in grid equipment is cost-intensive, it is furthermore difficult to forecast the necessary level of grid enhancement due to the increasing but unpredictable integration of decentralized generation units. Therefore the moderate investment in control intelligence seems more suitable.

Such a control approach was developed and reported with the project *iNES®* (see e.g. [21]). It consists of a few sensor components that are located at suitable positions within the grid and allow a continuous monitoring and assessment of grid conditions. An imminent overload can be countered in different ways. Therefore, variable distribution transformers and reactive power control units of decentralized feeders, such as photovoltaic systems, can be included in an overall control approach. Further, if control options have been exhausted and a critical grid state could not be solved, also the active power of feeders or consumers can be changed for a required, but typically short, time. Similar approaches were reported and compared in [22], on which we refer for further reading.

Much like the mentioned drawbacks for agent-based control solutions, the enrichment of distribution grids with new automated components is an appropriate but unfortunately only a short-term measure for solving current and future problems. Again, we might face a number of proprietary and closed systems that are unable to use the already available information sources within a grid. More sophisticated or "smart"

systems should provide their information here in order to support planning and control efforts in a distribution network, which will save investments for further sensors and actuators.
Especially against the background of a network capacity traffic lights [23], grid control needs an adaptive mechanisms that allows the inclusion of any kind of energy conversion process, but without additional development costs.

3. Approaches and Objectives

As part of the project, the required characteristics and applicability of unified, autonomous, decentralized operating and in different types of power systems located software systems are investigated. Conform to current definitions of software agents, but tailored for the application at energy conversion systems, this systemic approach is called “Energy Agent”. Following [1] and the VDI directive 2653-1, an Energy Agent is defined as follows [24]:

An Energy Agent is a specialized autonomous software system that represents and economically manages the capacitive abilities of the energy consumption, production, conversion and storing processes for a single technical system and that is embedded and thus part of one or more domain specific energy-networks, capable to communicate therein and with external stakeholders.

This definition is based on several considerations and with the goal to define a generalized prototype for an Energy Agent that is applicable in various situations and in different energy domains. With the concept of energy domains, we consider not only electrical networks (e. g. Smart Grids) to be more sophisticated in the sense of more dynamic in their resource allocation by using an additional piece of software. Rather, the Energy Agent is supposed to integrate all those energy systems that are subjected to the fundamental first law of thermodynamics. Taking into account this relationship, we assume all following Energy Agents (and their underlying technical systems) to be individual, but connected by (possibly) several domain specific transport or distribution networks, each with its’ specific form of energy.
In the sense of the first law of thermodynamics and the capacitive abilities of an energy system, the main task for an Energy Agent, connected to a network, is its ability to describe and handle the individual positively or negatively directed (produced/emitted or consumed/obtained) amount of energy over time, possibly in cooperation with its neighbouring entities. Consequently, additional and suitable assessment methods for energy flows and the resulting energy amounts are required that enable the mentioned economic management of the underlying system. For the project and in this article, the perception of economic management is rather a financial view on energy transactions and not merely the possibly parsimonious behaviour of a technical system. Accordingly, suitable cost models have to be provided that allow an economic assessment of energy conversion processes through an Energy Agent. Such questions, however, are very individual and strongly dependent on the organisational affiliation of a single technical system.
For reasons of space, we want to point to two further basic approaches and differentiations that are used within the project and that have already been described in more detail in previous publications.
The first point was introduced by different, so-called Integration Levels. They take into account that Energy Agents can have different levels of sophistication and thus different features, which results into another type of “hybrid” consideration [24].
The second aspect affects the development process that an Energy Agent has to pass, before it is used in on-site systems. Here requirement engineering, modelling, implementation and testing, as well as simulations and test-bed application will be considered before [25].

3.1. Agent.HyGrid Objectives

The primary goal of this project is to build-up a reference-development process for uniformly defined, but individual Energy Agents. Similar to process models in software engineering or automation, such as the V-Model or the Rapid Control Prototyping, the development process for Energy Agents will be systematically investigated and defined. The focus will lie on the above mentioned development stages from planning up to the real implementation on-site. Especially differences in the timing requirements for simulations and real systems will be investigated, highlighted and closed, in order to allow the uniform application and implementation of Energy Agents in all steps of the development process. With an interdisciplinary approach and the involvement of industry partners, the technical feasibility, stability and practicability of the Energy Agent approach will be investigated. Therefore, the following specific objective will be pursued:

1. Definition, formalization and implementation of largely unified Energy Agents that take into account the requirements for using the different stages of the reference development process for hybrid energy systems.
2. Proof of the feasibility as well as investigations regarding scalability and reliability of the resulting overall system. This involves agent-based simulations, test-bed applications as well as the real application in a selected area of a distribution network operator.
3. Evidence of the technical advantages of the developed methodology by using selected and / or generally accepted scenarios as well as a systematic comparison between the simulated and the real behavior of the involved systems.

4. Application Scenario

As mentioned above, it is one objective of the project to finally apply the developed Energy Agents in a real application scenario. For this purpose the Energy Agents will be located either on available or new hardware components that are located nearby or in the actual on-site systems. Consequently, the Energy Agents will be used for different tasks, with different level of sophistication and with individual goals. Figure 1 below shows a simplified example of the intended application scenario for the *Agent.HyGrid* project. It can be seen that the agents are basically used in a context of a low distribution network. Here it is planned that it is in principle possible to attach them both in electrical devices, such as washing machines or fridges, but also in topological higher lying locations. Here agents working as a kind of aggregator, connecting several sub-agents and their actual conditions and plans. This applies for example for a "Smart House" Energy Agent that is used as a connector and aggregator to the outside world for all other agents inside a house. But it also applies for Energy Agents that are used in order to monitor and control the stability of a distribution network. Quite similar at this point is also the role of the aggregator for a "Marketing Company", whose intention lies in the market oriented usage of the affiliated technical systems. In contrast to agents that are aimed at stabilization a distribution network, the goals of a marketing agent can be considered as contrary to some extent, especially if grid conditions allow only a regulated operation (e.g. because of a red traffic light). Additionally, this type of agent competes with other agents with different affiliations.
Hybrid energy conversation systems will be considered in different ways. In the picture this is indicated

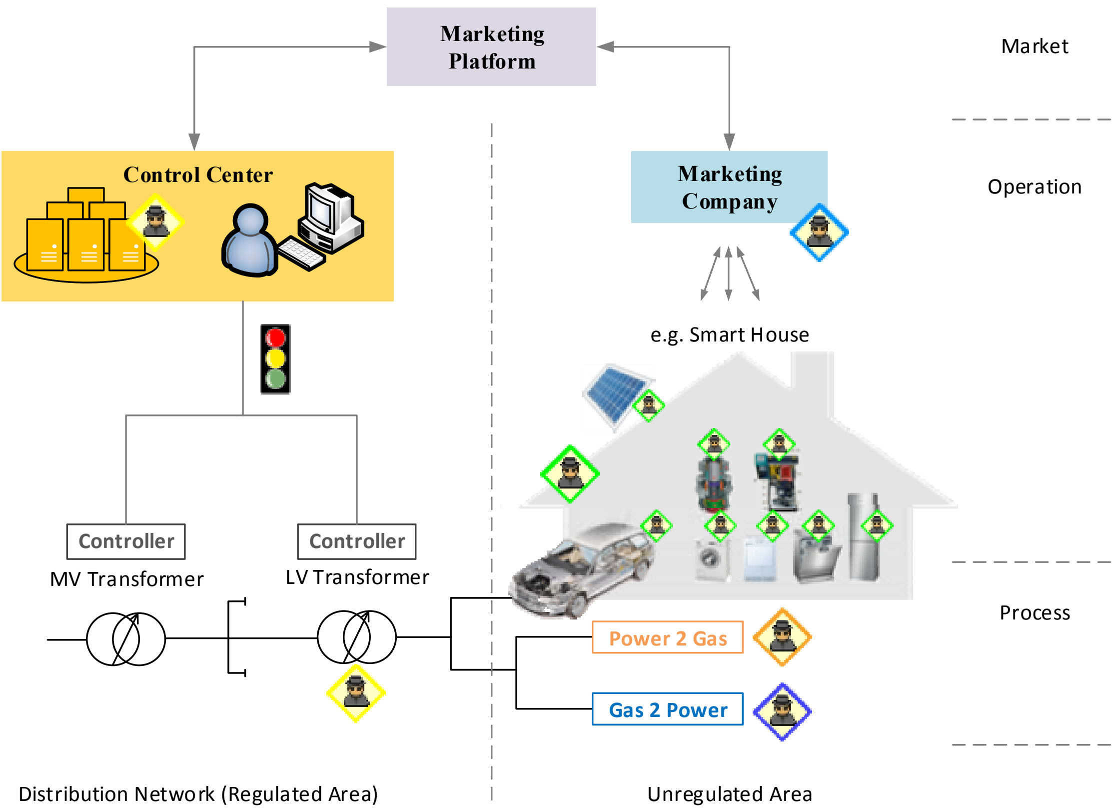

Fig. 1: *Agent.HyGrid* application scenario example

by the systems that are connecting natural gas and electricity networks. Here (micro) combined heat and power plants (CHP or µCHP) or power to gas plants (P2G) will be taken into account, as well as the resulting heat of them.

For completeness, it has to be mentioned at this point again that the above described scenario will also be validated in a test-bed application as well as in extensive simulations. The goal is, among other, to use as many software components as possible throughout the whole development process.

5. Discussion

It is the opinion of the author's team that complex problems require an intuitive description in order to find suitable and reliable solutions. Expecting globally interconnected energy systems in the future, the project questions and goals were formulated as general as possible, e.g. by considering different energy carriers and networks. Nevertheless, the targeted goal to define a systematic methodology by means of a well-structured development process can just be seen as next, but not as a final step towards a sustainable transition of the energy supply. Additional and new requirements might need an extension of the developed methodologies. The complexity induced by the Energy Agent project may require new optimization strategies that have to be answered with further research. This applies for example for the required legal framework under which decentralized software components have to operate and affects aspects like trust and reliability.

The major advantages of the *Agent.HyGrid* project and the approaches used therein can mainly be seen in the following aspects: (i) Through the creation and application of unifying approaches, further flexible producer, consumer and storage units can be integrated in a market-oriented management. Beyond that, a systematically described flexibility of technical systems can be used in order to increase the stability of energy supplies. (ii) The inclusion of information and automation knowledge provides the necessary synergies that allow to transfer and reuse software components from simulations to real, on-site systems. Thus the foundation of unified Energy Agents can form the basis for the development of realistic labs to be used for model studies of future energy supply scenarios. (iii) The paradigm of software agents provides an almost arbitrary scale and level of detail for simulation and control systems, which underlines the possible, realistic laboratory character even for very large systems.

6. Conclusion

In this paper we introduced the project *Agent.HyGrid* that intends to develop unifying concepts and approaches for a further systematic development of hybrid future energy grids. These include the formalization of so-called Energy Agents and their internal knowledge with respect to the flexibility degrees of underlying energy conversion processes, but also the needed data structures for an information exchange among the agents. All experiences and lessons learned will finally be concluded in a new and practically applicable software engineering methodology that can be used as reference development process for further developments. In this development process, the same Energy Agents shall be re-used in simulations, test-bed applications as well as in real-life on-site systems.

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Application Technologies like electric vehicles or solar home systems

SmartER Europe 2015

econnect Germany – Field trial Aachen

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Abstract:
This paper deals with a field trial in which the integration of electric vehicles in smart grids is investigated. It is examined, how the grid responds to the new loads and whether it is possible to use this loads for demand side management. It has been found that the use of smart grids is cheaper than a conventional grid expansion to integrate new loads and generation (for example PV) in the low voltage system. Also the customer behavior concerning the useage of dynamic prices is under investigation.

1. Introduction

Driven by the expansion of renewable energies and the consequent displacement of electricity from conventional power plants, the energy transition involves a massive reconstruction of the existing power grid and we observe a change from a central to a decentral energy generation. Furthermore it is required by the government that one million electric vehicles should be on Germany's roads by 2020. For this reason, seven different municipal utilities have joined together to form a research partnership and ha e successfully applied for “IKT for electromobility II” funded by Germany's Ministry of Economics and Technology (BMWi).

The aim of the project is to find out what are the best technical features of an electric vehicle. How can a flexible und comfortable infrastructure be introduced as widely as possible. But also how can electro mobility be integrated in the intelligent energy supply (smart grid) of the future.

The field trial in Aachen it focus on the integration of the charging process of electric vehicles into the smart home and smart grid. For this reason, STAWAG (Stadtwerke Aachen AG), smartlab Innovationsgesellschaft, IFHT, ISEA (both RWTH Aachen University), Kellendonk Elektronik, Siemens, PSI and Phoenix Contact E-Mobility joined together.. In this field trial, which started on 1st of October 2014, concepts and solutions are determined to integrate electro mobility in the smart grids of the future with the help of information and communication technologies (ICT). This field trial connects the complex structures of smart grids with the customer and the utility industry under real conditions.

In doing so, 10 households get an electric vehicle for half a year and try whether intelligently charging can be controlled and if it is possible to integrate it in their everyday life. During the field trail every participant gets an electric vehicle, wallbox, smart meter and components for information and data exchange.

2. Related Work

“Smart atts – the intelligent kilowatt hour” **[1]** is a research project, which successfully finished at December 2013 and it can be seen as a predecessor of the econnect project. In December 2012, a field trial was started in which 250 customers of the STAWAG were selected to test smart metering, which could be a permanent feature of our life in a few years. The smart meter includes a storage and communication unit, so that the grid operator is informed about the state of the network. Furthermore the customer has the possibility to monitor his consumption with the help of app to see his electricity consumption per day, week, month or year. Moreover, the field trial participant is able to see the actual electricity price and a forecast for the next 24 hours. With the help of the app the customer can adjust a price level for his home appliances, how much he would pay for the energy. For example, the washing machine or the dryer is only swichted on, if the electricity price is smaller or equal than the adjusted price.

The conclusion of the project is that smart metering is technically feasible, but in the residential area it is now not economically **[2]**.The project shows that there is only a potential for load transfer between 3–10 percent. Household customers could save about 10–15 euros per year, which is not very attractive.

A study conducted by German Aerospace Center (DLR), Frauenhofer ISE and RWTH Aachen shows that electric cars can have positive effects for the efficiency of electricity generation and environment and can relieve the power grid **[3]**. In a scenario where electric and hybrid cars recognize over 60 percent by the year 2050, the power consumption of 27 million electric vehicles would be 53.5 TWh per year in Germany. That represents around ten percent of the total consumption of electricity for the year 2013 in Germany. The energy consumption of the individual transport would decrease by 2/3 compared with the year 2010, provided that the electricity cars are charged with energy of renewable energies. In this case the CO_2 emission is reduced by 80 percent. Not only environment is relieved, but also the transmission system. Despite the high demand for electricity, electric cars are able to reduce excess power from wind and solar systems by using an intelligent battery management system. In addition, the decrease of peak loads leads to a reduction of power generation from fossil power plants. The study shows that with the help of the battery management system excess electricity up to 4 TWh per year can be used for load management. Overall, electric vehicles could reduce the surplus power of renewable energies up to 20 GW under these conditions **[3]**.

Based on the results of the project "Smart Watts" and the study for the perspective of electric vehicles for the future, in the field trial of econnect Germany it is examined whether there is a higher potential for load transfer through the integration of electric vehicles into the smart grids.

3. Theory

The federal government expects that electricity generated from renewable sources will be increased to 40–45 percent of total production by 2025 and to 55–60 percent by 2035. The integration of the large number of renewable energy sources involves new challenges on energy markets and the power system.

To ensure stability on the electricity grid, electricity supply and demand must remain in balance in real time. In the past, fossil power plants have controlled the balance of production and consumption.

Due to the decline of these power plants, other methods for balancing production and consumption must be found. Demand side management (DSM) works from the other side of the equation. Instead of balancing the generation how fossil power plants did it, the consumption is adapted to the production. With the help of an intelligent communication technology (smart grid), electric vehicles can be used. Their refueling with electricity is shifted on times where is a high offer of electricity from renewable energies. For this reason it is important that receives incentives to adapt his behavior of the electricity price.

The energy transition involves a great challenge for the network infrastructure. Figure 1 shows the traditional and the future electricity network.

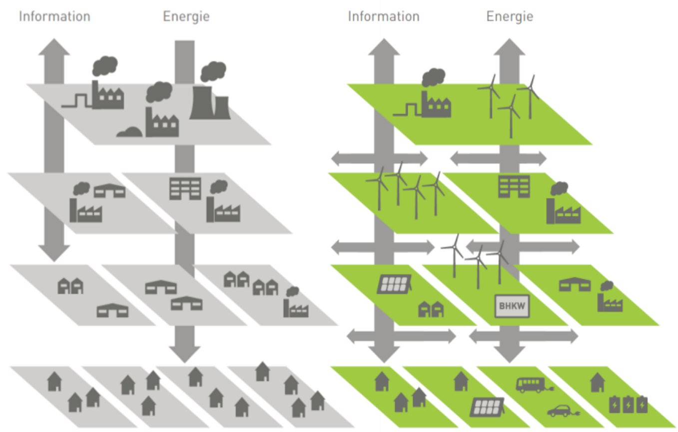

Figure 1: Traditional grid (left), future grid (right)

The traditional electrical grids are generally used to carry power from a few central generators (for example fossil power plants or wind parks) to a large number of users or customers. The power flow is from the high voltage level to the low voltage level and information is only exchanged in the high and medium voltage-grid. In contrast, the new emerging smart grid uses two-way ows of electricity and information to create an automated and distributed advanced energy delivery network.

This development trend arises a lot of new challenges, especially for the distribution system operators. They need to ensure a stable supply voltage in the low voltage grid and at the same time integrate an increasing amount of renewable energy and new large loads as electric vehicles.

There is a particular risk of exceeding the permissible voltage tolerances in small meshed networks in rural areas.The compliance of the product quality, for example the voltage quality, becomes more difficult and expensive.

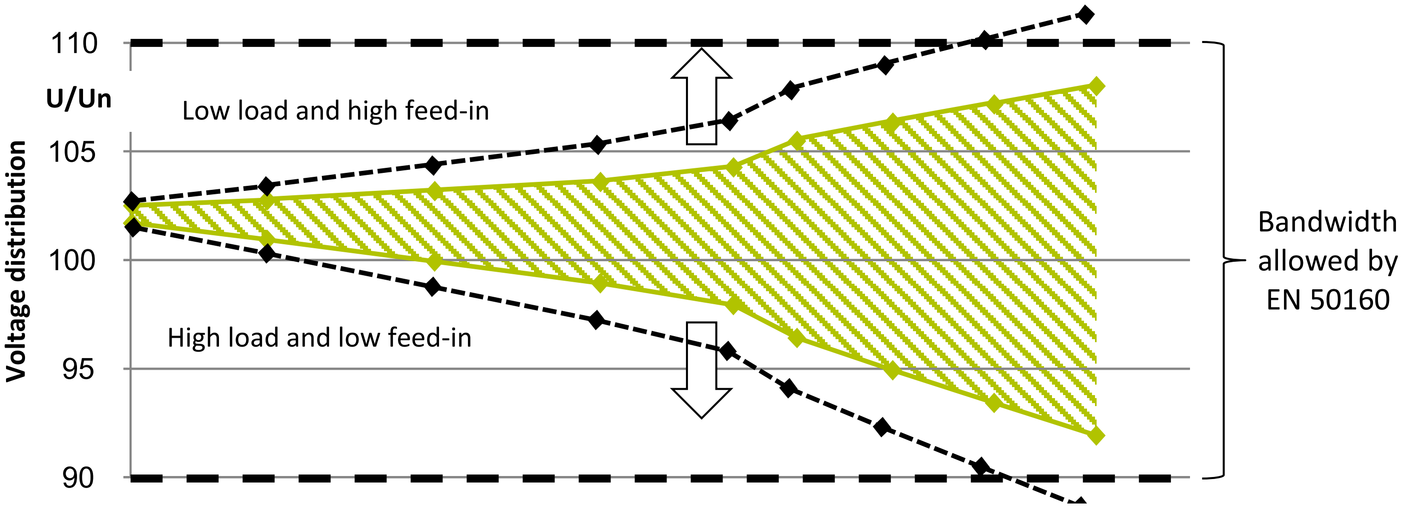

Figure 2: Risks with increasing feed-in of renewable energies and new loads

Figure 2 shows the voltage distrubution as a function of loads and infeed. Due the changes of the grid arise a lot of possible scenario. So far, the grids were designed in such a way that the voltage band could not be violated. Now it is possible that on days with a high production and a low consumption (high PV input and low loads), or on days with a low production and a high consumption (simultaneous charging and low input of renewable energies) the voltage band, which is normed by EN 50160, rises above or falls below the limit. The simultaneous charging of several electric cars was not considered in the previous grid planning. .For this reason the distribution system operator needs intervention to protect the grid from overload and damage. In order to maintain these tolerances and those of high supply levels, a massive network expansion which is expensive and time consuming would be necessary. Controllable local network transformers are a more effective and cheaper solution than grid expansion for the purpose of activating existing reserves on a medium and low-voltage level. By decoupling the medium and low-voltage networks, the capacity of the two networks and thus the possible voltage band would significantly increase. By a reduced conventional network expansion savings could be in the billions. The offer of renewable energies varies as a function of time of day and seasons. So it is possible that there are hours or days where is no infeed. Currently there are no incentives for consumers to shift their consumption depending on the availability of renewable energy.

Thus, incentives must be set that the customer adjusts his consumption behavior of the availability of renewable energy. Here dynamic rates for residential customers could be the solution.

4. Our Approach

As a part of a field trial, STAWAG has equipped ten households with a home demand management system and electric vehicles for a half year. These 10 households are all located in one local distribution system, which have a controllable local network transformer, measurement in the local network station, in all cable distribution cabinets and in all house connection boxes.

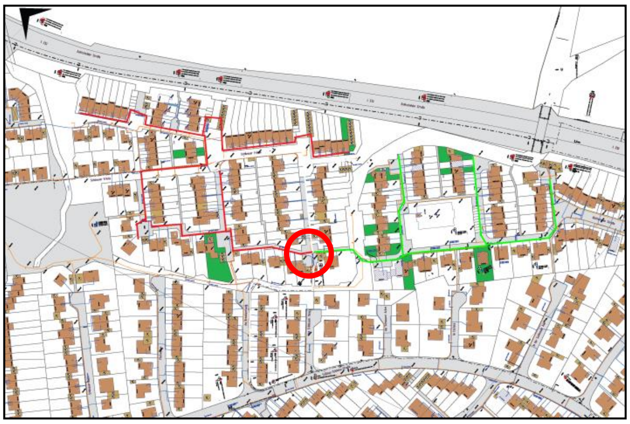

Figure 3: Overview local network

Figure 3 shows an overview over the local network of the field test. The red circle marks the local network station with the intelligent local power transformer.

There, all information of the field test are collected. The participants are connected at two different cables (green and red). At the red cable three households and at the green cable seven households are connected.

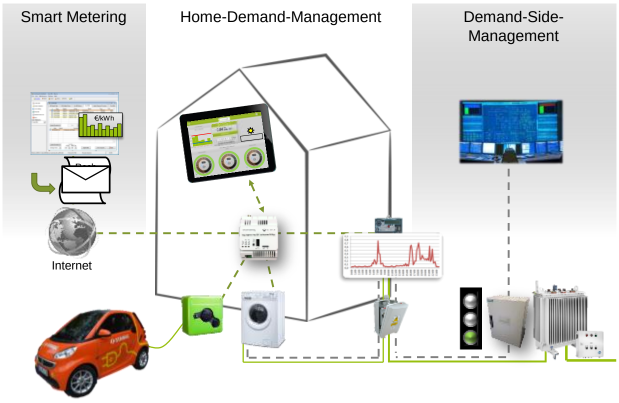

Figure 4: Management system

As Figure 4 shows, the overall system is divided into three sub-systems: Smart Metering, Home Demand Management and Demand Side Management.
The first sub-system, Smart Metering, deals with the development of a technical infrastructure for the customer, which shows a Price Forward Curve (PFC). For this, price forecasts must be created as a function of generation forecast of renewable energies, load profile, intraday market prices. These price forecasts for the next day are sent to the Home-Demand-Management system till 5 pm.
The Home Demand Management system is the primary tool for the customer. The customer has the possibility to control the timing of the loading operations over a user interface and so he is able to load at reasonable time points. The Home Demand Management system includes a wallbox, a human interface (tablet), a smart meter, three intelligent power plugs (for dryer, dishwasher and washing machine), measurement in the house connection box and home management gateway (HMG). The wallbox has a loading capacity up to 22 kW. This allows a full charge within 2 hours.
The HMG is the central of the Home Demand Management system. It controls and coordinates the loading operations of the wallbox, so that the charging is taken at the cheapest electricity price. In addition, it controls the intelligent power plugs. It is the connection between the app and the terminal.

Figure 5: Smart-Home App

Figure 5 shows a screenshot of the econnect app. It can be seen the price forecast, the battery capacity and the state of charge, which must be set for every charging. As figure 5 implies the customer has two opinions to load his car. He is able to choose between price-controlled and time-controlled charging. At the price-controlled charging the customer sets a price threshold under which the electric vehicle will be charged. At the time-controlled charging the customer sets a time by which the car must be completely charged. The HMG select the cheapest hours for charging. Similarly, the smart sockets can be controlled.
The Demand-Side-Management system gathers all the technical records of the field trial. For this purpose, with the help of a power line connection (PLC) all measured values of the local distribution system are sent to the local distribution station. From there the data is transmitted to the control room of the STAWAG. The monitoring and control of the local distribution system is assumed locally self-sufficient by the intelligent substation. In the case of a cable overload, the wallbox can be switched off by the local distribution station to protect the cable from overload and damage.
However, before the wallbox is switched off, the local substation reduces the charging capacity of the wallbox by specifying lower maximum charging power. The state of the network strand is shown to the customer on a traffic light. The transformer generates the traffic light signal and reports any intervention to the control system.

Green light: No restriction for charging.

Yellow light: Loading, but it can take a longer time.

Red light: Grid is currently overloaded. Loading is not possible.

5. Evaluation

After the first month of the field trial there are some results. First, it can be stated that the light was green about 95 percent of the time. At no time the traffic light was red.
The resonance of the participants to this field trail is very positive. The view on electric mobility has changed greatly at all. Indeed, it was established that the range of an electric vehicle is totally sufficient for the everyday life. In addition, the driving pleasure increases with an electric car. The participants tried to adjust their load behavior to the dynamic electricity price as good as it is possible, so that load transfer is possible within a certain range. Also they were glad to get an accurate overview of their current consumption.
But it also was encountered some errors and problems. In some households of the field test, there are problems with the power line or wireless lan technology. So it gets to communication problems between the individual components. The intelligent plugs are controlled via wireless lan. Dryers or washing machines are often placed in the basement, so that the wireless connection is not sufficient. Through the exchange of the various communication technologies, there was always found a workable solution. But there is no patent solution and it costs a lot of time to get the system to run.
A first software update brought some systems to a crash, so that the updates had to be installed on the spot for the customers. Furthermore, some bugs were still found in the first version, which could be corrected by an update.

6. Discussion und conclusion

It follows that the system operator has to invest a lot of time for the care of the system. For this reason, the complexity of the system must be reduced. If the goals for electric mobility of the Federal Government are achieved, electric vehicles can contribute to DSM. It has been shown that the use of smart grids can reduce the conventional grid extension. Here, the network operator can save a lot of cost. If the technical problems can be reduced and the goals for electric mobility are achieved, smart grids in connection with electric vehicles can become economical in the future.

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16.6.2012

Enabling demand side integration – assessment of appropriate information and communication technology infrastructures, their costs and possible impacts on the electricity system

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Abstract: Flexible demand processes provide an important potential to balancing variable renewable feed-in. However, they are not yet in the focus of most market players as they are heterogeneous and small-sized compared to the supply side. The paper aims to highlight to which extent demand side integration is an economic option for the provision of flexibility. For this purpose, cost-potential curves for demand side integration in Germany are provided and an assessment of cost savings as well as reduced investment capacity in an electricity system with 50% share of renewables is undertaken.

Key words: Demand side integration (DSI), flexibility options, information and communication technology (ICT), specific integration costs, cost-potential curve, electricity market model

1. Introduction

Integrating high shares of variable and distributed renewable electricity generation in the energy system requires flexibility. In this context, the concept of demand side integration (DSI, i.e., the targeted adjustment of the power demand) holds a prominent place in public debate in Germany beside other flexibility options (see e.g. [1]). In the recent years, several studies assessing the DSI potential in Germany (e.g., [2]-[10]), the costs occuring for the use of DSI (e.g., [2], [5]-[9]) and the possible system benefit by applying optimisation models (e.g. [2], [7], [8], [10], [11]) have been published.

To the authors' knowledge, no comprehensive publication on the specific costs for enabling DSI with appropriate information and communication technology (ICT) has been released to date. The paper aims to close this gap and draw an overall picture of possible costs and benefits for DSI in Germany.

For this purpose, first the technical DSI potential and its availability are assessed. Then, an approach for determining necessary ICT components for enabling DSI and their costs is presented and applied to generate cost-potential curves. These are finally used to analyse the possible system benefits DSI could have in the German electricity system if the share of renewable energy systems (RES) in gross electricity consumption was 50%.

2. Methodology

To assess the possible system benefit through application of DSI - reduced electricy generation cost and capacity investments - the fundamental linear optimisation model E2M2s (European Electricity Market Model stochastic version) is employed. Model inputs are cost-potential curves that contain information about the technical DSI potential, its availability (when and for how long) and its costs (CAPEX and OPEX). Fig. 1 provides an overview of the applied approach.

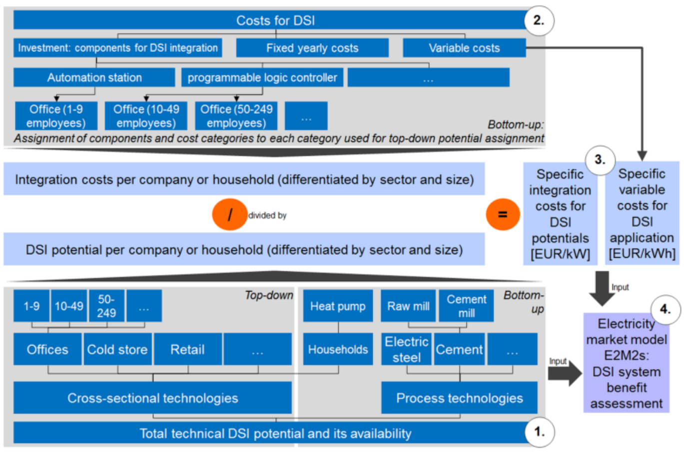

Fig. 1: *Approach for generating cost-potential curves to be availed for the assessment of DSI system benefits.*

A brief description of the methodology applied is given here. For a more detailed description of the approach for cross-sectional technologies all steps – including categorisation, calculating and assigning potential to company categories as well as defining existing ICT infrastructure – please refer to [12]. Further information on the approach for deriving potential and costs for process technologies are provided by [13] and for households by [14]. The modelling methodology is described in [11] and the comparison of DSI with other flexibility options in [15].

To assess the technical DSI potential of industry, commerce and households in Germany, DSI technologies are differentiated into two groups: process technologies that are specific to certain industries and cross-sectional technologies that are broadly applied in different sectors (definition in line with [9]).

For process technologies, the focus is on relatively few energy intensive industry processes that provide a large share of the accessible DSI potential. For the assessment of this potential and its availability, a bottom-up approach using knowledge about production sites from interviews with site operators and associations is applied and validated with literature and top-down calculations. Investment and fixed annual costs for the activation of DSI potential is negligible as a substantial part of the companies already have the appropriate ICT at their disposal and specific installation costs are low due to very high shiftable loads. By contrast, significant variable costs occur as production processes are affected (compare [9]).

For cross-sectoral technologies ventilation, air conditioning and chiller plants in industry and commerce as well as heat pumps in households are considered as most relevant DSI applications (cf. [14]). As these applications occur in a large number, a top-down approach is used to estimate their technical DSI potential. The DSI availability is assessed with a bottom-up analysis. As no production processes are affected directly and no comfort losses are supposed to occur, variable costs are neglected. On the contrary, there are investment and fixed annual costs for ICT infrastructure which enables the use of DSI. Table 1 lists the appliances and cost components in process technologies and cross-sectional technologies.

To evaluate the ICT infrastructure expenditure in order to reveal the DSI potential in cross-sectional appliances, the number of companies or households to be connected with ICT is calculated using employment statistics for the different branches from the German Federal Statistical Office and branch associations (e.g., [16]). Furthermore, empirical data is taken as an indication for the exisiting equipment with ICT infrastructure in these types of companies or households. Necessary ICT investments take into account the used DSI appliance as well as the size and branch of the connected company or household. All enabling infrastructure needed for DSI is incorporated under the term ICT, which includes components of building control systems and process control systems and, therefore, extends the traditional understanding of ICT.

Type of appliance	Considered appliances	Considered cost components
Process technology	Energy intensive industry processes	Only variable costs (negligible investment and fixed annual costs)
Cross-sectional technology	ventilation, air conditioning and chiller plants in commerce and industry, heat pumps in households	Only investment and fixed annual costs (negligible variable costs)

Table 1: *Considered appliances and cost components in process technologies and cross-sectional technologies.*

Specific integration costs for DSI potential results from dividing the estimated integration costs per company or household by the respective technical DSI potential. Together with the total available DSI potential and the variable costs for DSI, these specific integration costs result in cost-potential curves for DSI.

Based on the generated cost-potential curves, the possible system benefit of DSI is assessed. For this purpose, a model based analysis is conducted using a scenario framework with a 50% share of RES in German gross electricity consumption. This corresponds to roughly a doubling from the current share and equates to the target of the German government for the year 2030. It is, thus, necessary to consider the future development of the potential and costs for DSI. For each DSI application and branch, a development path concerning the total DSI potential and the potential per company or household is calculated based on assumptions on technology diffusion, energy efficiency and economic and demographic developments.

Two possible development paths for costs are considered in two different scenarios. In the pessimistic scenario, the identified costs for ICT infrastructure are fixed in real terms at today's level. In the optimistic scenario, an annual cost reduction of the ICT components of 3% is assumed. This is in line with other studies such as [2], [17]-[20]. The reduction of costs is as a result of technological advances, economies of scale and any other effect

leading to cost reduction (see [21] for an overview of factors potentially leading to cost reductions).
The model based analysis is conducted by the fundamental linear optimisation model E2M2s. Here, the German electricity system is represented as a copperplate without interconnection. A myopic optimisation is executed for one year with hourly resolution. The reference scenario without the DSI option is compared to the two DSI scenarios with optimistic and pessimistic development of investment and fixed annual costs for enabling DSI in the future (further description is given in [11]).

3. Cost-potential curves

3.1. DSI potential and availability

The technical DSI potential is assessed for selected process technologies in the German energy intensive industry with a bottom-up approach (Table 2). The analysis is based on comprehensive interviews with site operators, industry associations and other experts as well as public available data on relevant sites and production output [22]-[28]. A detailed description of the assessment and the assumptions for 2030 can be found in [13].

Sector	Process technology	Sites #	Installed capacity [MW_{el}]		Ø DSI potential down/up [MW_{el}]	
			2014	2030	2014	2030
Metal production	Aluminium electrolysis	4	1,150	1,150	288/138	288/138
	Copper & zinc electrolysis	2	80	80	50/12	50/12
	Electric arc furnaces (steel)	19	2,120	2,120	975/106	975/106
Chemical industry	Chloralkali electrolysis	17	1,190	1,140	583/166	559/160
Paper industry	Pulp grinder and refiner (mechanical pulp)	10	140	140	101/39	101/39
Stone and earth ind.	Raw and cement mills (cement)	49	510	480	362/149	341/139
TOTAL		101	5,190	5,110	2,359/610	2,314/594

Table 2: *Installed capacity and average DSI potential of selected process technologies in Germany in 2014 + 2030 (values according to [13] based on data from [22]-[28]).*

In the next step, a top-down approach is used to estimate the technical DSI potential of cross-sectional technologies in commerce and industry. Industrial and commercial loads that are utilisable and relevant for DSI are identified by a detailed analysis of the different subsectors and the installed facilities. As shifting time matters, the focus is on ventilation, air conditioning (AC) and chilling plants.
Table 3 shows the calculated installed capacities that can be used for DSI and their possible development until 2030 for the assessed applications and subsectors of industry and commerce.

	(Sub)sector	Capacities usable for DSI [MW_{el}] 2012/2030				Variation 2012/2030 [%]
		Ventilation	AC	Cooling	Total	
Commerce, trade, services	Hotel	11/12	253/393	164/214	428/619	+44.6
	Hospitals	16/14	45/40	38/57	99/111	+12.1
	Gastronomy	134/146	112/176	335/438	581/760	+30.8
	Offices	169/210	771/986	83/107	1,023/ 1,303	+27.4
	Retail businesses	196/176	547/600	1,108/ 1,099	1,851/ 1,875	+1.3
	Farming	535/503	-	99/94	634/597	-5.8
Industry and cold stores	Rubber & plastic ind.	26/26	88/95	-	114/121	+6.1
	Metal working	46/45	156/165	-	202/210	+4.0
	Mechanical engineering	105/113	356/410	-	461/523	+13.4
	Automobile industry	70/70	238/257	-	308/327	+6.2
	Food industry	48/47	165/173	281/259	494/479	-3.0
	Cold store	-	-	247/273	247/273	+10.5
TOTAL		1,356/ 1,362	2,731/ 3,295	2,355/ 2,541	6,442/ 7,198	+11.7

Table 3: *Capacities usable for DSI in cross-sectional technologies in commerce and industry in Germany in 2012 and 2030 [12].*

The average shiftable load per application and subsector is calculated by dividing the respective annual electricity consumption by the average full load hours. Where accessible, the electricity consumption per application and subsector is taken from existing investigations such as [29]. If no such data is available, the calculations are based on assumptions for the distinctive attributes of the subsectors listed in Table 7. The availability is determined with the help of typical load profiles. A very detailed description of the approach and the executed calculations can be found in [12]. In the domestic sector, heat pumps are considered according to the detailed analysis in [14]. The study calculates an installed capacity of residential heat circulation pumps in Germany for the year 2030 of 6.7 GW_{el}. Up to 12% of this capacity can be used for DSI purposes depending on the outside temperature.
The DSI potential of process technologies in the energy intensive industries in general does not underlay important intertemporal fluctuations as capacity utilisation is usually consistently high. Some seasonality occurs in the cement industry when fewer construction work and the annual clinker kiln maintenance reduce production in winter. An influence of week day and time of day is observed in

the cement industry and pulp production as the current tariff structure and some overcapacities facilitate optimised electricity purchase. By contrast, an important intertemporal influence has to be considered for cross-sectional technologies. Table 4 summarises factors for their temporal DSI availability over all subsectors in industry and commerce for work days (daytime), Saturdays (daytime) and Sundays/nights in the different seasons (intermediate represents spring and autumn).

Day/ week time	season	Factor for temporal DSI availability down/up [%]			
		Venti-lation	AC	Cooling	Total
Work day (daytime)	summer	68/28	47/53	53/23	54/37
	intermediate	63/32	10/30	42/34	34/32
	winter	33/63	0/0	32/44	19/30
Saturday (daytime)	summer	60/36	16/19	52/24	39/24
	intermediate	55/40	4/10	42/34	29/26
	winter	25/71	0/0	31/44	17/32
Sunday/ night	summer	47/48	1/14	63/36	34/30
	intermediate	20/75	0/6	55/44	24/35
	winter	16/79	0/0	46/53	20/37

Table 4: *Factors for temporal DSI availability of cross-sectional technologies summarised over all subsectors in industry and commerce [12]. The DSI availability of energy intensive industry processes is widely constant.*

Another important input for the assessment of possible DSI benefits is the shifting times of each considered load shifting potential. Table 5 gives an overview of the assessed shifting times per application (based on [12] and [22]).

Sector	Application	Shifting time [h]
Industry	Ventilation	0.9 – 1.6
	Air conditioning	0.2 – 0.8
	Cooling	1.2 – 5.8
	Aluminium electrolysis	< 2
	Copper & zinc electrolysis	< 6
	Electric arc furnaces	< 4
	Chloralkali electrolysis	< 4
	Pulp grinder and refiner	< 4
	Raw and cement mills	< 4
Commerce, trade, services	Ventilation	0.2 – 3.2
	Air conditioning	0.1 – 1.1
	Cooling	0.5 – 3
Households	Heat pumps	< 4

Table 5: *Shifting times for DSI applications ([12] and own assumptions based on [22]).*

3.2. ICT infrastructure and costs

After having identified the technical DSI potential, the next step is the calculation of the costs to make this potential available. Conceptually, the components and infrastructure needed are divided into two categories. First, there are components that are installed within customer premises and second, publicly accessible infrastructure and utility infrastructure. Fig. 2 visualises this distinction and, furthermore, highlights the components in orange that are taken into consideration when calculating costs.

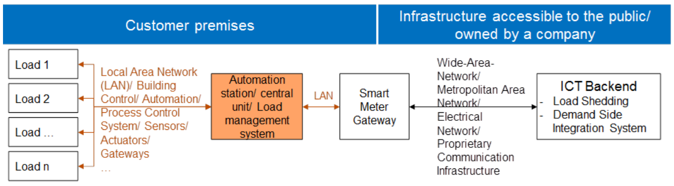

Fig. 2: *Enabling infrastructure for DSI.*

All other components - plotted in black - are required, yet supposed to be available already as customers with an annual electricity consumption above 6 MWh are recommended to have a smart meter infrastructure put into place [17]. Table 6 lists components considered in the calculation with their costs in 2012 and their electrical load per unit.

Investment Costs - Components	Costs [EUR_{2012}/pc.]	El load [kW/pc.]
Gateway computer	248.00	190
Automation station/ central unit (with Ethernet port)	800.99	24.5
Analogue output terminal	195.53	0.5
2-channel counter terminal	83.11	0.5
Radio-LAN-access-point	271.32	6
USB-radio-gateway	56.22	0.5
LAN gateway for programmable logic controller	587.50	6
WLAN gateway for programmable logic controller	757.50	6
Programmable logic controller	108.75	0.9
WLAN router	94.13	12.5
WLAN repeater	66.25	2.9
Repeater with antenna	92.36	0.6
Radio sensor for temperature/ humidity/ CO2	259.95	0.9
Radio actuator conditioning/ chiller unit	80.43	0.6
Radio actuator for ventilation system	84.40	0.9
AC electricity meter (wireless communication possible)	81.32	0.5
Fieldbus AC electricity meter	52.24	0.9
Radio gateway for conventional electricity meter	85.29	6
Sensor for CO_2	177.07	0.9
Direct Digital Control-LAN-Gateway	587.50	6
Radio sensor for wire temperature	143.16	0.5
Radio-module for automation station/ central unit	213.07	24.5
Adapter for heat pump	90	6
Software for visualisation and control	606.27	-
Reprogramming of existing programmable logic controllers	1,525.00	-
Commissioning of load management system	1,150.00	-
Operating Costs		
Connection to wide area network [EUR/a*customer]	279.96	
Maintenance cost as percentage of investment	0.20%	
Cost of repairs as percentage of investment	0.02%	

Table 6: *List of infrastructure components with corresponding investment and operating costs. Own assumptions and calculations based on [12], [14], [30]-[33].*

With respect to the infrastructure needed on the customer premises such as the automation station, the described bottom-up approach assigns each category of company and appliance initial ICT. For example, larger office buildings most likely have a building control system put in place that can be used for DSI purposes. However, a small bar with only 1-2 employees is very unlikely to have such a system put in place. Depending on this starting position and the consumption of the processes or technology to be shifted forward or backwards, the components required to enable DSI are assigned to each category.

Combining the bottom-up analysis of needed ICT components with their costs to enable DSI and the technical DSI potential allows calculating specific investment and fixed annual costs. The annuity of the investments is calculated by using a 7% discount rate. Due to calculation time restrictions, categories with similar costs are clustered. Thirteen cost categories are clustered as indicated with superscripts in Table 7.

(Sub)sector	Distinctive attribute	Segments and related cost categories					
Hotel	# beds	10-29^{12}	30 – 99^{12}	100 – 499^{12}	500 – 999^{8}	>1 000^{8}	
Hospitals	# beds	1-199^{10}	200-399^{10}	400-599^{9}	600-799^{9}	>800^{8}	
Gastronomy	# employees	1-2 (e.g. bar)^{13}	3-5 MA^{13}	6-9 (with HVAC system)^{12}	>10 (with HVAC system)^{11}		
Offices	# employees	1-9^{13}	10-49^{13}	50-249^{11}	>250^{9}		
Retail businesses	# m²	Ø250 (small stores)^{13}	Ø1450 (super markets)^{13}	Ø5000 (large supermarkets)^{10}			
Dairy farms	# animals	1-9^{13}	10-19^{13}	20-49^{13}	50-99^{12}	100-199^{12}	>200^{10}
Pig fattening plant	# animals	1-100^{13}	100-249^{13}	250-499^{12}	500-999^{11}	1,000-1,999^{10}	>2,000^{9}
Rubber and plastic industry	# employees	20 – 99^{11}	100 – 499^{9}	500 – 999^{8}	>1,000^{7}		
Metal working	# employees	20 – 99^{11}	100 – 499^{9}	500 – 999^{10}	>1,000^{7}		
Mechanical engineering	# employees	20 – 99^{10}	100 – 499^{9}	500 – 999^{7}	>1,000^{7}		
Automobile industry	# employees	20 – 99^{11}	100 – 499^{9}	500 – 999^{7}	>1,000^{7}		
Food industry	# employees	20 – 99^{10}	100 – 499^{10}	500 – 999^{8}	>1,000^{7}		
Cold store	# 1,000 m³	<25^{8}	25-50^{8}	50-75^{7}	75-100^{7}	100-125^{8}	>125^{7}
Energy intensive industry sectors	process	Electric steel^{1}	Chlo-rine^{2}	Raw and cement mill^{3}	Mech-anical pulp^{4}	Alumi-nium elect.^{5}	Zinc & Copper elect.^{6}
Households	technology	Households with a heat pump^{9}					

Table 7: *Overview of categories examined with the distinctive attribute and the assigned cluster as superscripts. Categories based on [12].*

Potentials within those clusters are aggregated and costs are calculated by weighting the specific cost of each category with the DSI potential made accessible. Table 8 summarises the range of costs for each category, the weighted costs used for E2M2s and the aggregated potential.

Cluster	1-6	7	8	9	10	11	12	13
Range of costs: opt/pess [EUR_{2012} /kW*a]	0/0	0.12-0.83/ 0.16-1.09	0.98-3.81/ 1.29-5.02	4.7-7.8/ 6.2-10.3	9.3-25.4/ 12.3-33.4	26.3-140.3/ 34.6-184.9	50.7-84.5/ 66.8-111.3	95.7-2399/ 126.2-3163
Weighted costs: opt/pess [EUR_{2012} /kW*a]	0/0	0.29/ 0.38	3.18/ 4.19	5.84/ 7.7	13.2/ 17.4	29.3/ 38.6	58.4/ 77.0	216.3/ 285.1
Aggreg. capacity [MW_{2030}]	2,314	784	823	1,308	2,127	706	1,024	1,228

Table 8: *Cost categories with range of costs, weighted costs used for E2M2s and the aggregated potential.*

Differences in specific costs are as a result of starting positions in terms of equipment installed (building automation, etc.), number of components needed to make DSI potential accessible and the size of the actual load accessed. E.g. small pig fattening plants (1-100 animals) are unlikely to have any building control system and, therefore, sensors, gateways and a central unit are needed to make a relatively small load accessible (1 kW of ventilation). In mechanical engineering a control system is already in place and the aggregated load of air conditioning and ventilation is higher than 1,000 kW.

3.3. Cost-potential curves

Fig. 3 shows the average technical DSI potential in GW_{el} (x-axis) and the associated specific integration costs (y-axis) in EUR_{2012}/kW*a for the clusters examined above. The black line represents the disaggregated cost curve (no clustering) for 2012. The orange steps represent the clustered costs in the pessimistic DSI scenario (without cost decline until 2030) and the blue steps represent clustered costs in the optimistic DSI scenario with an annual decrease in costs of 3%.

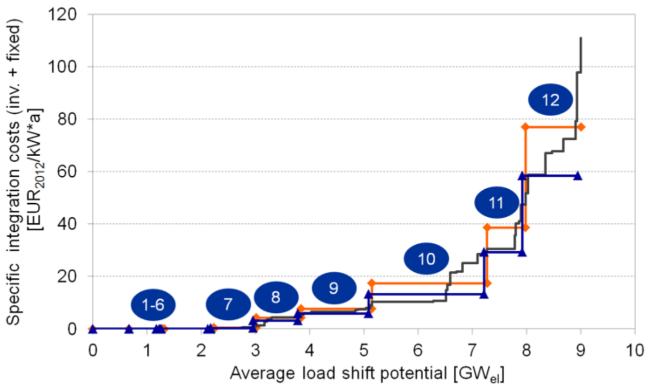

Fig. 3: *DSI cost-potential curves: 2012 disaggregated (black), 2030 pessimistic (orange), 2030 optimistic (blue).*

Due to the high costs of companies in cluster 13, this potential is neither used as input in E2M2s nor plotted in Fig. 3. Costs include both annuity of component investment costs and the fixed annual operation costs (incl. electricity costs). Whereas for cross-sectional technologies in the trade and industry sector as well as for heat pumps in the household sector further variable costs are neglected, for industrial process technologies variable costs occur as, e.g., described in [9]. Table 9 summarises these variable costs for load shifting in energy intensive industry appliances. The values are based both on interviews with site operators and associations as well as on literature review.

Process technology	Variable costs for load shifting [EUR/MWh]
Aluminium electrolysis	80 – 150
Copper & zinc electrolysis	100 – 250
Electric arc furnaces	270 – 1,200
Chloralkali electrolysis	100 – 250
Pulp grinder and refiner	< 10 – 120
Raw and cement mills	< 10 – 450

Table 9: *Variable costs for load shifting in energy intensive process technologies (own estimation based on [22], [2], [5]-[7], [9]).*

4. DSI system benefits

The generated cost-potential curves serve as input for an analysis with the electricity market model E2M2s. The example model scope is a possible setting for the German electricity system with a 50% share of RES. Most of the generation capacity is to be invested endogenously through myopic optimisation.

The consumer load is assumed to be on the level of the 2011 ENTSO-E load curve for Germany. Feed-in curves of variable RES are exogenously given according to the lead scenario in [34]. Energy prices are in line with [35]. DSI options are aggregated in the twelve clusters shown in Table 8/Fig. 3 and parameterised according to the previous section. Considered competing flexibility options are the construction and operation of electricity storages as well as the curtailment of surplus renewable feed-in. The representation of these options in E2M2s and their potential impact is described in detail in [15]. The E2M2s representation of grid expansion, power-to-heat and power-to-gas options as well as their possible impacts and interdependencies which are not considered here are also assessed in [15].

The assessed scenarios are shown in Table 10. A reference scenario without a DSI option is compared to two different scenarios with DSI that are distinguished by the assumed investment and fixed annual costs for DSI enabling.

Scenario	Considered flexibility options	DSI representation: Process technologies	DSI representation: Cross-sectional technologies
Reference scenario	Electricity storages, curtailment of surplus renewables	None	
DSI Optimistic	Same as Reference scenario + DSI	Cluster 1-6 (Fig. 3); max. 2,314 MW_{el}; no investment and fixed annual costs; variable costs according to Table 9	Cluster 7-12 (Fig. 3); max. 6,773 MW_{el}; inv. and fixed annual costs according to Fig. 3 – blue line; no variable costs
DSI Pessimistic	Same as DSI Optimistic	Same as DSI Optimistic	Same as DSI Opt but inv. and fixed annual costs according to Fig. 3 – orange line

Table 10: *Scenario definition for the E2M2s analysis.*

As a first result, Fig. 4 shows the endogenous investments in capacity for generation, storage and DSI in the three different scenarios. In the optimistic DSI scenario, investments are made for the integration of a DSI capacity of 5 GW_{el} (corresponding to the clusters seven to ten in Fig. 3). In the pessimistic DSI case this figure is 2.9 GW_{el} (corresponding to the clusters seven to nine in Fig. 3). For the application of the DSI clusters one to six in Fig. 3 no investments are required. Whereas the invested capacity of lignite steam turbine and combined-cycle gas turbine power stations virtually is not influenced by the DSI options, there are important differences in open-cycle gas turbines and pump storages.

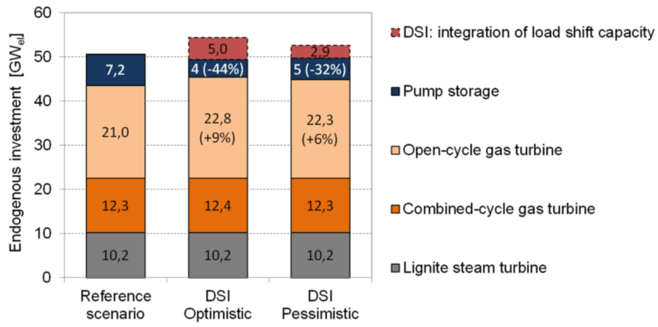

Fig. 4: *Influence of DSI on generation and storage investment.*

As the chart illustrates, the cost-optimal investment in pump storage is reduced by nearly half in the optimistic and by one third in the pessimistic DSI scenario. This indicates that the DSI options are able to adopt storage features at lower costs to some extent. However, due to shifting time restraints DSI options cannot provide peak load in the same way pump storage does and, therefore, need some extra backup generation capacity (which in this case is open-cycle gas turbines). In total, the overall invested generation and storage capacity (exclusive of DSI) is reduced by 3% in the optimistic and by 2% in the pessimistic DSI scenario.

Fig. 5 summarises the application of the DSI options in the optimistic (left) and the pessimistic (right) DSI scenario. The blue section of the bars represents the annual sum of the shifted load. The red section stands for the annual sum of the provided balancing power.

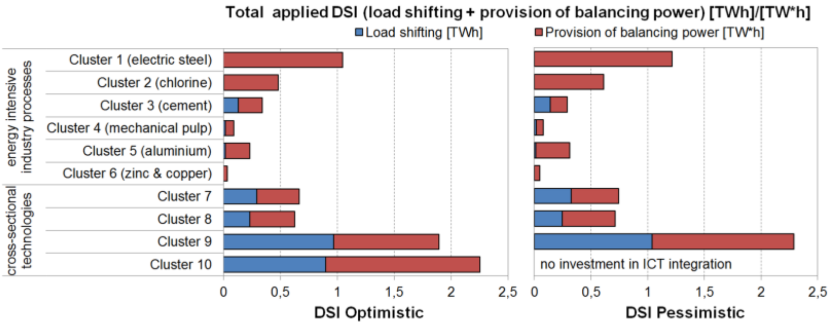

Fig. 5: *Total amount of shifted load and provided balancing power by the different DSI options.*

Load shifting amounts in total to 2.6 TWh in the optimistic and to 1.8 TWh in the pessimistic DSI scenario. The provision of balancing power amounts to 5.1 TW*h and 4.5 TW*h, respectively. Due to their variable costs, energy intensive industry processes are mainly applied in the balancing market. In contrast, the DSI clusters representing cross-sectional technologies are applied both for load shifting and in the balancing market.

The DSI application results in substantial savings in electricity supply costs. Fig. 6 highlights the savings or additional expenditure in the optimistic (left) and pessimistic (right) DSI scenario compared to the reference scenario in the different cost categories from a system point of view. The grey columns indicate savings in investment and fixed annual costs for new generation and storage capacities as well as system operation (exclusive of DSI). The blue columns represent additional expenditure for DSI (investment and fixed annual costs + variable costs). The sum of these values results in the total system savings pictured in orange colour. The numbers above the columns represent the difference between the respective DSI scenario and the reference scenario – as an absolute value and relative to the respective cost category (there are no %-values for DSI costs as there are no DSI costs in the base scenario).

The savings in infrastructure investments and related fixed annual costs (first minus fifth column) total in 257.1 million EUR_{2012} in the optimistic and 240.7 million EUR_{2012} in the pessimistic DSI scenario. It has to be considered that the investment decisions made in the model represent real world investments that would be made in the period between today and 2030. Yet, the attributed savings are the annuity of those investments.

The savings in variable costs (total of second to fourth minus sixth column) amount to 12.8 million EUR_{2012} in the optimistic and to 4.1 million EUR_{2012} in the pessimistic DSI scenario.

In result, the comparison of the different scenarios in E2M2s reveals that the application of DSI options can reduce the total electricity supply costs by a magnitude of hundreds of million EUR_{2012} per year. These savings result mainly from reduced investments in storage infrastructure, but also, e.g., from more efficient dispatch and less ramp-up on the supply side. As the difference between the optimistic and the pessimistic DSI scenario is not very distinct, it can be concluded that there is a certain robustness of the possible DSI system benefit against the cost development of ICT. Further analysis of DSI application in E2M2s and its competition or interplay with other flexibility options can be found in [10], [11] and [15].

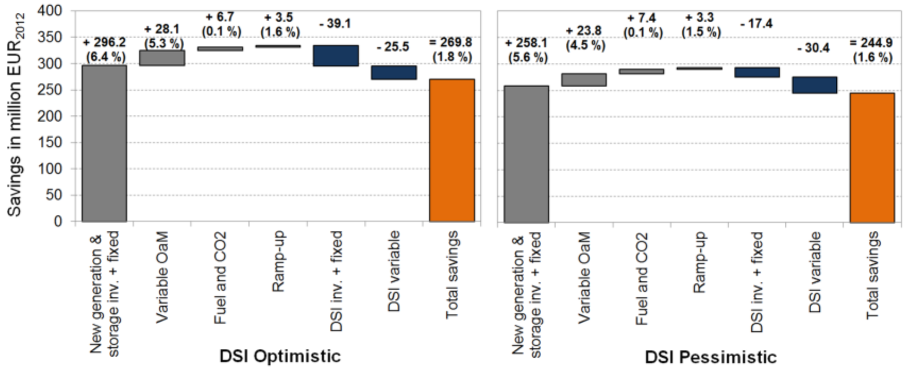

Fig. 6: *Savings from DSI use in the optimistic and pessimistic cost development case compared to the reference scenario without DSI.*

5. Conclusions and discussion

The analysis has shown that flexible demand processes can make an important contribution to a cost-efficient integration of high shares of renewables. The presented results of the optimisation model E2M2s indicate that both suitable industry processes and cross-sectional technologies with the lowest specific invest and fixed annual costs for DSI integration should be part of a cost-efficient evolution of the electricity system. Main system benefits of DSI application are the reduction of necessary storage capacity and a more efficient dispatch of power stations.

Production processes in energy intensive industry provide a technical DSI potential of more than 2 GW_{el} in Germany with steady availability. Operators of these processes either already place them on electricity markets or would probably do so, when prices would provide sufficient incentives. Specific investments for enabling ICT infrastructure are relatively low and the incentive to reduce energy costs is high. As production processes are affected, variable expenses occur for load shifting and make these appliances rather attractive for balancing markets, other ancillary services or infrequent application at energy-only markets.

In contrast, the DSI potential of cross-sectional technologies in industry, commerce and households in Germany is widely unused to date. The market participation of these appliances requires investments in appropriate ICT infrastructure. The costs for such a system integration vary widely and depend on the DSI appliance used, the accessible technical potential and the existing ICT. The assessed approach linking these factors with size and branch of the connected companies or households points to a capacity useable for DSI of more than 4 GW_{el} that could be integrated at specific costs smaller than 20 EUR_{2012}/kW*a (investments and fixed costs on customers premise only). As production and comfort by definition are not affected, this potential can be frequently applied on the energy market considering the temporal interdependency of their availability.

The application of DSI, not only in the energy intensive industry, should, thus, be seen as an economic option for bringing flexibility into the system. The actual benefit DSI can bring in the future electricity system depends on different influencing factors: the development of functionality and costs of enabling ICT (some robustness has been shown in the assessed sensitivity analysis), the quantity and composition of variable renewable feed-in, the development of competitive flexibility options like power-to-heat, the design of the regulatory framework (e.g., network charge regulation) and the awareness and readiness of DSI appliance owners and market players to place economic potential on the market.

The presented model results naturally underly some uncertainty. In particular, assumptions were made to assess potential and costs for DSI in 2030 and the applied optimisation model represents a perfect market without network restraints and focusses on Germany. Also, costs of ICT are only set against the savings from DSI and feed-in management while other aspects such as the functionality for security and comfort remain disregarded.

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Data and Software Solutions / Issues for Smart grids

SmartER Europe 2015

Energetic Neighbourhoods – Local Implementation of the Hybrid Grid Concept

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Abstract: Due to the energy transition in Germany, an efficient convergence of various energy supply infrastructures is more and more addressed by technical research. Both physical and virtual coupling points between the infrastructures have to be found. The proposed approach, which is termed Energetic Neighbourhoods, aims to realize the concept of hybrid grids on a local level. In the project example the processes from neighbouring enterprises are analysed in terms of incoming and outgoing energy flows as well as timely flexibility. Subsequently, automation architectures that technically connect the processes are developed based on the gathered data in order to gain economic advantages.

1. Motivation and Challenges

One of the central challenges of the energy revolution is the increasingly occurring "storage gap" in the electrical energy supply system. The term storage gap thereby describes the missing flexibilities of the grid to store electrical energy during periods of a low load and to provide additional electrical energy during time periods where it is needed. At the same time it should be noted that the heating / cooling sector gets more into focus because it offers the highest potential to save energy. One approach to improve the flexibility in the grid and thus to enable a temporal coupling of consumption and production processes is to use intelligent energy management approaches called Smart Grids. Thereby, the idea of a temporal shift of consumption processes is heavily discussed but long-term and seasonal demands cannot be addressed with this approach. This general problem will be exacerbated by the continuing expansion of renewable energy generating facilities [1].

In the following Section 2 the concept of hybrid grids is described and in Section 3 it is applied to local energetic neighbourhoods with, for example, industries having a heterogeneous energetic fingerprint. This concept offers high potentials for synergies but requires substantial research efforts for an economic exploitation. Section 4 describes a research project which addresses a case study to analyse and demonstrate these potentials. Sections 5 and 6 give a further outlook to future research and development activities.

2. Hybrid Grid

So-called hybrid grids are a possible solution to upcoming challenges raised by the ongoing transition process because they can deal with highly fluctuating demands on one side and a stronger integration of the heating / cooling sector on the other side. In [2] the German National Academy of Science and Engineering (acatech) describes a hybrid grid as a cross-domain (or inter-sectorial) energy system in which energy is consumed, stored or transported in its current form or can be converted into another energy form that can in turn be consumed, stored or transported. Figure 1 illustrates the possible conversion processes. So far the hybrid grid idea has been discussed on large-scale level and is usually associated with power-to-gas approaches [3]. In these approaches a variety of small-scale energy sources, coupling options and transformation possibilities are researched and tested [4]. In the urban context, additional subordinated energy sources can be exploited that have not been in the main focus so far such as gaining heat from waste water to operate heating devices via heat pump systems [5].

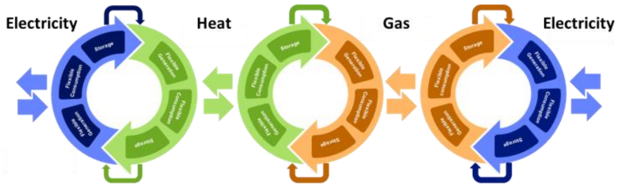

***Fig.1**: Coupling of processes in between the domains electricity, gas and heat*

3. Local Approach

The abstract concept of hybrid grids having a supraregional and national focus can be adapted for the municipal and local level through the concept of so-called Energetic Neighbourhoods (EN). The main challenge for the realization of this concept is the identification of suitable physical as well as virtual coupling points between particular energy systems. The approach aims to minimize the energetic process distances (number of lossy energy conversion processes) caused by the transformations as far as possible. Here, a variety of approaches can be combined:

- Direct coupling within a power domain
- Reduction of the transformation processes
- Reduction of line losses by spatial proximity
- Consideration of the respective energy levels

3.1. Energetic Neighbourhoods

From the perspective of enterprises, the approach of EN means that those who are in close proximity to each other exchange energy required for performing their common processes and energy surpluses with each other so that in total less primary energy is consumed. The coupling of the energy domains (such as electricity, heat, and cold) allows the balancing of energy supply (generation and procurement) and energy demand, resulting in a cost-effective use of energy. One hard requirement is that the production processes shall not be affected. The approach can also be used to specifically recruit companies for a settlement and involve them in an energetic overall portfolio of an area. In addition, the approach of EN may well be extended to other settlement areas (e.g., residential and commercial areas in immediate proximity).
An EN is thus a composite of actors, which are to each other in spatial proximity and convert the energy needed to carry out their usual processes as a side effect into other energy forms, which are required by another player from the composite as input for its own processes [13].
Energy efficiency measures are thus treated at the area level and are no longer left solely to the individual players.

3.2. Example: Industrial area

The first step to realize such an energetic neighbourhood is to identify suitable commercial and industrial areas. In detail, this includes to identify and analyse the energetic fingerprint of established companies to reveal the synergy effects described. For this purpose, it is advisable to first acquire the energy flows of the company for a process cycle (month, quarter, year, etc.) on the basis of detailed data and then prepare time profiles, so that interconnection points can be identified by a computer-aided analysis. An important aspect that must be considered in the following is that the industrial processes within the companies shall not be affected by designing an EN. In other words, energetic neighbourhoods shall be transparent for the involved players and mainly existing flexibilities should be exploited. In order to identify exploitable potentials the energy flows of the company are mapped over its time course. Based on this mapping an optimized (energy) system architecture can be derived for the targeted neighbourhood area.
Commercial and industrial areas, which have further development potentials (open areas, expansion possibilities) or subject to a pressure change may use the approach of EN for the development of the area. With the help of simulative potential analysis for energetic neighbourhoods, complementary businesses / energy flows can be identified. Based on the results of these simulations new companies can be attracted or recruited by offering them an energetically advantageous position in the EN. In addition to the usual criteria, such as price development and integration, energy will become a vital factor.
In general, the following key questions for potential pilot energetic neighbourhood areas have to be answered:

- Where and what kind of processes are coupled to each other?
- How should an infrastructure be designed (ICT, energy grid, etc.)?

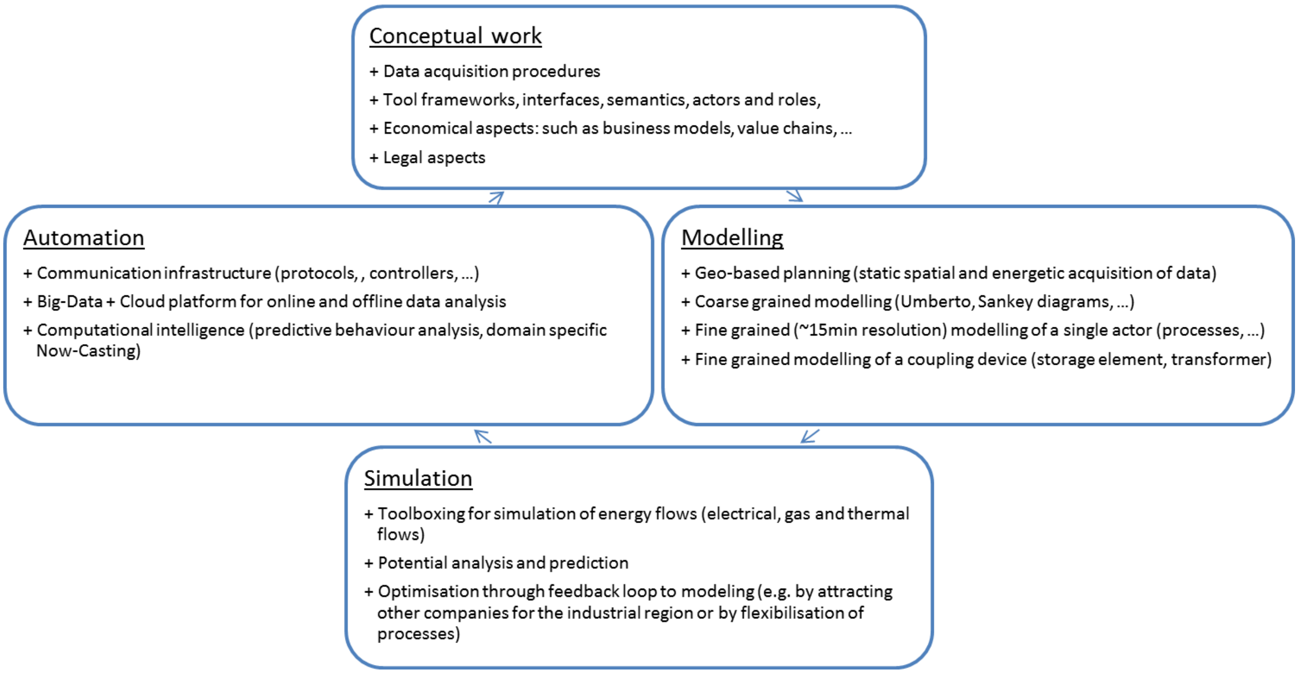

***Fig.2**: Research landscape for energetic neighbourhoods*

- How can forms of "energetic neighbourhoods" be organized?
- What untapped energy potential can be exploited (energy reduction and energy generation)?
- Can urban development plans be involved?
- What are the opportunities and risks for the specific area?

Figure 2 gives a graphical overview on the research landscape of the necessary conceptual, modelling, simulation and automation work in the energetic neighbourhood domain.

3.3. Questionnaire for Data Acquisition

As noted before an important preparation step is to acquire data about energetic flows and processes within the involved and neighboured companies in a targeted area. For this purpose, a questionnaire has been developed in order to collect the required data regarding energy consumption, transformation and thermal losses that may be exploited in an EN from different viewpoints (operators, enterprises, utilities). The questionnaire covers the following domains:

- Energy demand (electrical energy, gas, heat, cold) divided into base load, peak load and total amount
- Details on heated buildings (size, year of construction, type of usage, targeted temperatures,
- Information on used water/room heating devices, locations and its technical properties
- Available ventilating systems
- Energy production facilities (solarthermic, geothermic, photovoltaic, combined heat and power plants)
- Energy infeed data
- Cooling requirements
- Energy storages and properties
- Manufacturing facilities and processes as well as their demands
- Possibilities to shift production processes or loads
- Occurring thermal losses and possibilities to integrate other heat sources
- Information of applied energy management systems and certificates

3.4. Visualization of Energy Flows

The graphical representation of energy flows is an important tool that is used during the data acquisition. Established forms of representation of such flows (including material and energy flows) are Sankey diagrams as shown in Figure 3. However, there is no clearly defined semantics for the representation of Sankey diagrams. In [6], the following aspects are mentioned that are implicitly assumed in Sankey diagrams:

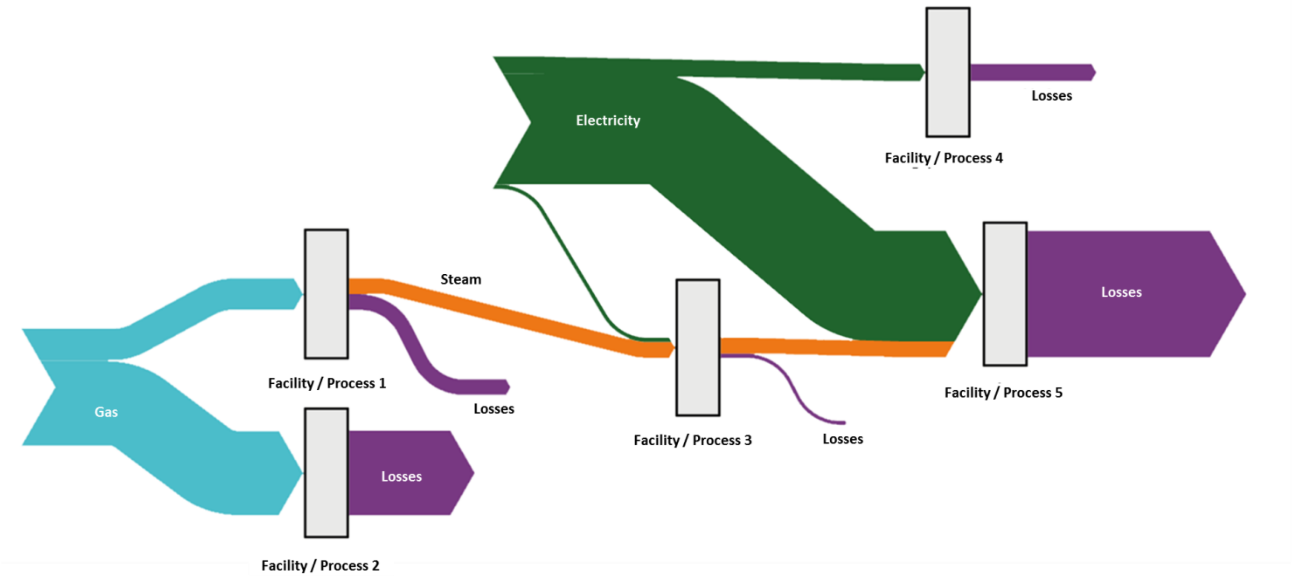

***Fig.3**: Schematic presentation of energy flows in a Sankey diagram*

- The flows are restricted to certain time periods.
- The quantity of energy flow is proportional to the arrow width, ie, a doubled amount of energy flow is represented by an arrow that is twice as wide.
- Storage capabilities are not considered in the diagrams.
- Energy and mass conservation is assumed.

In the context of energy transformation processes, two key points must be considered that are actually not supported by Sankey diagrams: On the one hand, it must be possible to represent transient flows over time. On the other hand, it must be possible to visualize transformation losses. Thus, the underlying data model has a significant role. Its specification is an integral part of the described in the following research project.

4. Research Project

The presented approach is analysed using the example of two industrial areas. To this end, a feasibility study funded by the Bremen/Oldenburg Metropolitan Region has started in late 2014. Besides the city of Oldenburg, the municipality Bad Zwischenahn, and the administrative district Ammerland also different companies, the Universities of Osnabrück and Oldenburg, and OFFIS are involved[1].

The study, the subsequent evaluation, and transfer of knowledge serve as a guiding model for gradual implementation of energetic neighbourhoods in the entire territory of the metropolitan region. In general, the concept can be transferred nationwide.

The considered case study is divided into three phases for the planning and implementation of ENs. These phases are shown in Figure 4.

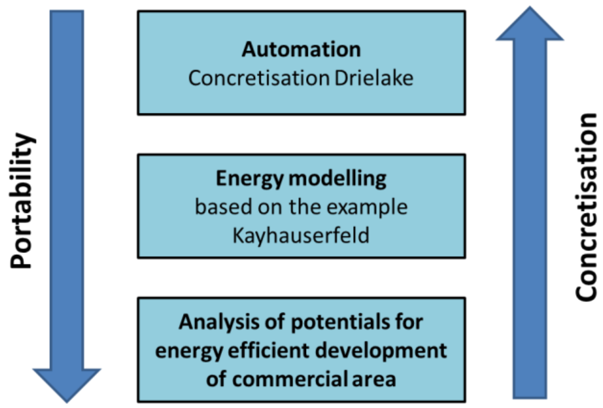

***Fig.4**: Development phases of the project to demonstrate the technical and economic feasibility of energetic neighbourhoods*

In the project a top-down approach is followed. This means that in the first step concrete automation measures are conceptually developed and evaluated. For this purpose, the commercial and industrial area Drielake/Wehdestraße/Stau (Oldenburg (Oldb.), Lower Saxony) serves as a demonstration site. The planning and testing of concrete measures is possible here, as the parties involved already possess highly automated processes for which detailed data is available.

If no such data exists or the processes of the companies are not documented or automated in an

[1] http://www.energetische-nachbarschaften.de/

area, a first modelling phase must be carried out. This case is exemplarily demonstrated in the commercial and industrial area Kayhauserfeld (Bad Zwischenahn, Lower Saxony).
Has no particular commercial and industrial area been identified, the process of implementation of EN starts with an analysis of potentials for energy-efficient industrial area developments. For this project, it means to develop based on the results of the previous phases a concept that allows to identify suitable areas on the basis of various analyses, to make assessments and thus to address targeted companies.
The two areas involved in the project are specified as follows:

- In the commercial area Drielake / Wehde street / Stau (Oldenburg) a focus is put on automation of processes (see Figure 5). In this area, the companies already have a very high level of automation in the production and energy processes. On the basis of the energy data that are provided by the companies with the help of the questionnaire indicated in Section 3.3, the usability of this basic data for a high-resolution simulative coupling of the processes is investigated. First simulation approaches are intended to show the possibilities and limitations. Thereby, the existing infrastructure of electricity, gas and wastewater lines is gathered and their suitability for an application of the EN concepts is evaluated. The coupling of processes of previously separated systems also involves legal issues.
- In the commercial and industrial area Kayhauserfeld (District of Ammerland, community Bad Zwischenahn) the focus is put on energy modeling. Therefore, energetic processes are captured and reviewed for their applicability. The data acquisition is performed for the entire industrial area. The provided data will be combined with freely available data and together it will be analyzed to what extent they allow a fine-grained representation of processes on comparable levels. Based on early experiences, tools for the collection and presentation of energy processes are developed. Again, the existing infrastructure of electricity, gas and wastewater lines is gathered and their suitability for an application of the EN concepts is evaluated.

The city of Oldenburg supports the approach of EN under their integrated energy and climate protection concept and will accompany the process by involving also companies from other industrial and commercial areas. To consider urban planning aspects, the community Bad Zwischenahn and the district Ammerland are involved in the operational phases of the project.

Fig.5: *Main area and extension areas for energetic neighbourhood case study (map created with ArcGIS)*

All involved companies of the two areas have agreed to provide their energy and process data. In summary, the study will provide the following results:

- Point out ways for a constructive collaboration (keyword: confidence-building measures),
- Identify energetic coupling possibilities as well as demonstrate possibilities for economic sustainability
- Create a guideline for portability and scalability of the developed concepts

5. Further Research and Development Approaches

The feasibility study described in Section 4 will be the first step in a series of further scientific but also implementation-oriented activities. Specifically, the following three steps are envisioned:

- The results of the case study will be refined and advanced in the project EN EnerGeoPlan [7]. In particular in the context of the development of an architecture for the targeted areas the simulation tool mosaik [8] is used. On the one hand this enables a consideration of the local planning rules and on the other hand to implement the architectures in an iterative manner without endangering the real system.
- As soon as hardware components such as Cogeneration (CHP) are integrated in the field to serve as interconnection points between the processes, they must be tested via a remote connection to a lab. The plan is to achieve a connection of these components to the Smart Energy Simulation and Automation (SESA) Laboratory of OFFIS [9].
- Further development of spatial analytical tools to explore energetic action spaces.

The consideration of the spatial dimension in future energy concepts is usually done in the context of spatial potentials and obstacles either solely in the energy domain [10] or with a limited focus to optimise the location of e.g. heat storages in the district heating network [11]. In the multidimensional energy system of the future with a variety of coupling options, the one-dimensional optimization will no longer be sufficient. Spatial analysis tools and methods have to be further improved for the EN context so that domain-specific spaces of action are coupled together.

6. Outlook

Both, locally organized energetic neighborhoods as well as national or international hybrid networks are promising approaches to address the key challenges of growing integration of fluctuating generation plants and are therefore a significant milestone on the way to implement the energy revolution.

For the individual actors there are great opportunities:

- Securing the business locations
- Comprehensive energy management for industrial, commercial and residential areas
- Reduction of primary energy use, thus CO_2 savings and support for climate change activities
- Development of new business models for energy companies
- Integration of crafts and local experts for the practical implementation

Using the approach of energetic neighborhoods the integrated energy and climate protection concepts that exist in many communities can be operationalized. In addition, the approach can also be used at the municipal planning level (urban land-use planning) to develop districts as energy efficient as possible [12].

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Rapid Modeling and Simulation of Hybrid Energy Networks

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Abstract: Local distribution grids suffer from the integration of highly fluctuating renewable energy sources, such as photo collectors, or the use of micro combined heat and power (µCHP). In order to keep such hybrid energy systems stable, new technologies have to be found and applied. In this paper we present components for the construction of interfaces and filters enabling a flexible and fast integration of such new technology models in simulation environments. These components are integrated in the simulation framework i7-AnyEnergy. The flexibility of the framework enables multi-paradigm modeling, which is required in order to model energy resources along with control mechanisms for new technologies. The applicability of the framework is demonstrated by presenting the results of two research projects: the assessment of different µCHP systems for households and the application of a central storage to rural local distribution grids.

1. Introduction

The local distribution grid is evolving from the former centralized system to decentralized smart grids. This results from the usage of regenerative energy resources which have to be used at their place of occurrence. Furthermore, the European Commission enforces the reduction of converting fossil fuels to electric energy [1]. In order to maintain high reliability of the electricity supply and enable further integration of regenerative energy sources, new technologies have to be found and used. This also requires the development of strategies for their application by means of investment and effectiveness. New techniques will only be applied, if stability of the power grid is maintained and investments are covered.

In order to judge about these two essential factors, simulation is an appropriate method. A flexible simulation environment enables to quickly build new system configurations, derive control strategies and assess the outcome, as it is done by rapid prototyping. Moreover, coupled simulation of different energy carriers (electricity, heat, gas, wind, solar) is needed for the simulation of high efficiency technologies. The hybrid simulation of continuous models and discrete events enables to model natural systems combined with control actions that are triggered at certain points in time.

In this paper, we present the concept for the construction of flexible interfaces and filters for components of hybrid energy networks. With these interfaces and filters, the various entities of such networks can be easily accessed and exchanged between different components and smart grid controllers of a distributed energy system. This concept allows for connecting models of various model languages and visual modeling for presentation and interaction. Furthermore the interfaces are themselves components and are used during the graphical modelling process.

The concept was integrated in the hybrid simulation framework i7-AnyEnergy and successfully applied in two research projects of the Energie Campus Nürnberg (EnCN) [2] and the ZAE Bayern e.V. (*Smart Grid Solar* [3]). We analyze two different scenarios of a power grid of 15 households with local storages and a central storage. A second example considers power, gas, and heat for a household with micro combined heat and power (µCHP) instead of PV. The mean annual energy costs are calculated on the basis of the current energy tariffs in Germany. The two hybrid simulation models make use of the presented interface construction and access concept.

The paper is organized as follows. The related work is addressed in section II. In section III the general software architecture and interface concept is presented. This concept is then used by the simulation models of section IV for the assessment of renewable energy systems. Finally, in section V a conclusion is drawn.

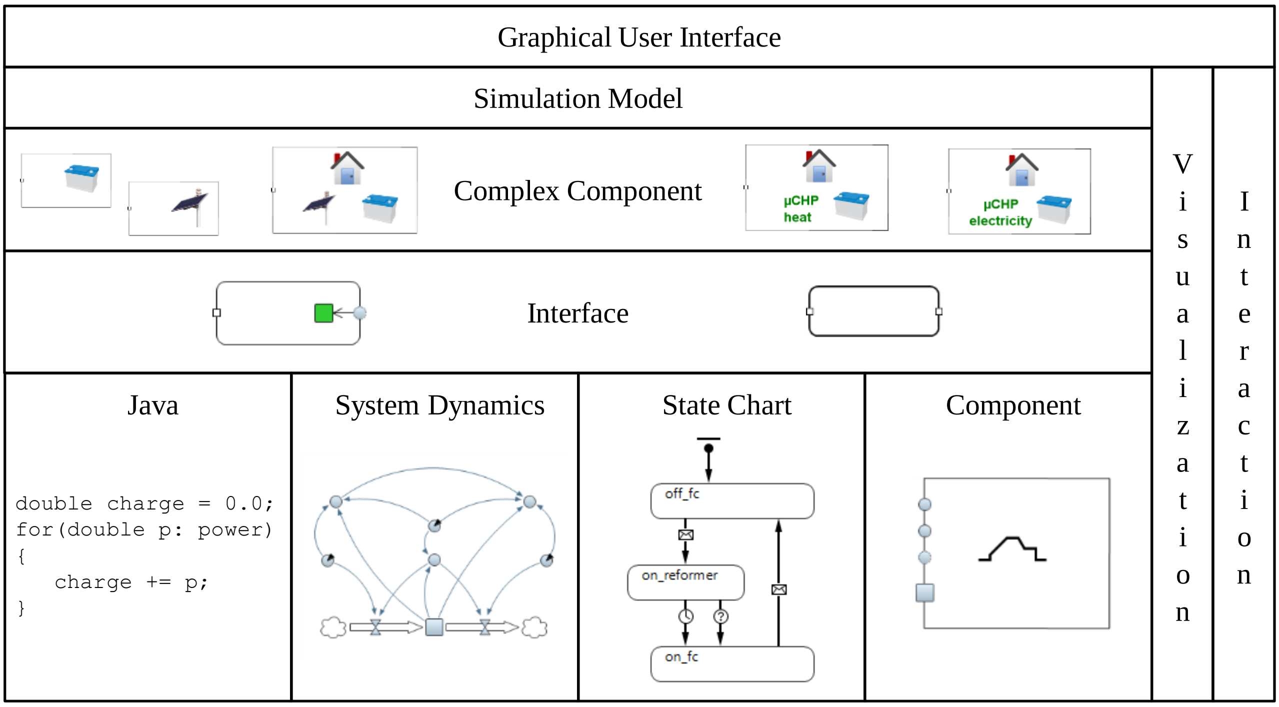

Fig.1:*The general software architecture of i7-AnyEnergy for hybrid energy system simulation*

2. Related Work

For the assessment of renewable energy systems, simulation tools are commonly used. A discrete time step simulation tool is the *Integrated Simulation Environment Language* (INSEL) which comes with predefined models of power system components [4]. In general, such a component based approach allows for the construction of complex power grids. The component based approach of the hybrid simulation framework used in this paper was inspired by the work in [5] and [6], where discrete simulation is used.

Hybrid simulation tools model the communication part of the energy system using discrete event simulation whereas continuous simulation is used for the energy part. Such hybrid simulation tools are *Grid-LAB-D* [7] and *GridSpice* [8]. GridSpice is capable of distributing the computational effort for large simulations over virtual machines. It makes use of Amazon Web Services, has Grid-LAB-D integrated for the power simulation, and the optimization is based on *MatPower*. A simulation framework for smart grid applications on the basis of freely available simulation, optimization, and communication tools is *SGsim* [9].

The *mosaik* platform [10] combines models, control strategies, and simulators to complex simulation models of energy systems and smart grids. It uses Python and is based on well-defined standards and interfaces. An important task of mosaik is to manage the data-flow between the different simulators.

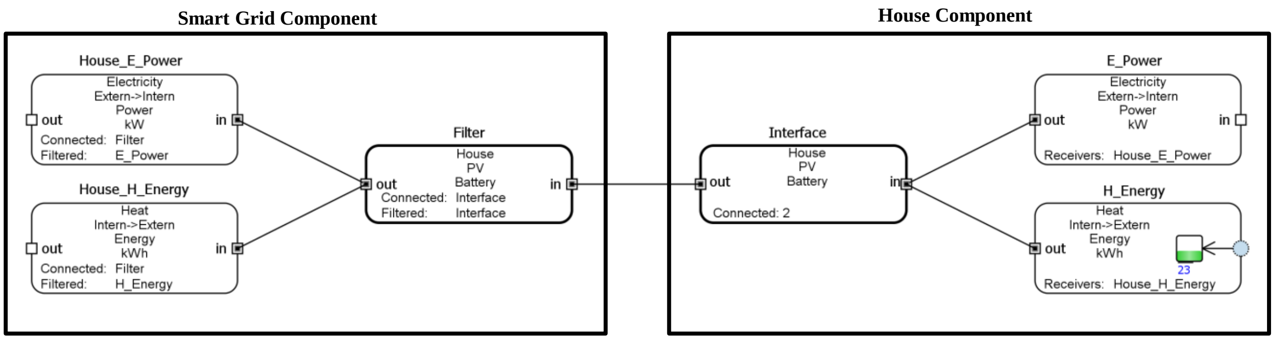

Fig.2:*Screenshot of an interface example for a house component (right) and a filter example for a smart grid controller (left) during runtime.*

The last two modelling and simulation tools are co-simulation tools and the model interconnections are mainly given in textual form. The tool in this paper follows a different approach. It utilizes an integrated modelling, hybrid simulation, visualization, analysis, and debugging tool. With this tool, components for hybrid energy systems can be built and connected to smart grids using a graphical user interface.
The interfaces of the components and the data-flow between them can be constructed with the graphical user interface as well. In addition, filter components enable an easy access to the interface components, allowing the fast implementation of controller algorithms.

3. Interface and Filter Concept

The multi-paradigm hybrid simulation framework i7-AnyEnergy used in this paper and its component-based design and energy-flow interfaces were first described in [11]. In [12] the energy-flow interfaces were refined and a message oriented communication interface concept was added. In this paper we present a new component based concept for the graphical construction of such interfaces along with filters. These components are integrated in the simulation framework.

The general software architecture of the framework is shown in Fig. 1. The simulation framework i7-AnyEnergy itself is based on the multi-purpose hybrid simulation tool AnyLogic [13]. With AnyLogic comes the possibility to build multi-paradigm components using the Java programming language, the System Dynamics paradigm (continuous simulation) for energy flows, and state charts (discrete event simulation) for control decisions and communication. These paradigms can be used for agent-based components. With the presented interface components, complex interfaces for components for the hybrid simulation of energy systems (complex components) can be built using a graphical user interface by simply dragging and dropping them onto the worksheet. The complex components are then the building blocks for the simulation models. The built-in visualization of the values of variables and active states of state charts helps for debugging the models. As well, variables and parameters can be altered during runtime (Fig. 1 Interaction).

3.1. Interface Concept

Basic interface components allow variable, parameter, and message passing or function calls.

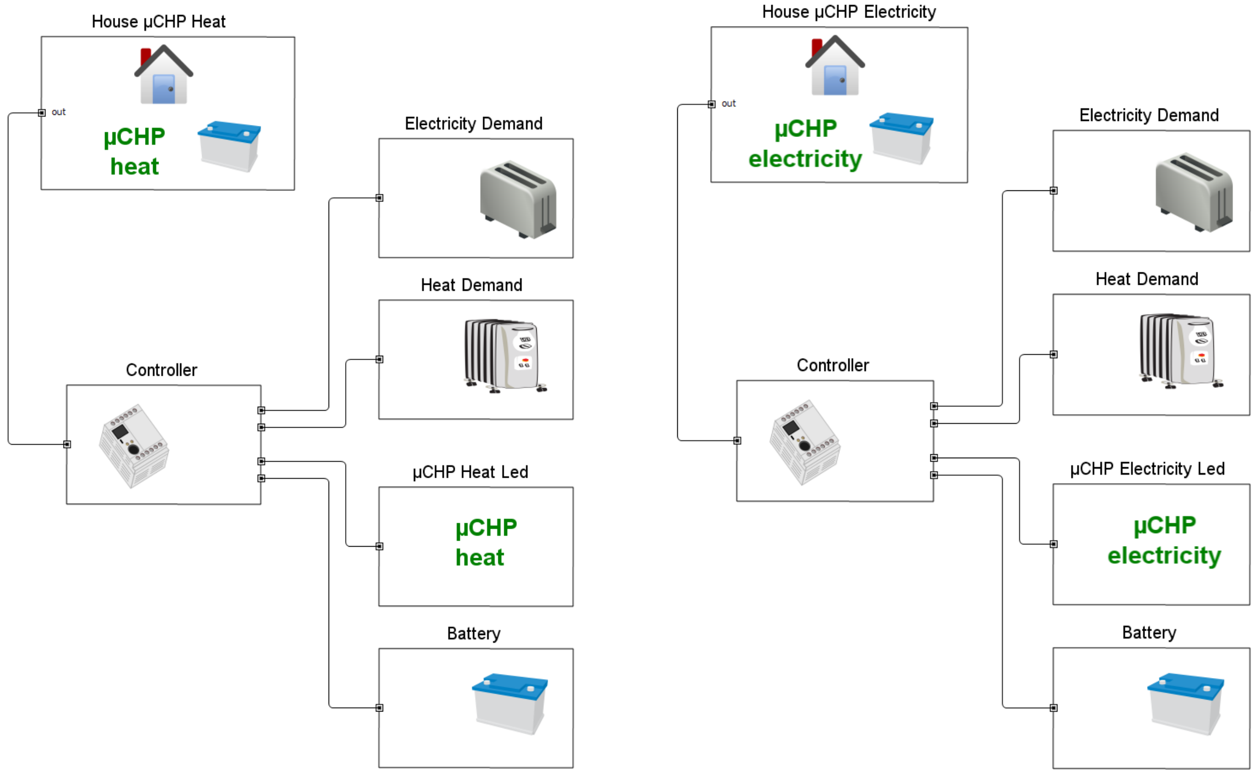

Fig.3*: Screenshots: The components of the heat-led µCHP house(left) and the components of the electricity-led µCHP house (right).*

Among other things, they can implement energy-, cash-, or message flows. Fig. 2 shows a basic interface instance named *E_Power* as part of *House Component* during runtime. Such an instance can be parameterized by four parameters. In the example the parameters describe the semantic of the connected variable. It is the electric (*Electricity*) energy flow (*Power*) from outside of the component into the component (*Extern->Intern*) in kW (*kW*). The basic interface instance *H_Energy* is connected to a variable representing a heat flow in kW. Because this basic interface integrates the variable over time, it calculates the energy in kWh.

Basic interfaces can be aggregated to interfaces as shown in the example. The interface instance named *Interface* is parameterized by three descriptive parameters and connected to the two basic interfaces *E_Power* and *H_Energy*. The number of connected interfaces is shown in the field *Connected*. It is also possible to connect interfaces to interfaces resulting in a hierarchical tree structure of interfaces with basic interfaces as leaves.

3.2. Filter Concept

Filter components are designed for an easy access to interfaces and basic interfaces. In Fig. 2 the filter instance *Filter* of *Smart Grid Component* is connected to the interface instance *Interface*. If the three parameters (e.g. *House*, *PV*, *Battery*) match all parameters of the connected interfaces, the interfaces are filtered. Basic filter components filter matching basic interfaces.

In the example of Fig. 2, the instance of the basic filter *House_E_Power* has filtered the basic interface instance *E_Power*. An access to *House_E_Power* is automatically translated into an access to *E_Power* and therefore algorithms of *Smart Grid Component* can be written in terms of the local *House_E_Power* without knowledge of the connected *House Component* or its interface structure.

During runtime the basic filter shows the filtered basic interface (in *House_H_Energy Filtered* is set to *H_Energy*) aiding the debugging of the model. Conversely, the basic interface signals that it is filtered by basic filter (in *H_Energy Receivers* is set to *House_H_Energy*).

The filter concept is more flexible than shown in Fig. 2. It is possible to filter in a smart grid model with one basic filter all state of charge values of all local installed house batteries. A grid controller can then add up the state of charge values to calculate the available stored energy. For this purpose, the controller must not access all corresponding basic interfaces of the interface structure, but can use the single basic filter component.

4. Assessment of Renewable Energy Systems

The presented framework was developed as part of the work at the EnCN and the Smart Grid Solar project and is used in both projects for the assessment of energy systems. The first example compares the energy costs of a house with a battery and a heat-led µCHP with a house equipped with a battery and an electricity-led µCHP. The assessment of different scenarios of a power grid with local or central battery storage is the second application.

4.1. Comparison of different µCHP control strategies

The EnCN contributes to the energy system of the future with respect to the whole energy chain which includes the combination of power generation from renewable sources, efficient energy storage and transport, and intelligent supply with efficient utilization and exploitation. This research is complemented by system-engineering, acceptance research, design and simulation. The simulation tool i7-AnyEnergy was developed for the hybrid

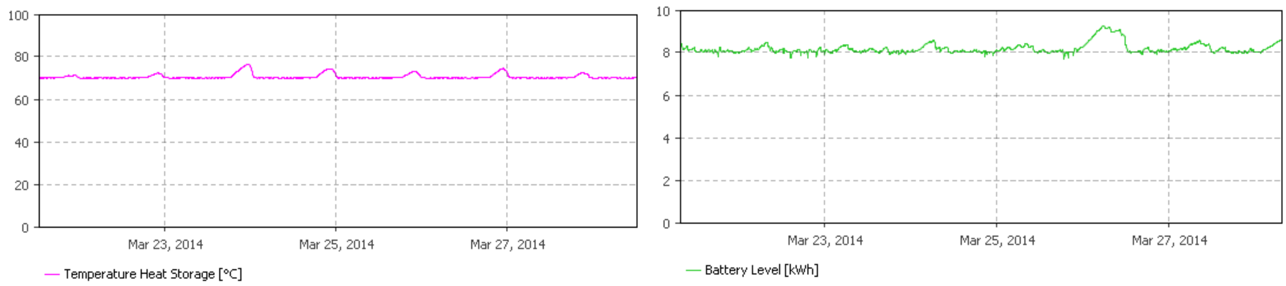

Fig.4: *Temperature of the heat storage for the heat-led µCHP (left) and fill level of a battery with a capacity of 10 kWh for the electricity-led µCHP (right).*

simulation of intelligent energy systems as part of the simulation project.
With the presented enhanced version the energy costs of a house with a battery and a heat-led µCHP (Fig. 3, left) and a house equipped with a battery and an electricity-led µCHP (Fig. 3, right) are compared. The two screenshots (Fig. 3) of the graphical user interface show how easily the components can be connected to construct different scenarios. The µCHP contains a fuel cell operated with gas, an auxiliary gas burner, and heat storage. The µCHP as well as the stochastic profile based electricity demand and heat demand are modeled according to [14]. Each house is a combined producer and consumer and tries to remain self-sufficient.

Parameter	Value	Unit
Battery		
Capacity	0-6	kWh
Electric efficiency	0.9	-
Self-discharge factor	0.002	-
Heat storage		
Volume	150	l
Maximal temperature	95	°C
Minimal temperature	40	°C
Gas burner		
Capacity range	4-20	kW
Efficiency	1	-
Fuel cell		
Capacity range	0.3-3	kW
Ramp capacity	9	kW/h
Electric efficiency	0.3	-
Thermal efficiency	0.7	-
Controller µCHP		
Maximal temperature µCHP	80	°C
Minimal temperature µCHP	60	°C
Maximal temperature gas burner	58	°C
Minimal temperature gas burner	53	°C
Thermal balance	70	°C
Electric balance	0.8	-
Start-up time	0.75	h
Gas use for reforming	1	kW

Tab.1: *Parameters of the components*

The parameters of the components are given in Table 1. The capacity of the battery is varied from 0 kWh (no battery) to 6 kWh with a step size of 1 kWh to show the influence of the battery size on the energy costs. The charge and discharge electric efficiency is 0.9 and the self-discharge factor 0.002.

The heat storage has a capacity of 150 l. At a maximal temperature of 95 °C a signal is given to shut off the fuel cell and gas burner. With a temperature of the heat storage below the minimal temperature of 40 °C, no heat can be taken from storage. The gas burner has a capacity range from 4 kW to 20 kW and an efficiency of 1. With a capacity range from 0.3 kW to 3 kW, the fuel cell has not as much power as the gas burner. It produces thermal energy and electricity. The thermal efficiency is 0.7 and the electric efficiency 0.3. It is assumed that the gas burner can follow a heat demand instantaneous whereas the fuel cell has a limited ramp capacity of 9 kW/h.
The controller shuts off the fuel cell if the heat storage reaches a temperature of 80 °C and switches it on if the temperature drops below 60 °C. If the fuel cell with its limited power can't maintain the temperature, the more powerful gas burner kicks in at a temperature of 53 °C and shuts off at a temperature of 58 °C. The start time of the fuel cell is 0.75 h. During this time, it delivers no heat or power but has a gas use of 1 kW. The heat-led controller tries to hold the temperature of the heat storage at 70 °C (Fig 4, left). The electricity-led controller tries to hold the fill level of the battery at 80 % of its capacity (Fig 4, right).
The systems are analyzed with the energy tariffs and refunds in Germany as of June 2014 given in Table 2. The tariff for the power from the power grid is 0 2 € and the gas tariff is 0 0 € The energy tax refund for the consumed gas of a µCHP is 0 00 € and the surcharge for its generated electric energy is 0 0 1 € The electricity exported to the power grid is rewarded with a base load price of 0 0 € and for the a oided network usage with 0 00 €

Tariff	[€/kWh]
Electricity	
From the power grid	0.28
Baseload	0.037
Avoided network usage	0.0049
Surcharge	0.0541
Gas	
From the gas grid	0.077
Energy tax refund	0.0055

Tab.2: *Energy tariffs for electricity and gas*

The simulation runs for each experiment are repeated 100 times and the mean values of the energy cost for different battery capacities are given in Fig. 5. The costs for the house with the heat-led µCHP are for every battery capacity below the costs for the house with the electricity-led µCHP. For this house, a battery with a capacity of 1 kWh reduces energy costs significantly by 00 € Howe er, a further increase of the battery size is no longer effective.

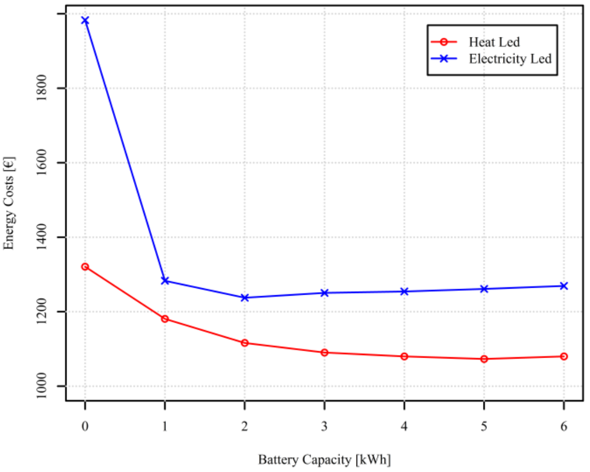

***Fig.5**: Mean annual energy costs for a house with heat-led µCHP and a house with electricity-led µCHP.*

4.2. Smart Grid Solar

The interdisciplinary and cofounded project "Smart Grid Solar", held by the ZAE Bayern e.V., is focusing on renewable energies brought to the urban and rural distribution grids. On the one hand, the project is addressing solar energy production modulation, characterizing energy storage technologies and improving net utilization on their own. On the other hand, newly developed approaches are assessed by model experiments as well as simulation models in terms of technical applicability and economic benefit.

In [10][15] the impact of photovoltaic systems (PV) on the peak load of the power grid was simulated and different fixed and load-variable grid pricing strategies for reducing the peak have been compared. An alternative or additional approach is the installation of energy storages in the power grid, both, for power and heat. In [16] such a system is analyzed and a pilot and demonstration project with 20 households is presented.

In this paper we analyze two different scenarios of a power distribution grid of 15 households (Fig. 6) with local storages and a central storage. The focus in this section is set to the application of storages for future scenarios. Storages applied the to the local distribution grids can be used for reducing energy fluctuation, peak shaping, technical stabilization of the grid and stabilizing energy markets. Storages currently used in non-research scenarios are used for increasing local energy stocking and therefore reducing energy fluctuation. Storages applied at central places in a local distribution grid are mostly installed for research purposes in order to stabilize voltages [17].

The simulation covers traditional households, which are only consuming energy, and modern households having solar collectors installed. By simulating these households and a connecting local distribution grid, storages applied to different places in the system can be compared by several parameters like energy throughput [kWh], time of usage [h], depth of usage [%] and resulting load after application [kW].

The most conservative strategy applied to local storages in households is the so called greedy strategy. This strategy tries to keep the most energy local, by always trying to store unused energy and to serve local demand by discharging the storage. The only limitation of the approach is the capacity of the storage and therefore the current SOC of the storage. This strategy shall serve as basic usage scenario and therefore will be used in the simulations presented in the following sections.

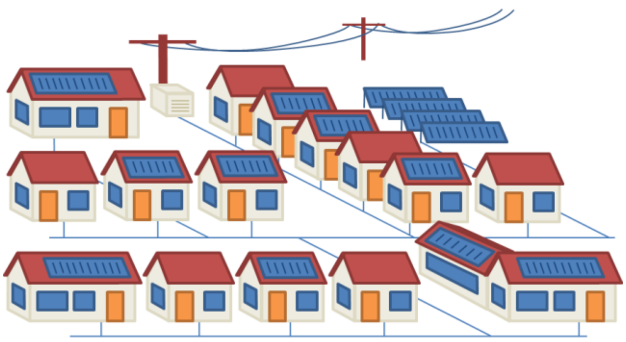

***Fig.6**: Smart grid with central storage for the grid or local storage for each house with PV*

Using the simulation framework i7-AnyEnergy, a basic configuration containing 15 houses connected by a local distribution grid, where ten of the houses have solar collectors installed (total peak power of 126 kWp). There are two storage configurations. Configuration A contains storages with the capacity of 10 kWh connected to each of the solar-equipped houses. In configuration B, the total capacity of 100 kWh is applied as one central storage system at

the transformer station. In order to get a statistical relevant result, the simulation is repeated ten times.
The Table 3 compares the parameters characterizing the storage usage in the two different scenarios, derived from simulation runs. The energy throughput describes the total energy that was charged to the storage over one year. The most important conclusion that can be drawn from this parameter is the wearing of the storage. Charging the storage from empty to full and discharging it again is one full load cycle. The throughput in this case is 10 kWh in configuration A and 100 kWh in configuration B. Depending on the average value of maximum load cycles to death, the expected lifetime of the storage can be decided. The storages are expected to hold for 30 years in configuration A and 25 years in configuration B. The reduced lifetime in configuration B results from higher throughput. Another important factor, in terms of economic acceptance, is the time of usage.

Parameter	Storage configuration	
	A (households)	B (central)
	Energy throughput	
min	1323 kWh	18,613 kWh
mean	1663 kWh	19,704 kWh
max	2000 kWh	20,820 kWh
	Time of usage	
min	4866 h	6437 h
mean	6070 h	6708 h
max	6535 h	6994 h
	Depth of usage	
< 10%	1563 h	2323 h
> 90%	2840 h	73 h
	Resulting load	
Autarky	3467 h	6566 h
max	22 kW	26 kW

Tab.3: *Simulation results for two Smart Grid Solar configurations*

A storage is considered to be used, whenever the current load for charge or discharge is larger than average standby loads (14 Wh). The simulation results for the usage is 6070 hours (~ 253 days) in configuration A and 6708 hours (~ 280 days) in configuration B. The higher time of usage in configuration B tells an investor, that the storage is unused in nearly 25 % of time, which is quite a lot. The third parameter is the depth of usage, describing how good the available capacity of the storage is used.

In configuration A, the SOC of the battery is less than 10 % in 1563 hours of simulation time, whereas it is charged more than 90 % in 2840 hours. This means, that the battery is nearly empty or nearly full in half a year. During this time, the storage control strategy is restricted by the storage capacity. In configuration B, the depth of usage is different. The storage is nearly discharged in 2323 hours and nearly charged in only 73 h of simulation time. The higher time of discharge results from five houses without solar collectors, which are powered by the central storage in configuration B. The lower time of full charge shows, that the central storage would be capable of storing a higher amount of regenerative energy – the storage is too large for the simulated grid. The last parameter tells about the impact to the distribution grid.
Using the house storages in configuration A, the local distribution grid is self-sufficient in 3467 hours of the year (~ 144 days) and has a maximum load of 22 kW. In configuration B, the autarky time is risen to 6566 hours (~ 274 days) and the maximum load is 26 kW. The higher autarky time is resulting from all houses being supplied by the storage and therefore not only the time having solar insulation can be used for self-sufficiency. The higher maximum load of 26 kW is possibly resulting from the higher time of a discharged storage.

5. Conclusion

In this paper we have presented a component based concept for a fast and flexible graphical construction of component interfaces for a multi-paradigm hybrid simulation framework. Access to the interfaces is implemented by filter components. They provide a simple connection of components and implementation of smart grid control algorithms.
With such an approach simulation models of new technologies are easier to integrate in an existing framework compared to a simulation framework with predefined component interfaces. The graphical user interface and visualization of system states aids the rapid modeling and debugging of hybrid energy networks. Additionally, it provides an insight of the behavior of the models.
The concept has been integrated in the framework that is then used for the modeling and simulation of renewable energy systems. The first application compared two houses with battery and µCHP. One house is equipped with a heat-led µCHP, the other house with an electricity-led µCHP. The simulation

results show that with the given energy tariff and refund structure of Germany, the heat-led energy costs are lower.
The second application examines central and distributed battery storages in a local distribution grid with PV. The evaluation of the storage parameters has shown that there are some advantages of central storages compared to the traditional house storages, like the higher autarky time and the higher time of usage of the storage. Furthermore, a central storage can help to tolerate more regenerative energy, because of the lower depth of usage (only 73 hours of full charge). At last, the four discussed parameters derived from the greedy-controlled storages only hint at the improvements of applying central storages. Control strategies have to be developed, which rise the time of usage and therefore max out the economic acceptance.

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A Generic Business Logic for Energy Optimization Models

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Abstract: The “Energiewende” changes the energy system in Germany substantially. In order to cope with the rising share of volatile and weather-dependent energy production from renewables, it is necessary to be able to adapt the demand to the current energy supply. In order to achieve this, we propose a software platform called *SmartEnergyHub*, which is able to optimize assets of larger and energy-intensive infrastructures. The optimization is done in a way that the infrastructure is able to support the energy system by acting either as an energy producer or a consumer, depending on the current situation in the grid. For this, the *SmartEnergyHub* has to collect sensor data from generators, consumers and storage facilities and to run real-time optimization algorithms which define an optimal scheduling of demand and supply. One major challenge in building such a system is the requirement for fast processing of large amounts of sensor data by the optimization algorithms. Since the research field of energy optimization advances steadily, it is important to make the data handling as generic as possible in order to be able to use the latest optimization approaches without changing the data management. To meet this challenge, Mesap, the operational energy datawarehouse, is proposed as a basis for data handling in the *SmartEnergyHub*. The Mesap software is introduced and we show two examples for generic interfaces to connect optimization algorithms to Mesap and discuss their scalability for handling large data volumes.

1. Introduction

Balancing energy demand and supply with the *SmartEnergHub*

The “Energiewende” changes the energy system in Germany substantially. In order to cope with the rising share of volatile and weather-dependent energy production from renewables, it is necessary to be able to adapt the energy demand to the current supply. In order to achieve this, it would be useful if larger energy-intensive infrastructures are able to optimize their assets in a way that they can support the energy system by acting either as an energy producer or a consumer depending on the current situation in the grid.

The research project *SmartEnergyHub* funded by the German Federal Ministry for Economics and Energy[1] investigates how to build a technical system which is able to fulfill this requirement. The project consortium consists of Fichtner IT Consulting AG, Seven2one Informationssysteme GmbH, in-integrierte Informationssysteme GmbH, Fraunhofer IAO, Fraunhofer IAIS and Airport Stuttgart GmbH.

The Airport Stuttgart serves an example for such a large and energy-intensive infrastructure.

The *SmartEnergyHub* has to collect a large amount of sensor data from generators, consumers and storage facilities, to run real-time optimization algorithms in order to find an optimal scheduling of energy production and consumption, and it has to be able to send signals to all assets in order to control their behavior accordingly.

Basis of the data management in the SmartEnergyHub is Mesap, the operational energy datawarehouse [1]. For a better understanding of the Mesap software technology, we start with a short introduction about the concept, the design and the use cases of Mesap in the energy market. As a next step, we show two generic interfaces to powerful mathematical modelling software, namely R [2] and MATLAB® [3] provided by Mesap. The integration of both software products in Mesap is described in detail and performance tests for reading and writing data in Mesap using these interfaces are presented.

1 Bundesministerium für Wirtschaft und Energie (BMWi)

The Mesap R and MATLAB® Integration allow to connect any optimization as well as forecasting algorithms seamlessly to Mesap which is a fundamental requirement to support energy optimization without changing the data handling as was one of the objectives in the *SmartEnergyHub* project.

2. Related Work

Due to the German “Energiewende”, profound energy management has become more than ever an important issue, especially for owners of large and energy-intensive infrastructures. A practical and sustainable approach to this challenge has to involve information and communication technology (ICT) in order to be able to process the necessary sensor data volume and to automate analysis and optimization processes.

In this context, the E-Energy research projects [4], funded by the German Federal Ministry for Economics and Energy[1] and the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, offer relevant research results. These projects investigated various individual aspects of the integration of renewable energy sources, decentralized plant operation and market incentives for six specific model regions.

However, in these projects private households were often in the focus of energy management arrangements, where the need to analyze frequent data input is not so much of an issue when compared to large infrastructures such as the Stuttgart Airport. Besides, integration of various different kinds of data sources, such as sensor measurements, business databases or market data, was never subject of explicit investigation in any of these projects.

When it comes to Big Data and Business Intelligence solutions, In-Memory databases such as Parstream [5], SAP HANA [6], BigMemory from Terracotta/Software AG [7] or Hyper of TU Munich [8] offer the possibility of fast data processing. However, there is no In-Memory database technology on the market which provides specific business intelligence functionalities for the energy sector, such as Mesap. Hence, one goal of the *SmartEnergyHub* project is to combine the Mesap software with In-Memory database technology.

There is a variety of software for data management in the energy sector. Most of these technologies however either support operational or analytical data provision. Mesap, on the contrary, integrates both approaches and can be used as a basis for transactional as well as analytical business processes. Mesap combines the advantages of systems which are designed to support online transactional processing (OLTP), which is needed to perform daily business applications such as accounting, and systems which support online analytical processing (OLAP), which is typically needed as a basis for strategic business decisions. It is, therefore, an ideal candidate to be integrated in the *SmartEnergyHub* and offers decision support as well as operational methods for business models in the Smart Energy context [9].

3. Our Approach

One major challenge in building a generic system for big data optimization is the requirement for fast processing of large volumes of sensor data in optimization algorithms. Hereafter, we describe the design principle of Mesap which will be part of the *SmartEnergyHub* technology and responsible for transactional data handling and provision of analytical data processing capabilities.

Generic business intelligence platform for big data optimization and real-time energy management

Assuming that optimization algorithms as well as the sensor technology will advance further in the future, it is important to make the data handling as generic as possible in order to be able to integrate novel optimization approaches. Furthermore, the social and economic conditions as well as legal provisions change constantly which affects the business processes that need to be supported by an ICT infrastructure. This emphasizes the need for flexibility in the underlying technical systems.

For these reasons, our approach is to build up a generic business intelligence platform which is able to collect all required sensor data input, as well as information from various other data sources, such as weather forecasts or market prices. The *SmartEnergyHub* has to be able to transform the input data into generic data objects which can then be accessed by a broad variety of downstream tools and systems via interfaces.

The Mesap software was designed according to the previously described principles. Mesap is a platform which offers generic data import, data processing, analysis and reporting functionalities. The platform can be customized via configuration according to the specific needs of the business application which it is used for. This highly flexible approach makes the software an ideal candidate for the yet evolving business models in the Smart Energy sector.

Mesap - the operational energy datawarehouse

The Mesap standard software is a platform for building customer-specific strategic information systems and was developed for analysts, planers, controllers and statisticians, to ensure that they are well informed, to provide a sound basis for decision making and to enable them to react efficiently, flexibly and quickly to new information demands. Mesap combines the possibility to support operational business transactions of conventional database software with the comprehensive data integration and analytical tooling of datawarehouse systems.

Based on the Mesap platform, a broad range of system solutions for the energy industry and environmental conservation are offered, such as

- Market Data Management for energy trading
- Power Plant Deployment Optimization and Reporting
- Risk & Portfolio Management for energy trading
- Regulatory Data Management for grid operators
- Environmental Information System for environmental protection agencies
- Planning, Simulation and Balancing of energy systems
- Complex mathematic modelling, such as price forward curve computation or power plant deployment optimization methods

and many more.

Figure 1 shows the structure of Mesap. Mesap's core is a powerful database in which all important information for company management, planning and documentation are brought together in a centralized data pool. Mesap supports a broad variety of different import interfaces which allow file-based as well as webservice-based imports. Due to the generic approach of data management in Mesap, technical data, market data, indicators and data from various external and internal sources can be administrated in a common context with reference to each other.

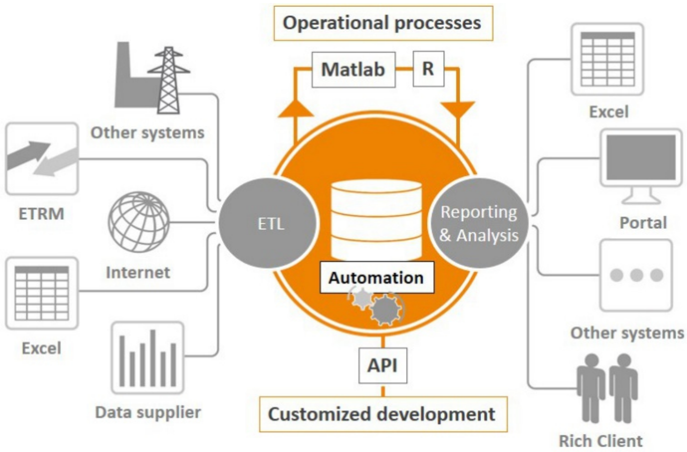

***Figure 1**: Structure of the Mesap software and its components.*

Mesap has a standardized data-object model and allows flexible data handling and access via an open application programming interface (API). Similar to a data warehouse, Mesap stores time series data of any resolution in a multidimensional structure. Moreover, Mesap manages source data (e.g. about power stations, distribution networks) and event records (e.g. trades or unavailability events of power plants …), which are similar to database table records. In addition to these three main data-objects, Mesap provides documentation items, data files for calculations (Excel-reports, R- or MATLAB®-scripts …), data snapshots and test results.

Based on these data-objects, Mesap provides multiple analysis and reporting systems and toolkits. The seamless integration of reporting and scenario based planning transparently connects past, present and future scenarios in one system. At the same time, all relevant information is brought together in a central system and in this way inter-company communication is specifically supported.

All tasks that occur in working with the Mesap software can be processed automatically via the Mesap scheduling component. The Mesap Scheduler automates all tasks that have a configurable time plan or which can be triggered via events through the Mesap API. Task automation is centrally controllable, can be configured using a basic workflow designer and can be parallelized.

Mesap R and MATLAB® Interfaces

Mesap provides standardized interfaces to the mathematical modelling software R and MATLAB®, which can be used to implement sophisticated analysis, optimization or forecasting methods. The data-exchange between Mesap database and the Mesap R or MATLAB® Integration component can be fully automated using the previously described Mesap automation engine. Hence, Mesap provides the possibility to integrate and automatically execute complex computation workflows which can form the basis for sound decision making in the energy sector. In order to be able to realize a concept such as the *SmartEnergyHub*, in which real-time optimization of demand and supply is necessary, such powerful computation engines are a major prerequisite.

The Mesap R Integration comes with a library which provides a variety of methods for accessing Mesap data-objects within an R development environment. These methods return data-objects of native R data-types, which makes it easy to handle the parameter transfer and the processing of return-values in an R development context. Until today, the Mesap R Integration library offers methods for reading and writing Mesap timeseries and timeaxis data-objects as well as event records.

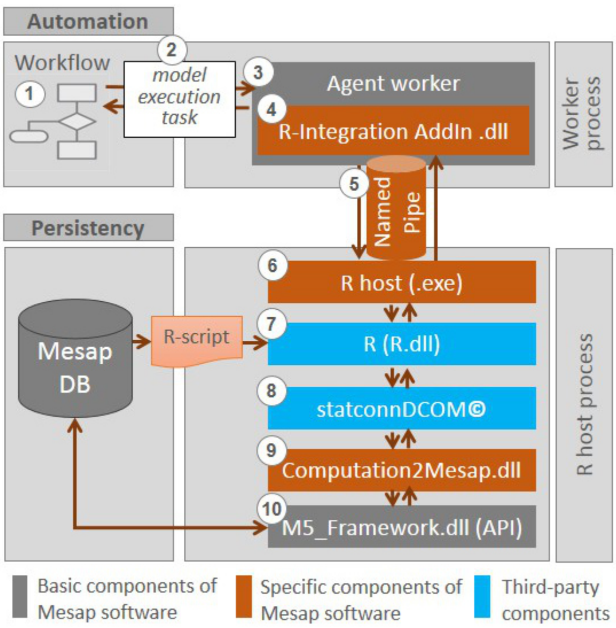

***Figure 2**: Technical architecture of Mesap R Integration.*

Figure 2 illustrates the architecture for the Mesap R Integration

Step one shows a Mesap automation workflow which can be used to embed R or Matlab computations in a business process and defines how and when the R-script will be executed. As soon as the specified point within the workflow is reached, a so-called model execution task is launched and the corresponding activity “start R-Modelling task” is executed. The Mesap automation component forwards a couple of execution parameters together with the model execution task to the agent worker, which represents the executing unit in the Mesap software framework.

One forwarded parameter corresponds to the R-script, which is persisted in the Mesap database. The other parameters represent input parameters which are defined in the R-script, e.g. dates, numbers or Strings, and which influence the computations in the script. These values can be used to parameterize the respective functions in R. Encapsulating R-method executions in working tasks provides full flexibility and allows multi-level computations and combined workflows with other Mesap tasks. Furthermore, each R or MATLAB® script can be used in various contexts and different business workflow processes.

The execution component Mesap Agent worker now calls the R-Host process via named pipe communication. This design allows executing units to run on different servers which makes the execution of R or MATLAB® models highly scalable and allows for parallelized execution of multiple models. The R-Host process assumes R-function calls and passes them on as batch calls towards the R.dll together with the R-script and input parameters defined in the model execution task. Since the Mesap Agent worker, as until today, is a 32-Bit program, the named pipe is used in order to allow the communication with the 64-Bit R application. As a result of this design decision, maximum RAM can be used to process the R and MATLAB® models.

The statconnDCOM© [10] component, as shown in step eight of Figure 2, is a third-party software that is used as middleware in order to integrate R in a Microsoft Windows application. Its primary task is to execute the R-script and the translation into R data-types.

The Mesap component Computation2Mesap.dll translates R function calls into the Mesap API (M5_Framework.dll) which in turn delivers the Mesap data-objects such as timeseries or event records from the Mesap database. Thereby, time resolutions, time zones, and measurement units are evaluated for the requested data objects by the Mesap 5 Framework. The database access via Mesap 5 Framework API is optimized for highly efficient timeseries exports and transformations as well as event record queries, providing very fast data access and transformation to the Mesap R and MATLAB® Integration.

The architecture for Mesap MATLAB® Integration follows the same principle as described in Figure 1 for the Mesap R Integration. The main difference is that the MATLAB® programs are not processed in form of text-based scripts but as a compiled dynamic link libraries (dll). The compilation is done before uploading the program to Mesap using the native MATLAB® Compiler. The host process unpacks this program-dll and runs it on the Mesap server in a MATLAB® Compiler Runtime (MCR). Only the MATLAB® Compiler Runtime needs to be installed on the executing server in order to be able to run a MATLAB® program. This runtime environment is available for free in contrast to the software needed to write and compile the script. Hence, there is no need to buy additional licenses to run MATLAB® models on the Mesap server.

4. Results

Performance tests for Mesap R Integration

Table 1 shows performance measures for reading and writing timeseries data with the Mesap R Integration. This experiment illustrates that the performance of the Mesap R Integration scales very well with the number of timeseries values, both for reading and writing data. This is an important observation with regard to the *SmartEnergyHub* scenario, in which optimization and forecasting models have to be able to deal with a large number of input and output values.

Furthermore, the experiment results indicate that accessing fewer timeseries with a large number of values is faster when compared to accessing a large number of timeseries which each holds few values. This is the same for reading as well as writing processes. The reason for this is the Mesap timeseries engine which has an optimized data structure that allows for data in the same timeseries to be treated as part of the same data object.

When comparing the performance of writing and reading values, it becomes apparent that reading is much faster than writing data. The reason for this lies in the overhead for checking and comparing existing values in the database when writing data. Also, Mesap adds meta-information whenever data is written into the database, such as a timestamp and source information, in order to make data changes transparent and comprehensible for the user.

Table 1: Performance measurements for reading and writing timeseries values with Mesap R Integration.

No	case	timeseries	values	s	values/s
1	read	1	35,064	1	42,246
2	read	10	350,640	6	58,440
3	read	1	1,016,832	18	55,717
4	read	97	3,398,880	58	58,601
5	write	1	35,064	11	3,148
6	write	10	350,640	106	3,308
7	write	1	1,016,832	561	1,813
8	write	97	3,398,880	992	3,429

Performance tests for Mesap MATLAB® Integration

Table 2 contains the experiment results for Mesap MATLAB® Integration. When comparing the results to Mesap R Integration it is notable that Mesap R Integration outperforms the Mesap MATLAB® Integration in almost all investigated cases, especially when it comes to reading values from the same timeseries object. In case three, where about one million values are read from the same timeseries object, Mesap R Integration is even 50% faster than the MATLAB® Integration.

A possible reason for this performance difference could be that the Mesap R Integration uses the native R data-type Posixct to store timeaxis information, while timeaxis in the Mesap MATLAB® Integration are stored as String data-types. However, the performance advantage of R does not increase with neither the number of processes values nor with the number of timeseries objects. Therefore, Mesap MATLAB® Integration, even though slightly slower than the Mesap R Integration, can still be a valid alternative.

Table 2: Performance measurements for reading and writing timeseries values with Mesap MATLAB® Integration.

No	case	Timeseries	values	s	values/s
1	read	1	35,064	1	36,909
2	read	10	350,640	5	70,128
3	read	1	1,016,832	27	37,521
4	read	97	3,398,880	57	59,214
5	write	1	35,064	12	2,851
6	write	10	350,640	115	3,049
7	write	1	1,016,832	544	1,869
8	write	97	3,398,880	1186	2,867

5. Conclusion

Balancing demand and supply is one of the key challenges in the future energy system. To achieve this goal, new information and communication technology, such as the *SmartEnergyHub*, is needed in order to be able to collect large amounts of sensor data from assets and to optimize and automatize the energy management in large infrastructure units.

We introduced Mesap, the operational energy datawarehouse, as a basis for data handling in the *SmartEnergyHub.* Mesap is highly flexible and adaptable to many business cases in the energy sector.

We further demonstrated how powerful modelling software such as MATLAB® and R can be connected to Mesap in order to provide a generic and efficient data analysis, as well as optimization and forecasting methods. The performance tests show that data access from the Mesap R and MATLAB® Integration scales very well with the number of values and that, even though the Mesap R Integration performs slightly better than the Mesap MATLAB® Integration, the performance advantage is stable in the number of values and data objects. This makes Mesap R Integration an appealing alternative to Mesap MATLAB® Integration, especially when taking licensing costs into account.

In summary, the Mesap framework allows for generic and powerful data analysis and mathematical modelling which makes it an ideal candidate for data management in the yet evolving Smart Energy business context.

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Technology issues and solutions in Smart Grids

SmartER Europe 2015

Flexible conventional power plants in smart grids – quo vadis?

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Abstract: In the ongoing discussions about the future energy system, smart grids are seen as a promising solution to match renewable energy production and energy consumption by using sophisticated information and communication technologies. However, flexible conventional power plants which play an essential role in stabilising the current energy system especially in terms of compensating the intermittent generation by renewables are not considered in these discussions. The aim of this paper is to propose approaches on how to properly integrate flexible conventional power plants into the future energy system by structurally combining virtual and conventional power plants in order to create reliable virtual power plants. It is shown that by extending the information exchange an almost constant power output can be provided by the reliable virtual power plant independently of the actual weather situation. Additionally, this structural adaptation is not only used to improve the control performance in terms of power output but also allows a decoupling of energy trading mechanisms by introducing compensation control power as a new service within the energy market explicitly dealing with the intermittent generation by renewables.

1. Introduction

Analogously to the electrification of railways, smart grids aim at improving the energy system by adding new technologies, i.e. information and communication technologies (ICT), to an existing infrastructure. The main goal of smart grid applications lies in balancing the power production and consumption in a decentralised way by means of demand side management strategies shifting the energy consumption to time periods in which the grid is fed by renewable energy sources [1].

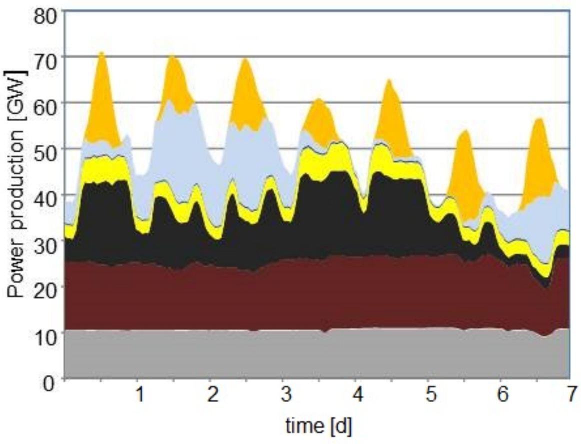

Figure 1: Power production of one week in April, 2014; relevant colours: black indicates hard-coal fired power plants, orange shows PV production and light blue indicates power produced by wind (sources: [2], [15], internal STEAG calculations)

Figure 1 indicates the share of the respective power producing sectors to the power production of one selected week in April 2014. The figure shows that, due to the low specific fuel costs, nuclear and lignite-fired power plants (grey and brown) act as base-load operating power plants whereas, due to the high fuel prices, almost exclusively must-run gas-fired power plants are in operation. Consequently, mid-load operated hard-coal fired power plants have to provide fast load changes including services (primary, secondary or tertiary control) to compensate fluctuations in the grid caused by intermittent renewable energy supply (PV a wind) [11]. Hence, from the perspective of renewables demand side management tasks are currently realised in an aggregated way by the load variations of these flexible power plants.

In particular, conventional power plants increasingly need to deal with prediction errors regarding the intermittent production by renewables of some gigawatts even on short notice [2] instead of purely focussing on reserve control power for compensating unexpected outages of large producers or consumers as initially intended.

However, despite the essential role of flexible and reliable conventional power plants in the current energy system, these power plants do not play any role in the current smart grid considerations. Taking the changing role of these power plants into account with the emerging focus on compensating intermittent generation, two questions arise:

- Are the current control and communication structures well suited to deal with the current and even evolving requirements of the renewable-driven energy system or are there structural adaptations which enable flexible conventional power plants to meet these requirements in an even more efficient way?

- Is the current energy market well suited to deal with the compensation of intermittent power generation or do adapted control structures allow for appropriately adapting the related energy trading mechanisms?

The focus of this paper lies in proposing concepts for suitably integrating flexible conventional power plants into smart grids by structurally combining renewable and flexible conventional power plants resulting in *reliable virtual power plants.*

The strategy uses the fact that in the current operation of conventional power plants sophisticated ICT solutions can hardly be found and services like reserve power and load changes either rely on purely analogue measurements (i.e. frequency of the grid) or very simple communication infrastructures. Consequently, by considering a conventional power plant as a structurally coupled counterpart to a virtual power plant (VPP) consisting of distributed renewable energy sources (RES) [3][13] and by using additionally available data such as weather forecasts as well as relevant aggregated data provided by the VPP an efficient compensation of the intermittent generation can be obtained. Suitable concepts are given by model-based control strategies, e.g. feed-forward disturbance rejection [4][10] or model predictive control (MPC) [6][7].

As a second effect this strategy enables adaptions of the energy trading mechanisms. Instead of the necessity of using day-ahead transactions, intraday auctions as well as control power to counteract the prediction errors in the RES production, *compensation control power* can be introduced as a new service provided by flexible conventional power plants purely focussing on compensating the intermittent generation by renewables.

The paper is organised as follows. In Section 2 the current role of flexible conventional power plants used in mid-load operation is described and state-of-the-art flexibility measures are introduced. Section 3 proposes concepts to combine flexible conventional power plants and virtual power plants showing potential benefits of establishing conventional power plants in future smart grids. Based on these concepts a new trading model introducing compensation control power as a new service is described in Section 4.

2. Flexible power plants

2.1. Current role in the energy system

Due to the lack of sufficient storage capabilities in the current energy system the power production and power consumption need to be balanced at any time. Therefore, the stability of the grid currently relies on the capability of flexible conventional power plants to provide fast load changes and control services (primary, secondary or tertiary control) in order to compensate unexpected outages of power plants or deviations in the power consumption. Additionally, the requirements on the flexibility of these plants have been recently significantly increased due to the necessity of counteracting the volatile energy production by renewable sources [11].

Beside this load change flexibility which is inevitable for preserving the stability of the grid, measures such as optimised start-up as well as reduction of minimum load likewise play an important role in the current system but more with the focus on running conventional power plants in a cost efficient way. All of these measures are briefly described in the following section.

2.2. Flexibility measures

2.2.1. Fast load changes and control power

To counteract unpredictable events such as outages of power plants or prediction errors regarding the energy consumption and to counteract the volatile energy production of intermittent sources, fast load changes and control services need to be provided by reliable and flexible energy producing units.

The measures to improve load gradients as well as pre-qualifying the power plant for providing control power very often simply adapt the control algorithms in the unit control system and use intrinsic storage capabilities, e.g., throttling of turbine valves or control of the extraction steam flow [8][12].

Severe modifications of processes can be generally avoided. Hence, as the current control algorithms of conventional power plants are rather designed to guarantee stability than focussing on the transient behaviour in terms of fast load responses the potential and the chances for the success of these optimisation measures are generally promising.

2.2.2. Optimised start-up and reduced minimum load

Both optimised start-up and reduced minimum load have the same goal, namely, to reduce costs which would occur due to starting the plant [9]. On the one hand the optimisation of the start-up procedure aims at reducing the oil consumption during the start-up process and making the process reproducible in terms of timing until synchronisation in order to avoid unnecessary waiting times.

On the other hand, reduced minimum load aims at completely avoiding the costs for start-up by bridging limited time intervals in which the plant would have been normally shut down due to low energy prices. Hence, if the minimum load is decreased the loss due to operating the plant in these time intervals is decreased as well.

2.3. Communication infrastructure

In the current operation of a conventional power plant, ICT only plays a secondary role especially when it comes to external data exchange. Services like reserve power and load changes either rely on purely analogue measurements (i.e. frequency of the grid) or very simple communication infrastructures which very often still require manual operations, i.e. load requirements provided by the load dispatcher are not directly forwarded to the unit control system but to the operator which has to manually set the necessary actions.

3. Compensation of intermittent generation

3.1. Current mechanism

The current mechanism to compensate intermittent generation provided by RES (PV and wind) uses a mix of two measures:

- Control power for compensating sudden prediction errors (primary, secondary, tertiary control).
- Rescheduling measures which are based on day-ahead and intraday transactions on the energy spot market due to refined forecast information [14].

Figure 2 shows the current situation in terms of primary control. The goal of the control loop is to keep the frequency f of the grid in a surrounding of the respective set-point f_{SET}, i.e. 50 Hz in the European grid. Based on the deviation between the desired frequency and the actual frequency of the grid, the controller provides the set-point $P_{SET,FCPP}$ adopted by the unit control of the respective controllable and flexible conventional power plants (FCPP) which together with the uncontrollable conventional power plants P_{UPP} and the energy produced by VPPs P_{VPP} and the remaining RES P_{RES} gives the complete power output P_{OUT} of the system. G(s), $G_v(s)$, $G_r(s)$, $G_g(s)$ and C(s) denote the respective transfer functions [4] of the FCPP, the VPP, the RES, the grid and the controller.

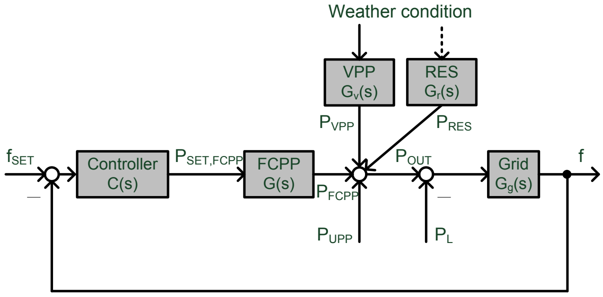

Figure 2: Primary control

As long as the power output P_{OUT} of all producing units coincides with the overall power consumption P_L the frequency does not vary and maintains the respective set-point f_{SET}. However, unexpected outages of conventional power plants or large consumers, and, increasingly important, deviations in the prediction of the power production provided by renewables affect the frequency and force the primary controller to establish a new operating point by adapting the power output of the FCPPs. As the primary controller is a static controller due to stability reasons, a steady-state error needs to be accepted. In order to drive the frequency to the desired set-point f_{SET} the secondary controller (PI controller) does not only take the frequency into account but also the exchange energy between concerned areas.

3.2. New approach

3.2.1. Motivation

The approach proposed in this paper aims at structurally combining unreliable renewable energy sources (PV and wind) aggregated within a virtual power plant (VPP) and reliable and flexible conventional power plants in order to improve and simplify the compensation of intermittent generation. Currently, the power generation of the renewables and the FCPP is indirectly coupled by means of the frequency of the grid (see Figure 2) which is a clear indicator whether or not the power production and power consumption are balanced. However, considering renewables a direct coupling is possible using a more involved information exchange between the VPP and the FCPP.

The underlying idea is that due to the increased energy production by renewables the control services should be split into:

1. Rescheduling and conventional control power (primary, secondary, tertiary control) for dealing with unpredictable outages of energy producing units or large consumers, or deviations in the predicted energy consumption.
2. Compensation control power for exclusively dealing with intermittent generation by VPPs which uses additionally available ICT-based information within the control loop.

In the following three approaches are described considering the second item. All of these approaches consider the FCPP and the VPP as a single energy producing unit which, henceforth, is denoted as *reliable virtual power plant (RVPP)* illustrating the idea that the varying production of the VPP is immediately compensated by the FCPP. Hence, the power output of the overall RVPP remains constant independently of the actual weather conditions and, therefore grid-related services (primary, secondary and tertiary control) as well as the necessity of rescheduling measures for the respective power plants can be reduced.

The adapted primary control loop is depicted in Figure 3 where the VPP and the FCPP are now represented by a single block.

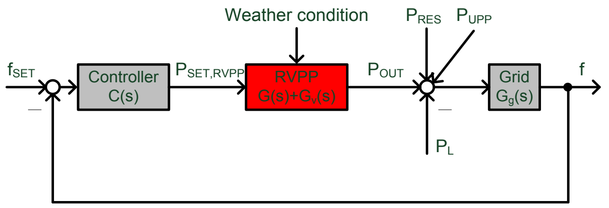

Figure 3: Adapted primary control loop

3.2.2. Indirect power coupling

A simple control structure for realising the RVPP is shown in Figure 4. Here, instead of the frequency the power output provided by the FCPP and the VPP is fed back and compared to the external set-point $P_{SET,RVPP}$.

The structure indicates that the variations of the power output coming from the renewable sources can be seen as a disturbance of the control loop. Consequently, the controller needs to be designed to provide suitable disturbance attenuation properties. This can be implemented by, e.g., suitably tuning a standard PI controller [5].

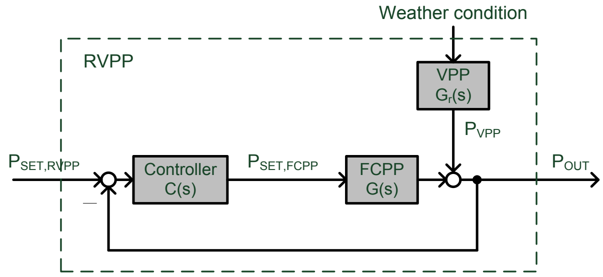

Figure 4: Simple closed-loop control

3.2.3. Direct power coupling using model-based feed-forward disturbance rejection

As the dynamics G(s) of the FCPP are generally known there are more involved control structures which can take G(s) into account in order to more efficiently compensate the effect of the disturbance caused by the VPP by means of additional feed-forward control [4][10].

This is depicted in Figure 5. Here, an additional path has been added which adapts the input signal of the FCPP $P_{SET,FCPP}$ to the current power output P_{REN} of the VPP. The feed-forward structure uses the inverse model of the FCPP and an additional filter F(s) which is generally necessary to get a proper realisation of the inverse transfer function of the FCPP and to face input constraints [4].

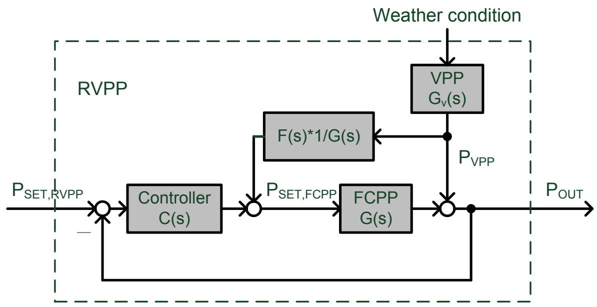

Figure 5: Model-based control using feed-forward disturbance rejection

3.2.4. Direct power coupling using model-predictive control

An even more involved structure is presented in Figure 6 using model-predictive control [6] where the controller, based on equidistantly updated input data, solves an optimisation problem to produce an optimal output $P_{SET,FCPP}$ with respect to predefined cost functions.

Beside the evaluation of the deviation between the current status of the system P_{OUT} and the requested set-point P_{SET} the input data can be chosen arbitrarily depending on the control goal. Hence, in the scenario considered in this paper, suitable information is given e.g. by weather forecasts and the current weather conditions affecting the VPP as well as the power output of the VPP.

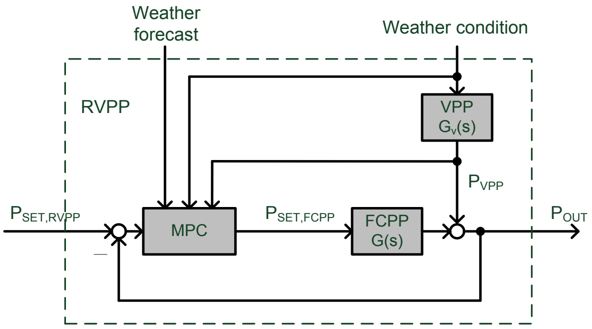

Figure 6: Model-predictive control

3.2.5. Simulations

The following simulations compare the simple closed-loop control (indirect power coupling) and the model-based control strategy using feed-forward disturbance rejection (direct power coupling) to illustrate that additional information and a suitable integration of this information can significantly improve the performance of the closed-loop system. In this example, the set-point $P_{SET,RVPP}$ to be followed by the RVPP is given by 450 MW, where initially

$$P_{FCPP} = 400\ MW$$
$$P_{VPP} = 50\ MW$$

holds. The FCPP is described by the third-order transfer function

$$\mathrm{G(s)} = \frac{1}{(1+60s)(1+60s)(1+60s)}.$$

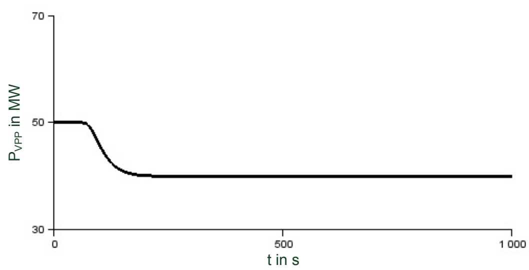

Figure 7: Decreasing power production by the VPP

The resulting RVPP is subject to a decreasing power production of the VPP by assuming that after 60 s the wind conditions change and the power output is quickly reduced to 40 MW (see Figure 7). By means of the PI controller

$$C(s) = K_P E(s) + \frac{K_I}{s} E(s)$$
$$E(s) = P_{SET,RVPP}(\mathrm{s}) - P_{OUT}(\mathrm{s})$$

with the controller parameters K_P=2.5 and K_I=0.01 the trajectory of the resulting power output of the RVPP with indirect power coupling is depicted in Figure 8.

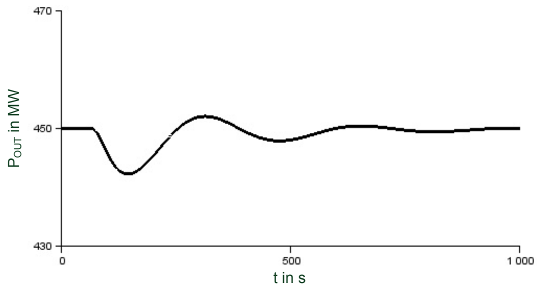

Figure 8: Power output of the RVPP using the simple closed-loop control

Stationary, the power output P_{OUT} matches the set-point but the transient behaviour shows large oscillations due to the change in P_{VPP} and the slow dynamics of the FCPP.
This behaviour can be improved by model-based control using feed-forward disturbance rejection as considered next. With the third-order filter

$$\mathrm{F(s)} = \frac{1}{(1+5s)(1+5s)(1+5s)}$$

the resulting power output is illustrated in Figure 9 which clearly shows a significant reduction of the oscillations during the transient phase.

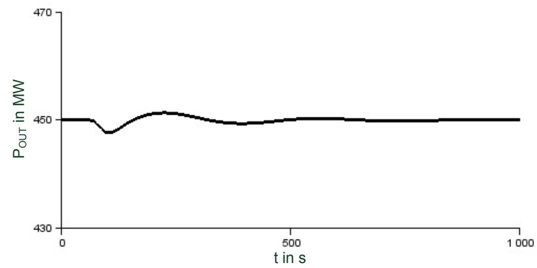

Figure 9: Power output of the RVPP using model-based control with feed-forward disturbance rejection

A drawback of this structure is given by the fact that depending on the system dynamics large input signals might result as shown in Figure 10. This causes problems if the input of the system is subject to constraints which occurs in almost all practical applications.
To avoid this issue the filter F(s) can be adapted accordingly which, however, degrades the control performance. Alternatively, flexibility measures using the intrinsic storage capabilities of FCPPs as briefly described in Section 2.2.1 can be applied to circumvent this problem (see Figure 11) or forecast information can be used to be able to start the required control actions already in advance.

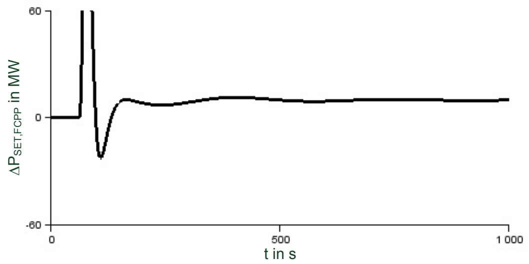

Figure 10: Plant input signal using model-based control with feed-forward disturbance rejection

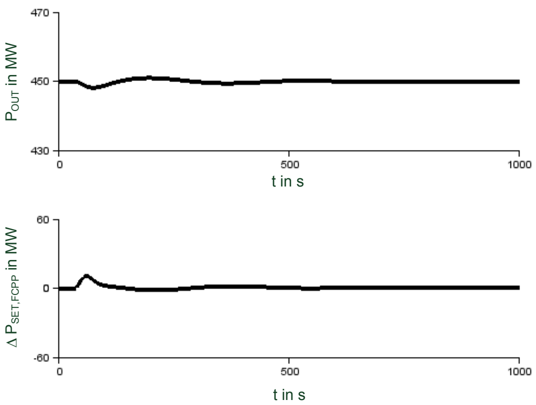

Figure 11: Potential power output and plant input signal when using throttling of turbine valves and control of the extraction steam flow in a coordinated way as additional measures

4. Compensation control power

In the current energy market the compensation of prediction errors in terms of energy production by RES (PV and wind) is mainly based on short-term transactions, i.e. day-ahead or intraday auctions based on refined weather forecasts, and on control services [2][14].

By considering a splitting of the control power market (see Figure 12) into

- the conventional provision of primary, secondary and tertiary control served by FCPPs including rescheduling measures which explicitly deal with outages and fluctuating energy consumption as well as RES which are not served by RVPPs, and
- a new compensation control power service provided by RVPPs which exclusively deals with intermittent generation by PV and wind,

transactions on the energy market required for compensating the weather-related prediction errors can be reduced. Moreover, new incentives for flexibility measures for conventional power plants can be set.

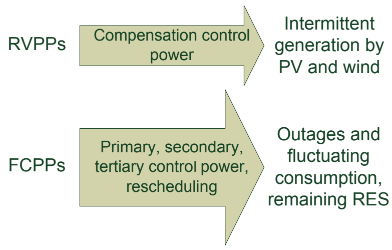

Figure 12: Decoupling of the control power market

However, the realisation of the RVPPs requires a distinct allocation of FCPPs (a single unit or a pool of FCPPs) to the respective VPPs where load specific requirements and even geographical aspects need to be taken into account. In the future, especially load specific requirements become increasingly challenging due to the increasing installation of PV and wind sources making a suitable clustering even more challenging.

5. Conclusion

In this paper concepts considering a structural combination of flexible conventional power plants and virtual power plants have been proposed which aim at efficiently compensating the volatile power production by PV and wind. The simulation results illustrate that the resulting reliable virtual power plant is capable of providing an almost constant power output by means of an involved information exchange between the conventional and virtual power plant. Consequently, grid-related control services and rescheduling measures including the relevant transactions on the energy market which are necessary to compensate the intermittent power production by PV and wind can be reduced.

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Smart Metering: Success depends on selecting the right information and communication technology

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Abstract: Smart meters will be deployed in Germany and other European countries. Various scenarios for the rollout have been and will continue to be discussed. Smart meters offer transparent energy consumption in homes and businesses and enable targeted energy savings. These benefits can also be exploited by energy providers in order to create dynamic billing rates structured around individual user profiles containing data such as energy consumption and timeframes. Against this background, finding the right underlying communication technology for the smart grid is an extremely complex challenge. A new process model helps structure the decision process and thus creates transparency. The article describes this new process model and its application with special focus on the situation in Germany.

1. Introduction

Today's prevailing smart meter roll-out scenario was outlined in a ground-breaking cost-benefit analysis conducted by consulting firm Ernst & Young [1]. Titled "The Germany Roll-Out Scenario Plus," the study points out that smart meters will be installed mainly in new construction and renovation projects. Residences and small businesses that consume less than 6,000 kilowatt hours per year will also be equipped with communication-capable meters. Furthermore, all existing and future renewable energy and co-generation facilities, as well as controllable consumption devices as defined in § 14a of the German Energy Act (EnWG) [3], will be furnished with smart meters.

More than 10 million of these installations will require connecting the smart meter to a smart meter gateway (SMG). The meter initially transmits its data to the SMG via a local connection. The SMG then addresses and analyzes the data and forwards it to a control center or direct to the authorized market partner. This is not the only information that flows through the SMG however. The amount of energy fed into the grid from solar or biogas systems also flows across the network, in addition to switch commands destined for these systems. In other words, energy management.

2. The challenge of communication technology decision

The smart grid requirements outlined in the Germany Energy Act, plus those stipulated by the German Federal Office for Information Security (BSI), underscore the challenges facing energy providers. With the EnWG, the German government aims to foster competition in the electricity market, and over the long term in the natural gas market. Stand-alone roles have thus been defined for market participants such as distribution network operators, metering service providers, energy producers and energy providers.

The BSI mandates a high degree of security as outlined in its TR-03 109-1 guidelines [2]. These requirements lead to the transmission of large volumes of data overhead in the wide area network (WAN). To cite one example, when transmitting a few bytes of data for the meter reading, the security certificate and encryption protocol information that has to be exchanged amounts to several 100 bytes.

This illustrates just how complex the decision is when selecting the right communication technology for the WAN, which establishes the connection between the SMG and the control center. In principle, both mobile wireless technology and powerline communication (PLC), which transmits data over the electrical lines, are viable alternatives.

PLC offers the advantage that it can be used through the network operators since this transmission medium belongs to them in most cases. There are two versions of PLC: narrowband and broadband.
Narrowband PLC has a transmission range of up to one kilometer. On the other hand, the limited bandwidth (up to 500 kHz) means that only extremely low data rates of up to 1 Mbit/s are possible. The upside to this alternative is the cost: capex (up-front investment) and opex (on-going operational costs) are less than the broadband version since it requires signal repeaters. This is because the range is limited to several hundred meters. The upside to broadband PLC is the significantly higher transmission rate of 100 Mbit/s. With all PLC versions, reception is relatively simple, even in the basement where most meters are installed in Germany.

Wireless technologies such as GSM/GPRS offer an alternative to PLC. This second-generation technology is the most widely used mobile communication system in the world. As a result it provides extensive network coverage in Germany as well. That means GPRS can already be implemented as the underlying smart grid communication technology. Although the upfront investment for GPRS is low, grid operators incur on-going usage fees for the service. In principle, this is an issue that occurs with any mobile communication technology. Another consideration is the fact that these technologies are essentially shared media, which means the frequency range is used by all of the network participants.
This can lead to situations in which there is no capacity to transmit the SMG data if a high number of users access the network simultaneously. GSM/GPRS also has a comparatively low transmission rate of up to 40 Kbit/s. And at 600 to 800 milliseconds, latency (transmission delay) is extremely high.
The same applies to UMTS. 3G mobile technology furthermore offers significantly less network coverage than GSM/GPRS. And when it comes to signal penetration to individual SMGs located in basements, this mobile technology leaves something to be desired.

Compared to GSM/GPRS, the upside to UMTS is the high transmission rate of up to 384 Kbit/s and latency of around 150 milliseconds.

Using this criteria, the fourth-generation LTE mobile technology clearly leads the pack. Latency during connection set-up is 50 milliseconds, after which it averages between 10 and 15 milliseconds. With a transmission rate of up to 100 Mbit/s, LTE also leaves the other mobile technologies behind in this category. LTE is considered future-proof given that it plays a major role in the federal government's broadband strategy. However, and this is the catch, rural areas currently lack full LTE coverage.

3. A process model for the technology decision

The bottom line is, a comparison of the pros and cons of the various communication technologies fails to highlight a clear favourite. What the comparison does reveal is that the selection of the right smart grid communication technology depends on the environment of the individual scenarios. With this the authors propose a five-stage process model that ensures optimal transparency and the best chance for success when selecting smart grid communication technologies. Simply put, the first step involves identifying the available technologies, after which an assessment is carried out to determine if a specific technology is suitable for the region being analysed. The third and final step involves examining to what extent the technology matches the future requirements of the energy provider.

3.1. Communication profile definition

The initial stage is used to ascertain the traffic volume and the communication profile, which basically involves assessing which application scenarios the communication technology has to manage. That could mean transmitting register, billing rate, control or load profile data.
Closely linked to this is the associated communication profile, which involves the question of what data needs to be exchanged, with whom and for what purpose. The issue of feeding energy into the grid from renewable sources also plays a role here. This step furthermore includes reviewing the corresponding BSI requirements to determine if they can be met.

3.2. Energy region analysis

The second stage is an analysis of the energy region that needs to be covered, with a focus on the distribution of the SMGs. An initial survey sheds light on the number of dwellings and small businesses in the cities and communities, as well as in new housing developments. The plan draws on statistical values gleaned from an analysis of comparable residential and commercial structures to yield an approximation of the number of SMGs that will be needed.

3.3. Roll-out strategy

Stage three is used to establish a roll-out strategy, or road map, which relies on the following thought process: from a business standpoint, in a full roll-out it makes more sense to implement a new communication technology since the return on investment is quicker than with a gradual roll-out. In the latter case, under some circumstances this can lead to the occasional underutilization of a special-purpose network infrastructure because not enough dwellings are connected.

Independent of this fundamental correlation, the roll-out strategy also has to take the regulatory requirements into consideration. This also applies to the roll-out regulations once they have been approved, which could happen this year. These aspects will then be consolidated with the corresponding target groups to determine the scope of the roll-out plan, including the establishment of a comfortable timeframe.

3.4. Technology assessment

Stage four includes the technology assessment based on a technical and economic criteria catalog, as well as a risk analysis. The selection of the technology that meets the transparency and capacity requirements in line with the process model is then carried out in stage five.

The technical criteria catalog is tied to the examination of the basic pros and cons of the PLC and mobile communication technologies.
For obvious reasons the data rate has special significance in the decision process. With mobile communication technology, network coverage is another key factor given that it can vary widely depending on the technology used and the energy region being served.

Accessibility then comes into play if many of the meters that need to be connected within the service area are located in basements. The issue of the future development and scalability of the smart grid also needs to be factored into the decision, not to mention whether the technology is interoperable with other existing and future standards.

The business criteria catalog focuses extensively on the terms capex (capital expenditures) and opex (operating ex-penditures) and analyzes the economic dependencies in detail. In the case of PLC, capex is relatively high. This can be explained by the fact that the networks have to be equipped with modems. With broadband PLC, the installation of repeaters adds to the cost. This alternative offers low opex however. With mobile communication technology, the situation is exactly the opposite. While capital expenditures are low, the usage fees incurred by the grid operator significantly drive up the operating costs. This also raises the question of whether this could lead to dependency on a single provider in a business-critical area.

3.5. Risk analysis

As part of a final but important step before selecting the technology, a sufficient risk analysis is carried out. With mobile technology one of the issues is when the license for a specific technology expires. In the case of GSM/GPRS, this could occur within a few years. There is also the risk that future services will be limited by restricted data transmission speeds, such as with narrowband PLC, or increased latency.

A further risk relates to a reluctance to invest, such as when the necessary regulatory environment or legislation is lacking. Problematic as well is when a specific technology fails to win the backing of key standards committees. Finally, there is always the danger that a service will not be accepted by the market, in other words by the customers.

4. Evaluation in two scenarios

Two ideal types of scenarios allow us to clearly illustrate how the process model approach can be utilized. In the so-called green field scenario, the aim is to connect a small rural town, far removed from any larger community, to a smart grid. The communication profile and traffic volume analysis are easy to generate. The service area analysis is also not particularly challenging. More complicated however is the technology evaluation, which requires examining the coverage of the mobile network while taking into account the distance of the individual smart meters and SMGs, an issue that is important when utilizing PLC.

Another factor is the density of the meters that have to be connected. This impacts the capex and opex analysis for the various alternatives. The results of the process model indicate that mobile communication technology is the most likely alternative for the green field scenario.

In the second example, the commuter belt scenario, the task is to connect a new development within a densely populated community on the edge of a major city to a smart grid. In this case, the sheer number of dwellings alone, including those with high consumption, and the numerous communication profiles, results in more traffic volume. That permits more dense installation of the SMGs, which prevents the network from having to overcome longer distances. This aspect plays a key role in the technology evaluation, which suggests that PLC is the best choice.

These two scenarios are intended to merely sketch out a process model rather than to serve as an overall, hard and fast check list. Considering the vast number of conceivable scenarios and technical and business parameters, there is no right or wrong decision pattern. This is especially true for an industry that continues to experience economic, technical and political unknowns. Nevertheless, a systematic process model such as the one described here provides a foundation for adequately addressing the issue of selecting the right communication technology, creating a transparent decision-making process and more importantly ensuring a reliable result that will promise success.

5. Conclusion

The selection of the suitable wide area communication technology is of major importance for a successful rollout of smart meters. The decision is influenced by technical and commercial aspects but also the distribution of smart meters in the power grid. In the article the authors propose a process model for the communication technology selction which implicates all the influencing factors.

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Business Models and competition analysis in Smart Grids

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Levelized Cost of Storage Method Applied to Compressed Air Energy Storage

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Abstract: This paper presents a method to calculate the levelized cost of storage (LCOS) dependent on the annual energy output. To allow comparing different storage technologies independently from costs for electricity supply, these costs are fixed at 0 € k h This allows a pure technology comparison and thus the LCOS serves as a first indicator for potentially profitable operation modes of different storage technologies. The method is applied to diabatic Compressed Air Energy Storage (dCAES) and adiabatic Compressed Air Energy Storage (aCAES) with a storage capacity of 1 GWh, a charging duration of 10 h and discharging duration of 6 h. The results show that mean LCOS values decrease strongly with increasing cycling of the storage. With a monthly cycling of the storage system (meaning that the energy storage is completely charged and discharged once a month) the LCOS are 0.36 € k h for d AES and 0 60 € k h for a AES ith a higher utilization the LCOS of aCAES are lower than the LCOS of dCAES. At daily cycling both technologies have an LCOS of about 0.10 € k h

1. Introduction

There are a number of calculation methods and several studies on the costs of electricity storage. In most studies the economics of storage systems are described and analyzed, but not in great detail. The focus of most economic analyses is on storage systems within a certain supply scenario. E.g. in [1], the supply task is described by a fixed number of cycles per day or per year. In other studies (e.g. [2]), the supply task of the storage is described by defining short-term and seasonal storage applications. The different calculation methods used have some drawbacks:

- With regard to storage systems, power and capacity need to be distinguished. The ratio of power and capacity has a high influence on the cost but is fixed in most studies.
- Storage operation plays a major role in the overall cost of storage systems. Some studies define different tasks for storage systems in the economic calculations impeding direct comparison.
- Costs for charging the storage influences operation costs considerably. Therefore, emphasis needs to be placed on this point.

In this paper some of the drawbacks of previous cost calculations of storage systems are overcome by:

- Accounting for the different components of storage systems by assessing the investment costs of all relevant components in order to enable independent scaling of charging, discharging and storage units;
- Presenting the levelized cost of storage (LCOS) method in dependency of the full load hours of the turbine and a consideration of possible operation modes;
- Placing special emphasis on operation and charging cost to analyze their influence on the overall storage cost as well as to simplify the comparison of LCOS of different storage options.

2. LCOS Method

The net present value is a common calculation method to compare investments. Due to the fact that the feasibility of an investment in energy technologies is highly dependent on the economic surroundings, e.g. market design and competitors in the field, it is necessary to look at the costs of the technology. Especially when analyzing storage technologies in an uncertain market environment with uncertain revenue streams, it is more valuable to compare the cost for storing each unit of energy (in kWh). Reference [3] uses the net present value method as a basis for the calculation of the levelized cost of electricity (LCOE). Similar to [4], where the LCOE is calculated for renewable energy technologies, the net present value method is used as a basis for the LCOS calculation.

The calculation of LCOS is described in (1). The numerator is composed of the capital cost *CAPEX*, as well as the yearly cost A_t of the storage at each point of time t in annual values over the lifetime n of the storage, discounted with the interest rate i. The numerator is divided by the sum of the energy output W_{out}, which is also discounted (as done in the LCOE calculation and described in [3]). The annual operation cost A_t is composed of the operation cost *OPEX*, the necessary reinvestments in storage components $CAPEX_{re,t}$ at the time t as well as the cost of electricity supply, which is determined by the electricity price c_{el}, multiplied with the sum of annual electricity input W_{in} (2). A recovery value of storage components is considered by R_n at the end of storage lifetime.

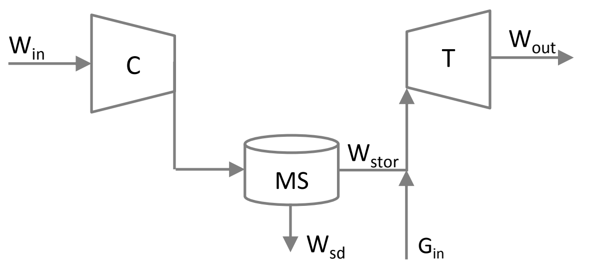
$$LCOS = \frac{CAPEX + \sum_{t=1}^{t=n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{t=n} \frac{W_{out}}{(1+i)^t}} \tag{1}$$

$$A_t = OPEX + CAPEX_{re,t} + c_{el} \cdot W_{in} - R_t \tag{2}$$

The LCOS is strongly dependent on the cost of electricity supply. To make the calculation comparable for different storage technologies independent from electricity purchase costs, the cost of electricity supply is fixed at 0 € k h and varied within the sensitivity analysis.

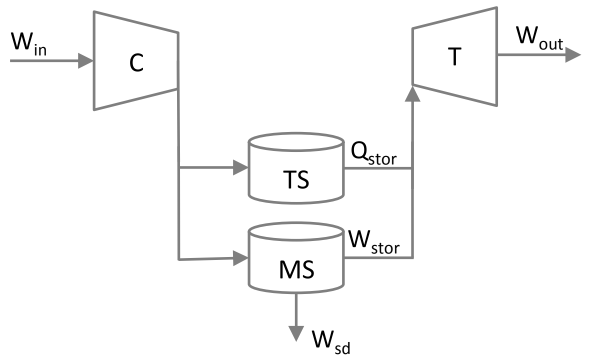
3. LCOS for CAES Technologies

In this section the technology specific considerations regarding the LCOS calculations for Compressed Air Energy Storage (CAES) systems are described. A diabatic (dCAES) system is composed of a compressor, a storage unit (e.g. a salt cavern) and a turbine. In addition, the adiabatic (aCAES) system comprises a thermal storage. Fig. 1 and Fig. 2 show schematics of components and energy flows for both CAES systems.



C Compressor MS Mechanical storage
T Turbine

Fig. 1: *Simplified schematic of a dCAES system*



C Compressor MS Mechanical storage
T Turbine TS Thermal storage

Fig. 2*: Simplified schematic of an aCAES system*

a) Components and Energy Flow

In this approach the cost for storage capacity and for power components are accounted for separately. The size of compressor and turbine refers to the power needed to charge the net capacity C_{net}, which can be calculated from the rated capacity C_r by multiplication with the depth of discharge *DoD* (3).

$$C_{net} = C_r \cdot DoD \tag{3}$$

In order to allow the comparison of storage technologies at different operation modes, the LCOS is calculated in dependency of the capacity utilization. Therefore, the electricity output W_{out} is calculated with regard to the full load hours of the turbine *FLH* and the turbine power P_{out} (4).

$$W_{out} = P_{out} \cdot FLH \tag{4}$$

The yearly number of cycles *cyc*, at which the plant is operated, is calculated by dividing the amount of full load cycles by the time of the process t_{disch} (5). The time for the discharging process is determined by the net capacity, divided by the turbine power P_{out}, which is multiplied with the share of power attributed to the air flow b_{mech} (6).

$$cyc = \frac{FLH}{t_{disch}} \tag{5}$$

$$t_{disch} = \frac{C_{net}}{P_{out} \cdot b_{mech}} \tag{6}$$

Due to the heat demand of CAES turbines, the energy needed to generate W_{out} is divided in mechanical energy from the storage W_{stor}, taking into account the share of energy coming from the mechanical storage b_{mech} (7) and energy from gas G_{in}, which is determined using the share of energy coming from the heat source b_{heat} and the efficiency of the combustion chamber η_{cc} (8). The electrical energy input W_{in} to obtain the required output is then calculated by adding the energy needed to replace the self-discharge W_{sd}, to the stored energy W_{stor} and by charging this figure with the efficiency of the compressor η_{in} (9).

$$W_{stor} = W_{out} \cdot b_{mech} \tag{7}$$

$$G_{in} = \frac{W_{out} \cdot b_{heat}}{\eta_{cc}} \tag{8}$$

$$W_{in} = \frac{W_{stor} + W_{sd}}{\eta_{in}} \tag{9}$$

b) Self-Discharge

One aspect which has not been regarded in previous studies is the impact of self-discharge on the cost of CAES technologies. Self-discharge occurs at times t_{sd} per year, when the CAES is neither being charged nor being discharged. The CAES stands still for the number of hours per year minus the duration of a full load cycle, multiplied by the amount of cycles per year (10). The duration of a full load cycle consists of the time to charge and discharge the storage.

$$t_{sd} = 8760 - \left(\frac{c_{net}}{P_{in} \cdot \eta_{in}} + \frac{c_{net}}{P_{out} \cdot b_{mech}}\right) \cdot cyc \tag{10}$$

It is assumed that the storage is always fully charged and fully discharged. The remaining time, the CAES is either at full state of charge or at lowest state of charge. This simplification is applied in order to make calculations comparable without referring to a specific operation mode.

It is assumed that the time when the storage unit is at its highest and at its lowest level is evenly distributed during the year. $W_{sd,f}$ represents the annual amount of energy that is self-discharged during the time the storage is fully loaded (½ t_{sd}). To calculate the amount of energy which is self-discharged during one cycle, the rated capacity C_r is reduced by the self-discharge rate r_{sd} and compared to the initial value C_r. To get the amount of annual discharged energy, this value is multiplied by the number of cycles per year (11).

$$W_{sd,f} = \left(C_r - C_r \cdot (1 - r_{sd})^{\frac{t_{sd}}{cyc \cdot 2}}\right) \cdot cyc \tag{11}$$

A similar calculation is performed to determine the energy loss by self-discharge during the times when the CAES is empty $W_{sd,e}$. Hereby, the rated capacity, reduced by the amount of *DoD*, is used to calculate the amount of energy that is still stored in the storage unit at its lowest state of charge (12).

$$W_{sd,e} = \left(C_r \cdot (1 - DoD) - C_r \cdot (1 - DoD) \cdot (1 - r_{sd})^{\frac{t_{sd}}{cyc \cdot 2}}\right) \cdot cyc \tag{12}$$

The sum of both amounts of self-discharged energy results in the total amount of energy lost through self-discharge W_{sd} (13).

$$W_{sd} = W_{sd,f} + W_{sd,e} \tag{13}$$

c) Cost Calculations

The capital expenditures (*CAPEX)* of the plant are calculated by the component specific CAPEX, which are multiplied by the power of the components or the storage capacity respectively. In the case of an adiabatic system, the cost for the heat storage tank needs to be calculated, which can be estimated with 25 % of the CAPEX of all other components [5].

The reinvest of the compressor is included in the calculations after the compressor lifetime of 25 years. The operational expenditures (OPEX) are calculated by summing up several specific costs (14): The power specific $OPEX_{spec,P}$ is multiplied by the average power of the compressor and turbine, the energy specific $OPEX_{spec,e}$ is multiplied by the average energy flow. The cost for startup c_{st} is multiplied by the power of the compressor and turbine as well as the number of cycles which are run per year. The cost for electricity c_{el}, is multiplied by the energy input, the cost for the natural gas c_{gas}, is multiplied by the amount of thermal energy needed for the process. In addition, the cost of CO_2 certificates c_{CO_2} is included by multiplying it with the amount of input energy and with the conversion factor eq_{CO_2}. The factor describes the amount of CO_2 equivalents per unit of thermal energy input, which is 0.000247 t/kWh [6]. The insurance cost is included by multiplying the *CAPEX* with the insurance rate r_{ins}.

$$\begin{aligned} OPEX = {} & OPEX_{spec,P} \cdot \left(\frac{P_{in} + P_{out}}{2}\right) \\ & + OPEX_{spec,e} \cdot \left(\frac{W_{in} + W_{out}}{2}\right) \\ & + c_{st} \cdot (P_{in} + P_{out}) \cdot cyc + W_{in} \cdot c_{el} \\ & + G_{in} \cdot c_{gas} + G_{in} \cdot eq_{CO_2} \cdot c_{CO_2} \\ & + CAPEX \cdot r_{ins} \end{aligned} \tag{14}$$

For each component the residual value at the end of the plant lifetime is determined, using the CAPEX of the component $CAPEX_c$, which is multiplied by the residual time of the component n_{res}, divided by the component lifetime n_c (15).

$$R_c = CAPEX_c \cdot \frac{n_{res}}{n_c} \tag{15}$$

The total residual value R is the sum of the component specific residual values R_c.

d) Interest rate

The interest rate i, which is used as discount factor in (1), is calculated depending on the expected return on equity i_{eq} and the interest rate on debt capital i_{de}. The share of debt capital with regard to the total CAPEX is described by s_{debt}. Since the cost of debt capital is reduced by a tax benefit from corporation tax, the corresponding tax rate r_{tax} is considered (16) [7].

$$i = (1 - s_{de}) \cdot i_{eq} + s_{de} \cdot i_{de} \cdot (1 - r_{tax}) \tag{16}$$

4. Input Data

The LCOS method is applied to Compressed Air Energy Storage (CAES) systems with a net capacity of 1 GWh, a charging duration of 10 h and discharging duration of 6 h. Two technologies, the diabatic (dCAES) and adiabatic (aCAES) are regarded. The input data for the technologies is shown in Tab. 1. The mechanical compressor efficiency is higher for dCAES. While the efficiency of the dCAES compressor is characterized only by the mechanical efficiency, a thermal efficiency is added for aCAES. Therefore, the overall compressor efficiency is higher for aCAES due to the availability of aCAES to reuse the heat from the charging process in the discharging process.

While for dCAES data about the mechanical efficiency is available (see [8]), for the aCAES system the overall compressor efficiency is split into the mechanical and thermal efficiency according to a reference system (see [9]).

The specific energy demand of the turbine consists of a mechanical and thermal component (b_{mech} and b_{heat}). Again, values for dCAES are based on literature research ([10], [11]) while values for aCAES are based on the reference storage in [9].

Input variable	Values dCAES	Values aCAES	Source
Compressor power [MW]	170	220	
Turbine power [MW]	470	250	
Rated storage capacity [MWh]	2500	2500	
Compressor efficiency (mechanical)	60 %	45 %	[8] / [9]
Compressor efficiency (thermal)	-	37 %	[8] / [9]
Combustion chamber efficiency	78 %	-	[12]
Turbine specific mechanical energy demand (b_{mech})	0.353	0.504	[10], [11] / [9]
Turbine specific heat energy demand (b_{heat})	1.118	0.642	[10], [11] / [9]
Depth of Discharge (DoD)	40 %	40 %	[13]
Self discharge rate [%/h]	0.021	0.021	[13]

Tab. 1: *Technical input data for dCAES and aCAES with 1 GWh net storage capacity*

Tab. 2 shows the economic input data for the LCOS calculations. Higher requirements for aCAES components and the additional need for a thermal storage result in higher specific CAPEX compared to dCAES. On the other hand, total OPEX per kWh are lower for aCAES than for dCAES due to the fact that combustion of natural gas is not required for aCAES. For dCAES, the cost of natural gas and CO_2 certificates is also included.

Input variable	Values dCAES	Values aCAES	Source
Specific CAPEX:			
Compressor [€ k	442	444	[8], [13] [14], [15]
Storage capacity [€ k h	58	54	[8], [13] [14], [15]
Turbine [€ k	393	399	[8], [13] [14], [15]
Thermal storage (total)	-	25 % of CAPEX	[5]
Specific OPEX:			
Energy based OPEX [€ct/kWh]	3.1	2.5	[8], [16], [17]
Power based OPEX [€ kW·a]	9	10	[8], [16]
Startup cost [€ k]	0.015	0.015	[8]
Natural gas cost [€ct k h]	3.76	-	[18]
CO_2 certificate cost [€ t_{CO_2}]	4.69	-	[18]
Insurance cost	0.5 % of CAPEX	0.5 % of CAPEX	[3]

Tab. 2: *Economic input data for dCAES and aCAES with 1 GWh net storage capacity*

In Tab. 3 the component lifetimes for the calculation of the residual values are listed. The financial lifetime of the plant is assumed to be equal to the lifetime of the storage capacity.

Input variable	Values dCAES	Values aCAES	Source
Component lifetime			
Compressor [a]	25	25	[14]
Storge capacity [a]	30	30	[14]
Turbine [a]	35	35	[14]
Thermal storage [a]		30	assump-tion
CAES financial lifetime [a]	30	30	[8]

Tab. 3: *Lifetime input data for dCAES and aCAES*

The parameters for the calculation of the interest rate are summarized in Tab. 4. The interest rates on equity and debt capital as well as the share of debt capital for both CAES technologies are based on data from a modern combined cycle power plant [4]. The value considered as corporation tax refers to the German Corporate Tax Act [19]. These input variables result in an interest rate of 8.46 %.

Input variable	Values dCAES	Values aCAES	Source
Terms of financing			
Interest on equity capital	13.5 %	13.5 %	[4]
Interest on debt capital	6 %	6 %	[4]
Share of debt capital	60 %	60 %	[4]
Corporation tax	15 %	15 %	[19]

Tab. 4: *Financing input data for dCAES and aCAES*

5. Results and Discussion

Fig. 3 shows the LCOS for dCAES and aCAES between 0 and 3300 turbine full load hours. For yearly full load hours of up to 1800, the LCOS of dCAES are below the LCOS of aCAES due to the lower investment cost. Monthly cycling, which corresponds to 312 full load hours, results in an LCOS of 0.36 € k h for d AES and 0 60 € k h for aCAES.

With increasing capacity utilization and energy output, the share of OPEX in the LCOS for each kWh supplied by the storage grows while the share of CAPEX decreases. Since dCAES requires the combustion of natural gas, its OPEX are higher than those of aCAES. Therefore, with more than 1800 full load hours, the LCOS of dCAES are slightly higher than the LCOS of aCAES: at daily cycling (2136 full load hours) the LCOS are 0.104 € k h for dCAES and 0.095 € k h for a AES With maximum operation of the storage, the LCOS decrease to 0.09 €/kWh for dCAES and 0.06 €/kWh for aCAES.

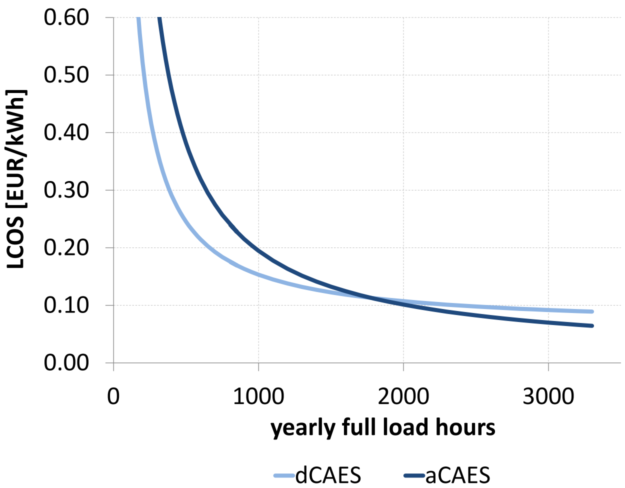


Fig. 3: *LCOS for dCAES and aCAES depending on the number of full load hours*

6. Sensitivity Analysis

Fig. 4 shows the results of a sensitivity analysis for dCAES with 2136 full load hours (daily cycling). Since fuel costs represent the largest share of variable cost of dCAES, this cost component has the strongest influence on the LCOS: With a variation of natural gas cost between 80 and 120 % LCOS vary up to 10 %. The influence of the energy and power based OPEX on the LCOS is much less pronounced (less than +/- 1 % for a variation between 80 and 120 %). Naturally, with higher specific CAPEX, the LCOS rise. Among the components' CAPEX, the cost of the turbine has the strongest influence on the LCOS with up to 3.5 %. The DoD has a contrary influence: the higher the DoD, the lower is the LCOS. With a 20 % larger DoD, the LCOS decreases by about 2.3 %.

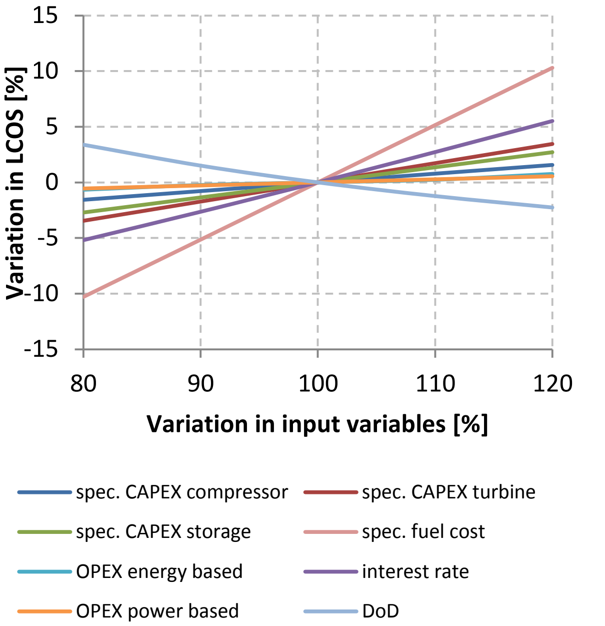


Fig. 4: Sensitivity analysis for dCAES

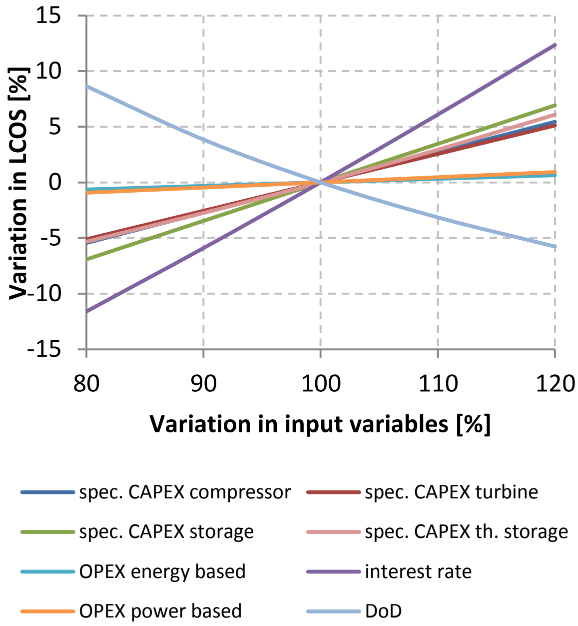


Fig. 5: Sensitivity analysis for aCAES

Fig. 5 shows the results of the sensitivity analysis for aCAES with 2136 full load hours (daily cycling). Eight parameters are varied in a range between 80 and 120 % of the reference case. The interest rate has the highest influence on the LCOS with a variation of up to 12 %. Among the components' CAPEX, the specific CAPEX of the storage has the strongest influence on LCOS. It causes a variation in the LCOS by up to 7 %. The impact of the specific CAPEX of the compressor and the turbine is similar to the influence of the specific CAPEX of the thermal storage, but less distinct, resulting in a variation of up to 5 % in LCOS.

A smaller influence is determined for energy and power based OPEX. The variation of both parameters in a range of 80 to 120 % results in a variation in LCOS of less than 1 %. As for dCAES, with higher DoD the LCOS decrease. Due to the higher specific CAPEX of the storage unit for aCAES, the impact on the LCOS is higher than for dCAES.

The small influence of the variation of input parameters on the LCOS can be explained by the fact that there are a large number of parameters in the calculation. The number of full load hours of the CAES has a much stronger influence on the cost of stored energy than the other parameters used in the calculation.

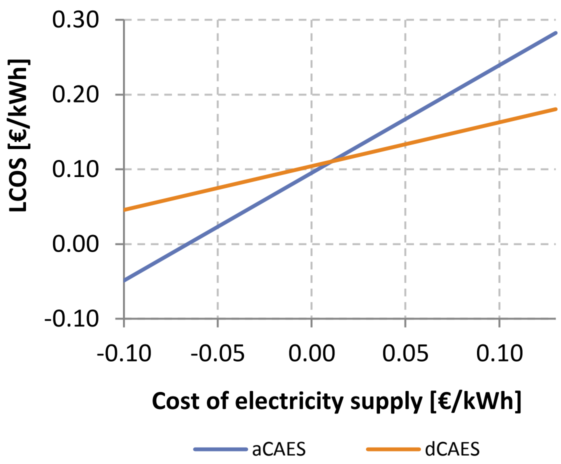


Fig. 6: Influence of cost of electricity supply on LCOS

Fig. 6 shows the influence of the cost of electricity supply on the LCOS for dCAES and aCAES operating at 2136 full load hours (daily cycling). The electricity supply cost is varied between the minimum and maximum day-ahead price at the European Power Exchange in 2013 [20]. The LCOS for both technologies are linear functions of the electricity supply cost. If the cost of supplied energy is increased by 0.05 € k h, the S rises by 0.03 € k h (about 28 %) for dCAES and 0.07 € k h (about 76 %) for aCAES respectively. The steeper slope of the LCOS of aCAES shows that this technology is more dependent on electricity prices than dCAES. This is explained by the fact that aCAES has a higher specific electricity demand than dCAES, which uses natural gas as fuel in addition to electricity.

7. Conclusion and Outlook

In this paper the LCOS method for CAES is described in detail and first results are presented for dCAES and aCAES systems. The method accounts for all components of the storage system by including component specific investment and operation costs. The LCOS method is therefore appropriate for analyzing the cost of different types of storage such as short-term or seasonal storage systems, which differ in the ratio of storage power to storage capacity.

In addition, the presentation of LCOS in dependency on the yearly full load hours makes a concise comparison of the cost for different types of operation possible. The cost of electricity supply is fixed at 0 € to make the calculations comparable

The sensitivity analysis confirms that these two input parameters, full load hours and cost of electricity supply, have a strong influence on the LCOS. It is therefore reasonable to have a special focus on these parameters when analyzing the LCOS.

The results show that CAES of the analyzed size are not financially attractive for seasonal energy storage due to high costs per stored kWh at a small number of turbine full load hours. For an LCOS of 10 €ct k h, the storage needs to be cycled at more than 2000 turbine full load hours for aCAES and more than 2400 turbine full load hours for dCAES respectively. CAES with about 2.5 GWh storage capacity are therefore more attractive to be used for short-term storage.

Even though worldwide there are only two dCAES plants in operation, the technology can be classified as mature due to the fact that the technology uses standard components: compressor and turbine are used in power plant engineering; cavern storage options are used in natural gas storage. In addition, the existing dCAES plants have been in operation for several decades. Experience in operation therefore exists. Accordingly, it is assumed that the cost reduction potential of dCAES is comparatively low. Due to the fact that a large share of the LCOS of dCAES is caused by the need for fuel, the cost of this technology strongly depends on the development of natural gas prices. The LCOS may therefore even rise in the future.

The aCAES technology is currently in the development stage. The compressor needs to resist high temperatures and pressure and turbines operating with air need to be newly developed. The development of robust and efficient heat energy storage is also a major development goal. Accordingly, there is a larger potential for cost reduction for aCAES technology in the future.

Acknowledgement

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Perspectives for Energy-Aware Data Centre Management in Smart Cities

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Abstract: One issue in smart cities is how to deal with the energy hunger of their inhabitants and how to reduce their CO^2 footprint. Another issue of the smart cities life-style is a mushrooming amount of data creation that needs to be processed in data centres. This makes data centres one major energy consumer group in cities. And this connection of smart cities and data centres is in the focus of a research project that suggests a software solution for increasing the share of renewable energy at the data centre's energy mix.
However, the suggested technical solution must prove to be also economically viable. In order to evaluate where and how the concept can be marketed, the relevant market must be identified and the parameters affecting its size and location determined.
This paper aims at shedding some light onto the impact factors on these questions and at showing up where in Europe to find the most promising economic starting conditions for the suggested technical solution.

1. Introduction

Today, more than two thirds of the population in the EU 28 are living in urban areas, and more than two thirds of our energy is consumed in cities [1]. The impact of cities on climate change is therefore high. This is one reason why cities need to become smart and optimize the energy consumption and CO2 footprint of their inhabitants.
The increasing smartness of many aspects of life, be it health, industrial production or education, leads to a mushrooming expansion of data and thus of data centres processing them. This makes data centres one of the major consumer groups of energy inside smart cities – specifically of electrical power.

Technically integrating data centres into the energy management of smart cities and enabling data centres to take part in energy management schemes maximizing the use of renewable energy are the goals of the EU research project DC4Cities[1]. But the question is: Is this concept economically viable? Does a market for a software system that manages the energy mix of data centres exist – and how are the cost recouped?
This work identifies the determinants of these questions and shows up the most favourable locations in Europe for the suggested technical solutions. To this end, section 2 shortly introduces the general framework, section 3 explains in detail the approach to answering these questions, section 4 presents first results. In section 5 these results are discussed critically, and finally section 6 gives an outlook on future work.

2. Concept of DC4Cities

The overall goal of DC4Cities is to establish a control system that enables data centres to adapt their individual workload and energy plans to the availablity of renewable energy. This adaptation is based on objectives for renewable energy shares given by a smart city energy management authority.
The approach to this endeavour is three-fold:
(i) Establishing a communication scheme between the data centre and the smart city energy management authority, (ii) implementing a management software inside the data centre that interacts with workload and HVAC (heat-ventilation-air-condition) management, and (iii) supporting the technical collaboration through bilateral contracts between the participants of the scheme. So-called RenEnergy contracs [2] between data centre(s) and energy management authority determine how workload and power plans are mapped and how the adaptation effort of the data centre is rewarded. Additionally, so-called GreenSLA contracts [3] between data centres and their customers settle the

[1] FP7 STREP # 609304, www.dc4cities.eu

conditions under which the customer grants the data centre extra flexibility to comply with the requirements from the energy management authority.
The technical background to increasing the flexibility of the power demand in a data centre is that its power profile is highly dependent on the workload run inside the data centre. And with continuous hardware and software improvements, data centres even aim at becoming “energy proportional”, i.e. the energy consumption of a data centre develops proportional to its workload [4].

3. Approach and Data Sources

The goal of DC4Cities is to support a data centre in adapting their workload and thus their power profile to the availability of intermittent and volatile power. The keypoint for understanding a market for such a tool is to identify the factors that influence this flexibility from a data centre perspective. Generally, a market exists only where the benefit of the flexibility for the data center is higher than the cost connected with it. This means that the factors influencing the cost and benefit of power flexibility for a data centre need to be identified. This task stretches both on hard facts as well as on rather elusive costs and benefits like CSR (Corporate Social Responsibility) strategies or the geographic and political context of a data centre.

3.1. Cost Factors of Implementing Power Adaptation

On the cost side the adaptive potential of a data centre is impacted by both technical and business factors. Technical factors determine the direct cost associated with physically implementing adaptive strategies like turning on and off machines or downsizing applications as well as the cost of setting up and configuring the software and communication tool. These technical cost, however, are low compared with the cost associated with the business model and SLA (Service Level Agreements).
Generally speaking, the nature of the business model of a data centre highly influences the flexibility of its power curve. Even though the extent to which the data centre is flexible depends on its specific characteristics regarding business model design, customer basis, SLA rigidity as well as also the political and geographical setting, there are some basic trends which are determined by the “SLA flexibility” and the “outsourcing factor” of the respective data centre business model. The outsourcing factor represents the degree to which the data centre manager is allowed to manage the workload running in her data centre. In colocation data centres, for instance, her scope is rather limited: in this business model, data centre space and/or servers are rented to the customers and the data centre manages power distribution, cooling, sometimes security or backup processes. In Software-as-a-Service based business models, on the other hand, the data centre runs the applications themselves and thus has much more influence on the shape of the work- and energy load.

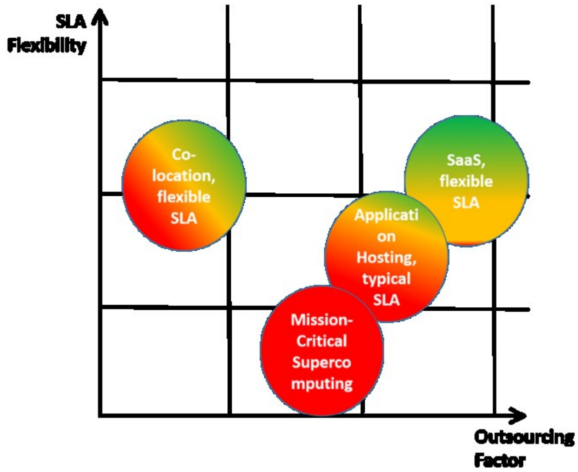

Fig..1: *Positioning data centre business models*

The second dimension, however, is the level to which the data centre manager is allowed to use the scope outlined by the business model. It is determined by the service level agreements, SLAs, i.e. technical constraints like redundancy or performance laid down in a SLA contract. Figure 1 positions some examples for well-known data centre business models with respect to these dimensions.
What further increases the complexity of such an evaluation is that in reality many data centres have more than one business model, i.e. they offer both colocation and for instance SaaS.
In order to clearly determine the market size for a DC4Cities-like tool, the fraction of data centres with business models pertaining a data centre wide high outsourcing factor and a comparably low level of SLA needs to be determined because these two factors are part of the economic boundaries for the market.

In summary, the following cost factors must be considered:

- cost of setting up and configuring the adaptation and communication tool
- cost of implementing each adaptation strategy in the data centre
- cost of GreenSLA contracts offering special flexibility for the data centre management
- cost of breaking SLAs in cases where this is necessary
- cost of losing customers in cases where an aggressive adaptation strategy is planned.

3.2. Benefits of Implementing Power Adaption

A market for a DC4Cities based tool can emerge whenever and wherever the technical potential of the approach can be successfully implemented and turned into an economic benefit. For a data centre this benefit is determined by the following factors:

3.2.1. Reduction of power budget

The most direct motivator for a data centre to take part in this scheme is to save money on the power budget. This option implies that DC4Cities is set up in a context where the adaptation effort of the data centre to renewable power patterns is rewarded financially. Under current conditions, however, only the small fraction of DC4Cities' impact that reduces energy consumption has an effect on the power budget. Because nowadays, adjusting to renewables' availability to our knowing is not rewarded in any energy tariff throughout Europe. For most energy consumers, including commercial or public consumers like data centres, the volatility of energy prices at the wholesale energy market is not put through to their energy tariffs. Also, dynamic prices on the wholesale energy market do not necessarily reflect the share of renewable energy on the market.

One way out would be enhanced energy contracts with an organization that has an interest in fostering the consumption of renewable energy, like for instance a smart city.

3.2.2. Marketing and CSR

Additionally to hard financial incentives, data centres or their mother companies may be interested in following the patterns of renewable energy supply due to ambitious CSR guidelines. Even though the benefits of CSR may not be easily traceable, large companies invest heavily into this field. So, for instance, SAP announced in 2014 that they will run their data centres entirely with energy purchased with green certificates[2] and the huge US tech companies Apple, Box, Facebook, Google, Rackspace, and Salesforce are pursuing the same goal [5]. Also in a 2014 survey [6] 74% of respondents claimed that sustainability and clean tech strategies positively impact the data centre attractiveness.

More direct effects of implementing DC4Cities or a similar tool are to win new customers in the "energy aware" and "sustainable" customer segment. However, in the B2C segment, according to behavioural studies regarding (today) more costly renewable energy tariffs, there is a wide gap between customers' green consumption attitudes and their real choices: Even though more than 80% of customers in most European countries report a positive attitude towards renewable energy sources, in reality, renewable energy tariff contracts are less than 10% [7]. In the B2B market the endeavor for data centers to win energy-aware customers is limited if not supported by competitively low prices.

3.2.3. Geographical and Political Context

Finally, the political and geographical context of data centres influences their inclination to use a tool that technically facilitates the utilization of renewable power. In some regions the geographical characteristics enable the on-site use of renewable power without much ado as for example in Iceland or the Nordic states where huge data centres are located due to the ready availability of hydro or geothermal power. However, in other areas with high availability of intermittent renewable energy sources (solar, wind) data centres with on-site power generation use the renewables as a supplement to the regular power grid. Depending on the relative difference in power cost of these sources, they might be interested in using the stand-alone function of DC4Cities that technically employs strategies to follow the patterns of wind and sun and offers business model support through the establishment of GreenSLAs.

Lastly, if price signals from the energy market fail to indicate the availability or scarcity of intermittent renewable power, the political context where a data

[2] http://www.sapdatacenter.com/article/zero-emissions/

centre is located gains importance. This political context can be EU related or national legislation or taxes, but also guidelines and levies issued by smart cities. There are manifold well-known EU guidelines for national law like the Energy 20–20-20 package, however, to our knowledge there exists no data centre targeted law or tax aimed at the integration of renewable energy sources. Only the UK has a specific Carbon Reduction Commitment (CRC), which data centres (or other industries) can conclude in order to achieve a tax exemption.

There is however, an indirect means to foster the integration of renewable energy sources into data centre operation: The roadmap for smart cities as part of the energy 20-20-20 strategy is laid down in the SET plan technical roadmap [8]. It aims at having 25-30 European cities with more than 500.000 inhabitants becoming low-carbon until 2020. This endeavor is supported by EU projects; the results are monitored. There is a strong incentive for large cities in Europe to become part of this scheme – which also influences their policies towards data processing in general and the location and operation policy for data centres within their city limits.

4. Results

Following the considerations of section 3, in order to determine DC4Cities business perspectives in Europe, both data centre candidates independently of their location and favourable geographical and political settings need to be investigated.

4.1. Corporate Data Centre Candidates

As the incentive of the most direct benefit, reducing the cost driver "power budget", is hardly applicable in the current case, a market for DC4Cities needs to build on soft benefits like CSR or the immanent flexibility of business models.

The data centre market in Europe is geographically more or less evenly distributed all over Europe with data centre conglomerations in the hubs, especially the "big 4" data centre hot spots London, Frankfurt, Amsterdam, and Paris; together they comprise 85% of data centre CAPEX[3]. Sometimes the "big 4" are extended to "big 5", adding Madrid. Also the Nordic states like Norway, Sweden or Iceland have more data centre floor space than expected in relation to their population due to extremely low energy prices (hydro and geothermal energy sources).

Regarding the shares of the different business models mentioned in section 4.1, the currently prevailing type is colocation (dedicated and managed hosting), which offers only little scope for workload management of data centre operators [9,10]. However, as presented in figure 2, the share of flexible cloud based models has been increasing sharply – with an upwards trend.

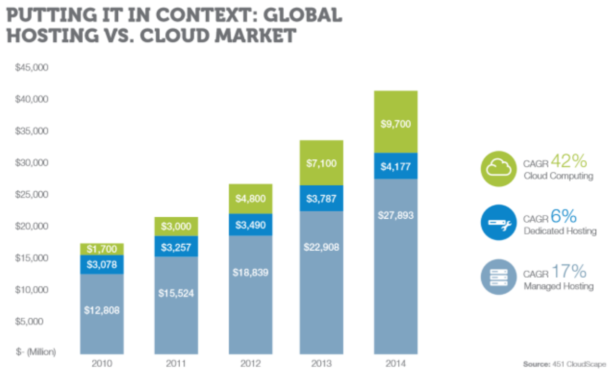

Fig.2: *Expansion of the Cloud Market [9]*

But this image also shows that currently only around 1/3 of the market have a business model, that offers the full scope of flexibility to adapt to the availability of renewables (additionally of course depending on the strictness of SLA contracts); the rest is "traditional", mostly colocation based which may offer some flexibility but to a more limited extent. Of course there are additional market segments with more flexibility like application hosting, especially for interactive services which are used more during the day than at night.

To nail this down to the European market, in a study [11] from 2011 the European cloud computing market in 2015 was expected to be well above 20 bn €, in another recent study the European managed hosting market was projected to increase from 2bn € 2013 to nearly 5bn € 2018[4]. This means that for the near future there is a European market between 20 bn € and 25bn € that offers the technical and contractual opportunities to adapt to renewable energy profiles – provided that the incentive is high enough. As mentioned in sections 4.2.1 and 4.2.2, the current European power market does not offer any kind of incentive to adjust to

[3] http://www.broad-group.com/report/europe

[4] http://www.riello-powersystems.de/blog/1335-european-data-centre-services-market-to-grow-16-cagr-till-2018

renewable power – such strategies would rather be part of a sustainability or CSR strategy.
There are no statistics on expenses for CSR in data centre industry. Most of the big data centre companies have CSR reports which regularly give information on activities but no financial data. This means that big pan-european data centre companies like Interxion or Telecity might be inclined to invest into DC4Cities based products. To which extent CSR investment is made is hard to estimate: the only evidence to get an idea about a likely extent of spending is given by the new Indian law that requires big companies to invest 2% of their 3-year-average net benefits into CSR. Roughly applied to the 20-25bn € relevant share of the data centre market this would shrink the market size to 20-24 Mio € in the absence of financial incentives.

Apart from corporate data centres there are also enterprise data centres, i.e. data centres owned by companies from other industries. This is a huge market which may offer some flexibility based on day-night activities and usage patterns, however there are no data as to the financial volume of this market.

4.2. Smart City Data Centres

The second pool of data centres with incentives to adjust their power profiles to the availability of renewable energy resources are data centres in smart cities and/or controlled by smart cities.
Again, the situation is complex: There is a plethora of definitions of what a smart city is or should be; the most widely used definition goes back to [12] who defined several dimensions along which smart cities should develop: Smart governance, smart economy, smart people, smart mobility, smart living, and smart environment. What is a common requirement for all is a set of sensors throughout the city that enables the “smartness” – meaning the ICT based control and optimization. This development results in a huge amount of data (most probably so-called “big data”) which need to be collected and processed by data centres. Some of these data centres are within city boundaries and therefore subject to the overall smart city’s goal of a high share of renewable resources at the smart city’s energy mix. These smart city related data centres are the second source for a DC4Cities market. They consist of publicly-maintained data centres, private data centres processing data for the smart city or private data centres directly offering smart city services to the citizens (which then overlap with the date centres identified in section 4.1). Obviously the workload (and therefore the energy profile) of publicly-maintained data centres can be most directly controlled by the smart city. Data centres under smart city contracts can be controlled to the extent defined in the contract – and other corporate data centres will participate in the proposed scheme only in case the benefit outweighs the cost (see section 5.1). This means that the market for a DC4Cities based tool in a smart city depends on its specific “data centre mix”.
The next issue is how to determine which European cities are smart cities or on the verge of being smart and which are potentially most interested in raising the share of renewable energy sources in the city’s specific energy mix. Assuming the smart city definition in [12] this means looking for cities with ambitious goals in the area of “smart environment” and with high levels of ICT penetration. However, there are only very few empirical studies in the area of European smart cities. With the Smart City index, IDC is looking into the details of Spain and Germany[5], but not into Europe as a whole. [1] aims at identifying the smart city maturity level of the nearly 500 cities in Europe with more than 100.000 inhabitants. Relying mostly on online information sources, they estimated the maturity level of a smart city based on the degree to which smart initiatives within those cities seem to be successful. Using their background data[6] it was possible to determine 68 cities in Europe with maturity level 4 representing nearly 43 Mio people. Interestingly, this group comprises also the data centre hubs London, Amsterdam, Paris, Frankfurt, and Madrid.

City	Inhabitants
London	7.074
Madrid	3.265
Paris	2.212
Barcelona	1.620
Cologne	1.007
Amsterdam	780
Helsinki	589
Frankfurt	680

[5] http://www.idc.com/getdoc.jsp?containerId=EIRS02U http://www.idc.com/getdoc.jsp?containerId=EIRS55U

[6] Based on the generous permission of the authors

Copenhagen	542
Brussels	156

***Tab.1:** Examples of the Smartest European Cities, sorted by number of inhabitants, adapted from [1]*

Obviously, these 68 cities are the most promising markets in the EU, considering that they are on the verge of producing a huge amount of smart city data which need to be computed. The more closely the commissioned data centres are linked to the smart city, the higher the probability that they will be incentivized to adapt their energy profile to follow sun and wind.

4.3. Summary

Putting all above considerations together it becomes obvious that the market for renewable power adaption tools for data centres is largely determined by regional and political characteristics. As a starting point the intersection among smart cities, data centre conglomerations and favourable climate conditions is determined. This is done in a map, created on the basis of the information found in [1], as well as of information from an international portal for data centre offers[7], and based on the EU ESPON website that gives information about the regional distribution of solar and wind power potential[8]. The star-icons in this map signify smart cities with a maturity level of 4 (see section 5.2), the screen-icons the presence of more than 4 data centres, and the solar and wind power potential is represented by sun and cloud icons respectively.

This map reveals that although the big data centre cities London, Amsterdam and Frankfurt are also smart cities, the weather conditions will make it harder to justify a “follow the sun/wind” policy than in other regions. In other words: the share of intermittent renewable power will be relatively low in

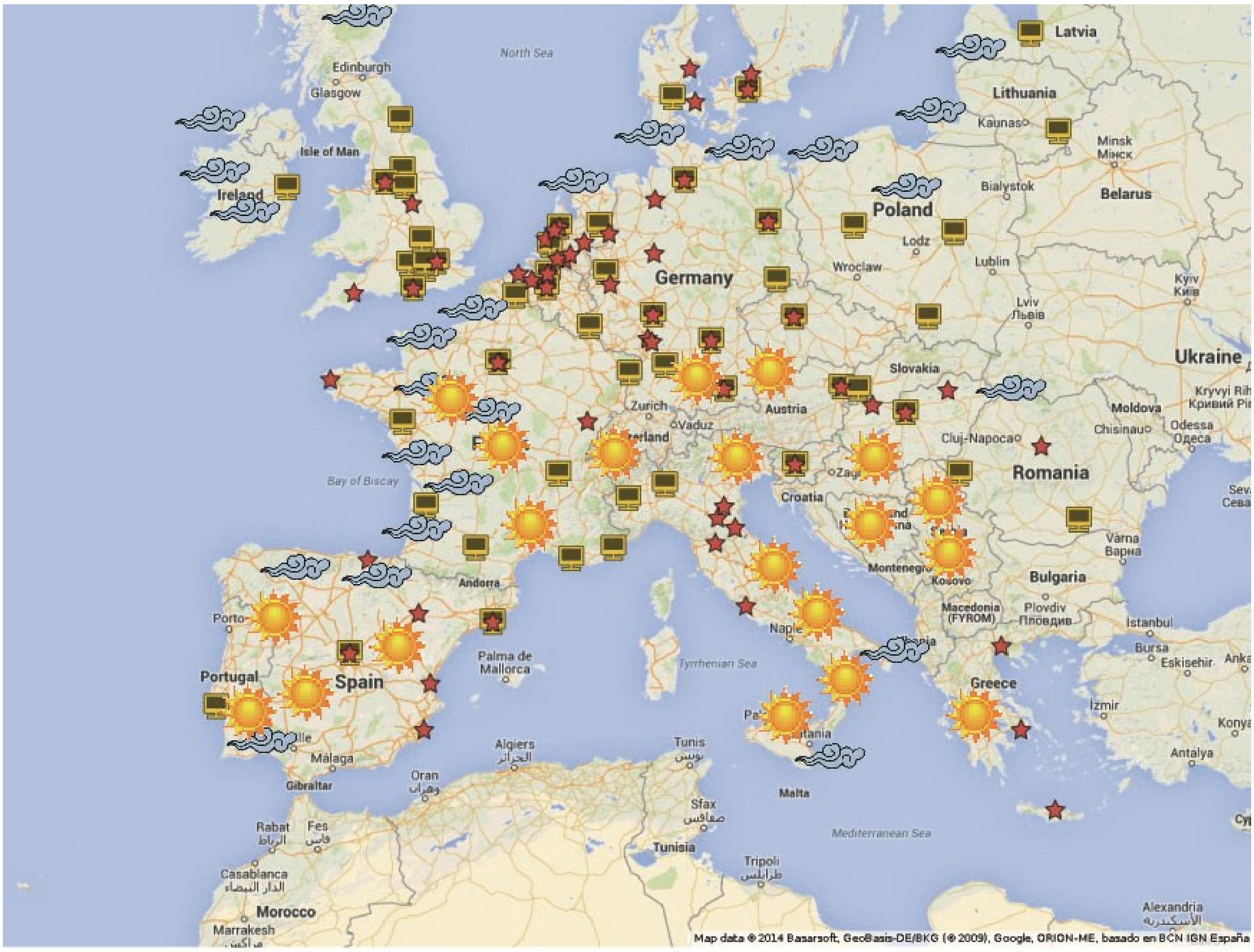

***Fig.3**: Map of Good Starting Conditions for DC4Cities in Europe*

[7] www.datacentermap.com

[8] http://www.espon.eu/main/Menu_Publications/Menu_MapsOfTheMonth/map1101.html#

the close vicinity of these areas even if incentives are high. Paris, also both data centre based and smart city, has a little more sun and thus a slightly improved potential. On the other hand: Spain and Portugal offer perfect conditions: There are data center hubs in Madrid, Barcelona, Lisbon and a few others which are also maturing smart cities – and the solar potential is huge, in some areas (e.g. Lisbon) paired with wind energy whenever the sun is not shining. But also Austria, Germany and Hungary have big cities which are at the same time smart and seemingly attractive for data centre companies: Munich, Vienna, and Budapest. Italy seems to have hardly any areas where data centre conglomerations and smart cities overlap; however, it has a great variety of smart cities which will need to have their data processed and a very good solar potential. And there are more to come, as Italy has a high number of smart cities of maturity level 3 which are not represented in figure 3. Poland, Latvia, Lithuania as of now on the contrary have no noteworthy smart cities – but they have data centre agglomerations and a lot of wind. So, if incentives from the side of customers, politics or the energy system were tempting, also there DC4Cities or a similar tool could be marketed well.

5. Discussion and Outlook

This work demonstrated that even under current conditions there are some places throughout Europe with opportunities to market a "follow-the-sun" tool for data centres; especially in areas where smart cities are evolving that subscribe to the Energy 2020 goals and beyond. Also, there are some areas with data centre conglomerations and favourable climate conditions where data centres investing in eco-aware customer segments might be targeted.

Unfortunately, the data basis of the presented findings is small and may be biased: The data centre market is extremely intransparent; studies with more detailed information are available, but very costly and out of the scope for public institutions. The utilized paper about smart cities is well researched, but dependent on the underlying realities of the cited webpages because the mostly used study relies only to a very small degree on a measurable impact. These restrictions of course limit the validity of the presented research.

As mentioned before, the overall success of a product or a service always depends heavily on the economic framework formed among others by legal guidelines, levies and taxes. Traditionally, in Europe labour as well as energy is highly burdened with taxes and levies. However, power prices are averaged and CO^2 is hardly priced at all so that there is no incentive for energy retailers to offer carbon saving energy tariffs. This economic frame renders many potential applications of DC4Cities unprofitable and thus limits today's market for a product or service similar to DC4Cities to a some extent.

On the other hand this situation implies that there is a high potential for a future market of such a product, provided that the economic framework develops in a favourable direction.

And judging from manifold technical and political trends, this might happen:

- Following the EU Energy Trends to 2050 study [13], the share of renewable energy at power generation will reach 43% until 2030 and 50% until 2050. This projection presupposes that due to the implementation of EU guidelines and national legislation, the ETS price (CO^2 price) increases by a factor of 7 until 2030 and the smart grid is enhanced throughout Europe – both developments that heavily support business opportunities for power adaptation schema like the one proposed.
- The expansion of the smart city as foreseen in the SET plan concept [8] certainly will boost the market for DC4Cities: the roadmap aims at a first milestone of 25-30 low-carbon European cities with more than half a million inhabitants until 2020.
- Another trend that fosters the expansion of the data centre industry and thus the necessity for low-carbon computation is subsumed under the buzzword "big data": the sky-rocketing growth of global data volumes due to the always-and-everything-online way of modern life.
- The same applies for an increasing awareness of the European people for the climate challenge – as far as this translates into economic decisions.
- The development of energy storage technologies (thermal, batteries, power-to-gas etc.), which are projected to make huge steps forward in the next decades (and

supported by governments to do so[9]) has a two-fold impact on the DC4Cities market: The more energy storage will be employed by power generators or power grid operators themselves, the less the necessity to rely on active consumers for the integration of renewable energy. However, on the other hand, the more affordable storage gets for consumers like data centres, the higher the chances to time-shift power.

6. Conclusion

The EU project DC4Cities creates a software solution that enables data centers to follow the patterns of intermittent renewable power managed by the smart city. For this technical approach to live up to its potential, it needs to penetrate the data centre and smart city market. The presented work showed that even though today's economic framework is not supportive of integrating renewable power into a data centre's workload and power profile, there are enough promising starting points in Europe to open up a new market. It could also be shown that based on current political roadmaps the prospect for a DC4Cities-like product or service are much brighter in the coming decades. However, for a more accurate estimation of a market for such a product or service package it would be necessary to get access to more detailed data, especially regarding the data centre market.

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The central control system of a virtual power plant - managing thousands of decentralized power generators

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1. Introduction

Renewable energy is on the rise; a significant infrastructural change that brings a large amount of volatile energy to the European market. This change also means growing fluctuations in the power grid because the sun doesn't always shine and the wind does not always blow as expected. But does a change towards a more volatile power generation also inevitably mean risking the security of power supply on a general level? If one reviews the SAIDI [1] index which shows the average duration end-users suffer from a loss of power supply due to power shortage in the past years, the answer is no. The most notable thing here is that with an increasing amount of renewable energy providing power this index is in fact decreasing. What does this mean for the future of the European energy market? Is the future power supply already secured? What kind of means need to be addressed for ensuring a stable power grid? How can the challenge of a more volatile energy supply be directed towards a secure grid?

As much as renewable energies are responsible for grid imbalances they can also help to resolve this problem through a virtual power plant. A virtual power plant integrates thousands of small, decentralized power plants like biogas plants into one large " irtual "power plant providing energy from a single source. If we are serious regarding a complete integration of renewable energies into the existing energy market, it is pivotal that we find solutions that offer reliable control reserve through these decentralized small scale power plants. The following presentation will show how a virtual power plant works and how it offers a suitable solution for providing reserve capacity from sustainable energy resources.

The transformation towards regenerative energy resources also brings a significant change to the general system of power generation and provision. While formerly the power generation can be characterized by a small number of power plants providing large amounts of power, now the overall number of power plants is increasing. But these power plants offer limited amounts of power per unit. The exceptions are large-scale on- and off-shore wind energy parks. It is remarkable that the renewable energy power plants providing the most energy are usually rather volatile power (in regards to their maximum peak). These assets can be a number od different power plants such as such as biogas, biomethane, Biomass heating systems (based on wood for example) or even systems that are not gineuinly based on renewable energy sources such as emergency standby power systems that can be used for generating positive control reserve.

With an increasing number of single power plants providing power to the grid, it becomes more difficult to organize a secure and stable grid. The reason is that it is more complicated to forecast each individual power plant than just a few large ones. At the same time the vulnerability of the grid decreases as single points of failures are reduced – a decentralized power plant with 500 kW not providing energy to the grid doesn't affect the general power generation as much as the failure of a nuclear power plant providing 800 MW.

The networking of decentralized power plants via a virtual power plant (VPP) offers a number of advantages. First, this aggregation offers the opportunity of providing the energy from a vast number of small power plants through one single provider. This reduces the complexity of the energy market – in terms of trading but also in terms of balancing group management. Furthermore, this leads to an increased redundancy regarding the individual power plants – since the number of power plants networked within a virtual power plant is rather large.

Second, a virtual power plant is the most effective way of organizing the vast number of decentralized power plants in order to provide control reserve, which wouldn't be manageable at a financially iable level if handled differently. The shift towards more

renewable energy production would not be possible otherwise, since large scale fossil power plants would need to be kept on the grid).
Third, it is important to find the right amount between the number of power plants and the amount of power each unit provides. Relying on only a few large power plants increases the need for equally large redundancy measures, which results in large economical liabilities or elseways risks losing backup in case of a failure. One example for the negative impact relying on large scale power plants is Belgium. More than 55% of the Belgian power is provided by nuclear power plants. But what happens when one or more of these large-scale power plants fail to provide energy? This is just the case at this very moment in Belgium, resulting in a risk of 30% of the country being cut off the grid. [2]

2. Theory

The idea behind the virtual power plant is to hold the producers of renewable energy accountable for the increased fluctuation in the power grid. One of the major obstacles to overcome is the fact that the entry point for the control reserve market is a flexible amount of short-term capacity reserve of 5 MW. Since many of the controllable renewable energy power plants are a lot smaller than the needed 5 MW, it is not too far-fetched combining them into one integrated provider: a virtual power plant. This would mean networking the small power plants in order to allow for monitoring and controlling of their status and power generation. Only this way, it will be possible to provide a reliable and manageable source of renewable energy to the control reserve market. In addition, with providing control reserve through a single aggregator such as a virtual power plant, the auctioning and accounting of each individual participant will still be kept at a minimum level of complexity.

3. Your Approach

So how does providing control reserve through a virtual power plant work? A virtual power plant is based on a star topology that integrates all decentralized small power plants into a centralized system. The virtual power plant uses a GSM connection for establishing a secure communication infrastructure to each production facility. The needed data is not transmitted through the "regular" publicly available data network, but through a private usergroup network between the Transmission System Operators, the virtual power plant and each individual power plant. For maximum reliability the virtual power plant runs on an entirely redundant system that is mirrored to an off-site system.
Since there is no established standardized interface for remotely controlling small-scale energy power plants, a specialized interface for connecting the individual facility to the virtual power plant offering remote monitoring and controlling of the individual power production of each unit is needed. This interface such as the Next Box, developed by Next Kraftwerke, translates the decentralized plant's data to a protocol, which is then used within the virtual power plant to communicate with all participants. It would be a great step forward – also in regards to the power grid's stability – to rely on an entirely standardized protocol for all existing virtual power plants in the market. But this development has not seen the day of light yet, but is certainly welcome [3].
The protocol enables the control room of the virtual power plant to automatically check the status of each integrated facility. This way the virtual power plant is always up to date regarding available decentralized power plants, their production capacities, the amount of capacity reserve they can provide at any given point, etc. An algorithm determines, which power plant will be used for providing capacity reserve. Upon each call the algorithm decides anew which production unit is used in order to achieve a combination of maximum reliability and fairness to all connected plants within the pool. Since this process is fully automated, all orders from the Transmission System Operators can directly be implemented and processed through the system.

Today, Next Kraftwerke, as one of the largest virtual power plants in Germany, integrates more than 1 GW of power that can be utilized for control reserve (positive & negative secondary & tertiary control reserve combined) in all four German control areas. More than 2,500 single decentralized facilities are integrated into the virtual power plant.
The virtual power plant runs without any direct human interaction and is set up entirely redundant for offering the most reliable operation. Communication between the Transmission System Operators and the virtual power plant happens fully

automated in order to allow for a direct and quick reaction. As of today, virtual power plants already play an important role in balancing the German power grid. With growing possibilities in terms of large scale batteries on the horizon, the scenario will change further. But this is a rather long term development; virtual power plants already play an important role today in keeping the power grid balanced with the support of renewable energies.

For enabling a reliable provision of control reserve, every integrated power plant needs to undergo a so called prequalification. With this test the power plant is controlled through the virtual power plant as if it would be providing control reserve according to the transmission code[4]. The test results are then sent to the according Transmission System Operator for final approval.

4. Conclusion

After more than three years, we can clearly state that the delivery of control reserve from small and decentralized power plants through a virtual power plant works perfectly. It is an important keystone in finding a solution in order to establish an energy market that supports the energy transitions to more sustainable production methods. This does not mean that conventional power plants will be rendered useless shortly, but in the long run this will help to make the transition a lot smoother and it shows that a different approach is possible. In the future it will become more important to not only network renewable energy power plants into a virtual power plant but also integrate the demand side. This will furthermore help to level the fluctuations in the power grid.

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Stability in Energy Grids

SmartER Europe 2015

Ant-Colony based Self-Optimization for Demand-Side-Management

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Abstract: Demand-Side-Management (DSM) is one of the key factors in the future smart grid, utilizing the consumer side as an additional degree of freedom for planning and controlling the grid. Caused by the growing dissemination of distributed energy resources (DERs), the classical top-down oriented modus operandi transforms towards new operational models. While some DER-types are dependent on environmental conditions and thus, rely on forecasts and heuristic predictions, optimizing and scheduling these dynamic loads in smart grid applications adaptively is still a matter of concern. We will present a distributed implementation of the Ant Colony System as an optimization algorithm combined with a MAPE-K feedback loop that optimizes loads towards dynamic changes of the generation conditions adaptively. Thus, the self-optimizing system uses the available energy more efficiently.

1. Introduction

Since Germany decided on an energy transition in 2011, the amount of renewable energy resources in the German power grid rises steadily. Currently the German power supply faces a structural change from conventional bulk energy generation to smaller, decentralized regenerative energy resources. Therefore, apart from the development on the production-side, operational concepts are currently under development so that domestic households as well as utilities can profit from energy management. Additionally, new coordination and control concepts are required to integrate the renewable energy resources in order to ensure the stability of the power grid even with the unsteady power generation dependent on environmental conditions. The usage of controllable loads in the power consumption in order to adapt to the producer side is called Demand-Side-Management (DSM) [1].

Current research deals with the connection of the demand-side to the smart grid. The coordination and control of this side is an important and critical aspect for the success of the smart grid. Single small-scale appliances located in domestic households on the consumer-side, like fridges or washing-machines have only a small power-footprint but form a high amount on the daily peak load of the power grid in total.

Therefore, they offer a lot of potential for DSM. In order to facilitate this potential for load planning and balancing new intelligent control concepts are required combining Energy- as well as Information- and Communication-Technology (ICT). The next paragraph introduces a promising software- concept for the development of energy systems that are able to coordinate and control themselves in an adaptive way.

The reminder of this paper is structured as follows: The next two Sections introduce concepts of adaptive systems and related work in the DSM domain. In Section 4 the self-optimizing system will be described and the Ant-Colony-System Algorithm is presented. Section 5 evaluates the presented approach with regard to a case study. Finally, Section 6 concludes the paper by pointing out future work.

2. Self*-Properties

Traditional approaches of engineering and operating distributed systems are substantially challenged by current trends in computer science, like mobile and ubiquitous computing in combination with an increasing diversification of hard- and software platforms. In the past, distributed systems were mainly closed systems. Tasks, challenges, and users were known a-priori. Nowadays, with an increasing pervasiveness of distributed systems, they have turned into an integral part of both, the business world and the private life of the domestic consumers, which implicates new challenges for their development. Todays distributed systems are forced to deal with high and unpredictable dynamics, increasing complexity as well as the satisfaction of non-functional requirements like availability, scalability and robustness. Therefore, a new generation of distributed systems is required, that is capable of adapting its behavior autonomously.

A promising approach to solve this issue are the so-called self-*properties. These are different properties that relieve the burden of complexity by maintaining at least some aspect of operation automatically without human intervention. There are different characteristics of these self-* properties, e g “self-healing”, “self-protecting and “self-optimi ing” In the following, a short description of these four aspects is given, for a formal definition and further aspects see [2].

- Self-healing refers to systems that are capable to overcome a violation of their safety property by themselves (with regard to a subset of possible failure conditions).
- Self-protection traditionally refers to systems that are able to protect themselves against external actions that have malicious intent by applying mechanisms or privacy policies to secure the system and its data.
- Self-optimization focuses on the value of an objective function as the system property, and aims at maximizing (or minimizing) this objective function [2].

The Autonomic Computing initiative, started by IBM in 2001 [3], is a vision to create systems that implement some of these. As mentioned before, the self-* approach is highly suited for the fulfilment of nonfunctional requirements like scalability, availability, and robustness as they can adapt automatically to changing internal and external influences. Energy systems implemented with these aspects in mind can profit from these benefits and become more robust and adaptive to changing internal and external conditions. Self-optimization, as described in this paper, can be used to implement adaptive DSM optimization systems that are able to optimize their DSM adaptively to changing conditions.

The mentioned challenges for distributed systems are also addressed by a research area called Organic Computing [4]. Both Autonomic and Organic Computing aim at providing new approaches to solve these challenges in a systematic way. It is achieved through different types of feedback loops, relying on (usually) centralized control elements. Feedback loops have been identified as the key design element within a distributed system in order to exhibit adaptivity [5].

A feedback loop in this context consists of three main components: Sensors, actuators and a computing entity. Sensors observe the behavior and the status of the system respective the environment it is situated in. Actuators are able to change the configuration of the system. The computing entity serves as a connector between the sensor and actuators. It can be every different w.r.t. its internal architecture and abilities (cf. [6]). For instance, the Autonomic Computing control loop [3] is based on a monitoring, analyzing, planning, executing and knowledge loop (MAPE-K). It contains a centralized computing entity, which can be associated with an autonomic manager to hardware and software components in order to equip them with adaptive behavior. The authors of [7] classify this class of approaches that are based on centralized control concepts as self-adaptive systems. Approaches based on decentralized architectures which utilize distributed feedback loops and coordination mechanisms are called self-organizing systems [7]. Due to their decentralized system architecture, they seem to be better suited to deal with the before mentioned non-functional requirements.

The concept of self-organization has been observed in many other domains like biology, physics, or sociology. Furthermore, it has proven its applicability for distributed systems already before (e.g., [8, 9]). In summary, adaptivity defines a general system view that can be further decomposed into the self-* properties of distributed systems [7]. They refer to any properties or processes of a system caused or maintained by the system itself. Self-adaptation and self-organization are two modelling approaches to realize self-* properties. Many approaches target the provision of (a subset of) these properties (e.g. self-healing [10], self-protection [11] and self-management [12, 13]).

3. Demand-Side-Management

Demand-Side-Management is defined as planning and implementation activities of utilities and operators in order to influence the consumer's demand so that the intended consumer-behavior is achieved [1]. In Germany, apart from energy savings, the purposeful use of volatile effects from renewable energy resources is a significant use-case [15].

The examined time frame of different demand-side use- cases ranges from near real-time applications [16] to applications that focus more on day head planning [17]. Common DSM approaches mainly differ on how the load control is realized. It can be differentiated between direct and indirect control. Where direct control focuses on the used protocols as well as signaling, the indirect control approaches focus on price signals, auctions or optimization on the consumer- side. A direct control approach with a reliable system response for pre-defined signals is presented in [18]. In this approach, the according service provider resp. operator has complete control over the loads. Therefore, it implicates hard constraints on the consumer-side concerning the conditions under which load can be switched centrally. It requires detailed information about the controllable loads and time frames to anticipate the effects of according control signals. Thus, the approach seems to be more interesting for industrial consumers without the heterogeneity and complexity of domestic households.

Close to direct control approaches is the use of price signals [19]. Based on the familiar top-down communication of price signals through a central control center is it a consequent enhancement of existing tariff models.

Common in the area of indirect control are auction-based approaches where the consumer either bargains directly with the distributed energy resources or via aggregation agents [16,17,20]. All this approaches share the fact, that the generator and load resp. the prices are tuned and negotiated in a bilateral way. This comes with the common challenge that price barriers and acceptance levels for each distributed energy resource or load through the producers and consumers have to be agreed on a priori.

Another class of approaches focuses on the optimization on the consumer-side to generate an optimal degree of efficiency related to the according business- or operational-model. Exemplary applications with regard to specific use-cases are described in [21,22].

4. Description of the Self-Optimizing DSM-System

Planning day-ahead DSM activities usually relies on estimations of the generated power of related distributed energy resources (DERs). Many of these DERs depend on weather conditions like wind or sunshine and thus, directly on the quality of the weather forecast. These changes can also influence the energy markets, which have additionally their own dynamics and constrains. In a grid with more and more DER Units, grid restrictions and conditions must be also considered. An evidence of the growing importance of grid-condition monitoring is the increasing degree of standardization (i.e. IEC61850) and ICT-connection of the components.

In conclusion, sudden changes of environmental-, market-related- and grid-conditions may result in missing the original targets of the energy scheduling. Being aware of such conditional changes through sensors in all three described domains (environmental, markets, grid) allows reacting accordingly with a dynamic and adaptive DSM-System.

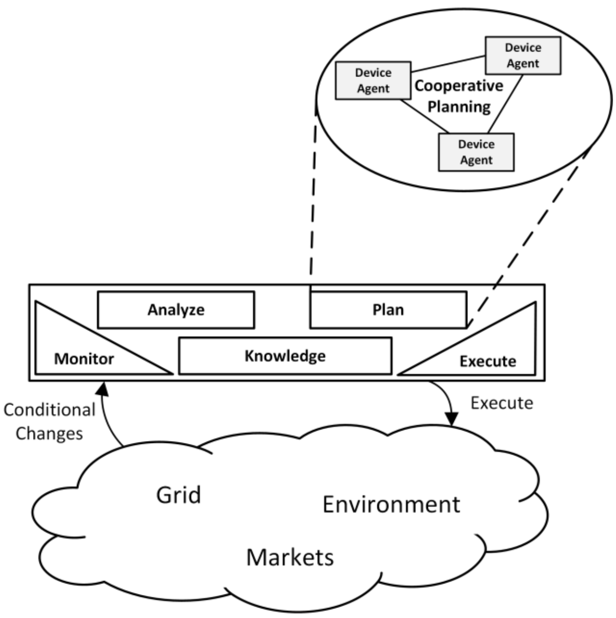

Fig. 1: *MAPE-K Loop for distributed planning and optimization.*

Therefore, an adaptive DSM approach that is able to react on changing environmental conditions and to adjust the scheduling of consumers accordingly, is proposed in this paper. The architectural approach was presented in [23] and showed the general application of such a decentralized Demand-Side optimization with regard to the usage of existing or envisioned standardized components. The distribution concept of the optimization was described in [24], while this paper focusses on the well-established MAPE-K feedback loop (see Fig. 1) from Autonomic Computing [3]. Deviations, e.g. changing forecasts or changing load schedules (for example represented through IEC61850-7-420 Schedules) are monitored by the concerning entities. If the external impacts on the original scheduling are considered significant for the achievement of the system targets (Analyze), readjustments of the original load-schedule or even re-optimizations can be planned and executed. The planning, e.g. optimization of the schedule, is performed cooperatively by the participating Agents with an adopted Ant-Colony Optimization Algorithm.

4.1. Model and Problem Structure

The system itself thus contains a set A of Agents, referred as Multi-Agent-System. An Agent $a_i \epsilon A$ represents a device in the physical system to be optimized. Each Agent has a load-profile $L_i(n)$ and a set of possible discrete operation times S_i within the planning horizon. A possible starting time for operation $s_{ic} \epsilon S_i$ is based on the operational constraints C_i of the physical device. These constraints could be based on the user's input and/or predictions with models and sensor data.
The task of the optimization is to choose for each Agent a_i in A a time of operation out of S_i which minimizes the total cost of operation I. A generic description of the market model and the calculation of the total cost of operation are provided in [24]. In this paper a simplification of the market is used, so costs are calculated according to the provided schedule for the whole system to be optimized. A (simplified) schedule is an array containing a 3-tuple (or *triplet*) for each scheduling period k in the form:

$$O_k = (P_k, v_{k,low}, v_{k,high}) \qquad (1)$$

with P_k as the power offered in the period k at price $v_{k,low}$. When the planned consumption $P_{k,planned} > P_k$, the difference power costs $v_{k,high}$ per unit. As less consumption as requested is typically not considered as harmful as a system that exceeds the requested consumption, usually $v_{k,low} < v_{k,high}$. Due to the elasticity of the demand, the total difference between $v_{k,low}$ and $v_{k,high}$ can be neglected.

To obtain a beneficial structure of the problem for the application of different combinatorial optimization algorithms, the Agents in A can be ordered in a list, choosing an arbitrary permutation. Thus, the arrangement of the Agents in A can be understood as a directed graph, as well as their sets of starting times (see Fig. 2).

An optimizer traverses this graph and chooses from each set S_i one starting time s_{ic} according to the optimi er's rules

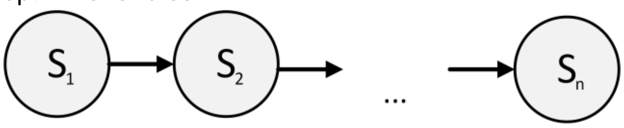

Fig. 2: *Abstract formulation of the optimization problem as directed graph of discrete starting times sets.*

This paradigm is sufficient for so called semi-automatic devices with just a single operation time during the time-frame to be optimized. This class contains e.g. washing-machines or dishwashers, which run one time between the initialization and the time the user wants the device to be finished. A constraint for such an device controlled by the Agent a_i can be for example:

$$C_i = t_{now} < s_{ir} < (t_{end} - t_{operation}) \qquad (2)$$

For a fully-automated device that maintains a state between certain limits with actors and sensors (e.g. a thermal load), the $1:1$ relation between agent and set of operational times is not sufficient as the dynamic nature of these devices is not represented. The first set of possible operational times usually allows operations within the operational borders. Depending on the chosen time, a new set of possible operational times, maintaining the state of the device, emerges. So the number of sets for a fully-automated device changes dynamically during the optimization phase, depending on the operational times chosen, as in Fig. 3 for Agent a_2 is shown.

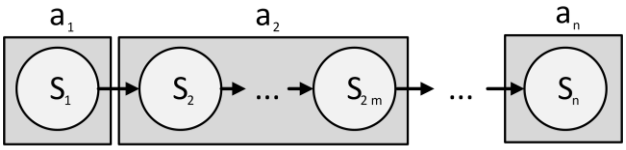

Fig. 3: *Directed Graph with dynamic constraint-based subsets.*

Devices with more than one runtime during the optimized frame have a $1 : m$ relationship between Agent and number of sets of possible operation times, while m depends on the actual path through the directed graph.

This problem description allows the optimization of consumers without any further external resource and with minimum (and adjustable) efforts. In contrast to e.g. [25], no centralized run-time adaption of the business model is necessary, as the scheduling in conjunction with the price-elasticity of the devices allows an exact control of the system a priori, and penalizes misbehavior (typically deviations above P_k) through higher prices. Although the problem complexity grows exponentially with a rising number of devices, the number of messages within each optimization step increases linear with the number of sets S through the avoidance of expensive Broadcast- or Multicast-operations.

4.2. Ant-Colony System Algorithm

Ant Colony Optimization is a meta heuristics for solving graph-based problems, inspired by the natural behavior of foraging ants. Ants place a chemical substance, called pheromones, on their path between food source and nest in order to indicate favorable trails. This behavior was adapted by [26] and extended as the reinforced learning algorithm Ant Colony System (ACS) by [27]. Ants traverse the links of a graph sensing the distance between nodes and the pheromone-amount on the links. After traversing the graph, the best Ants place pheromones on their routes (Elitist-Concept). The ACS has been proven as an interesting approach on natural computing, with a performance comparable to other established Evolutionary Algorithms like Genetic Algorithms [28]. In the described DSM-domain in conjunction with the ACS Algorithm a node is defines as a starting time $s_{ic} \epsilon S_i$. A link of the directed graph is described as a starting time $s_{ic} \epsilon S_i$ of the agent a_i towards a starting time $s_{jd} \epsilon S_j$ of agent a_j, which is a successor of a_i in the ordered list of agents. The link in the ACS-domain is further described through a *distance* between the two nodes, which is the cost of the operation in such a configuration and the *pheromones* on it.

The probability of choosing a node s_{jd} from the node s_{ic} out of a set of available nodes $\mathrm{S_j(r)}$ of agent a_j is described by

$$\mathrm{p(c,d)} = \frac{\tau_{cd}^{\alpha} \cdot \eta_{cd}^{\beta}}{\sum_{u \,\epsilon\, S(r)} \tau_{cr}^{\alpha} \cdot \eta_{cr}^{\beta}} \qquad (3)$$

where η_{cd} is the inverse of the cost of this configuration and $\alpha \geq 0$ is the pheromone weight parameter and $\beta \geq 0$ is the distance weight parameter. The cost of the configuration is calculated by the solution-so-far adding the cost of operation at the time s_{jd} in conjunction with the load-profile $L_j(n)$. Each time an ant traverses the vertices between the nodes c and d a local pheromone update of τ_{cd} is performed:

$$\tau_{cd} \leftarrow (1 - \varphi) \cdot \tau_{cd} + \varphi \cdot \tau_0 \qquad (4)$$

with $0 \leq \varphi < 1$ as local pheromone decay parameter and τ_0 as initial pheromone value.

Listing 1: ACS - Algorithm

```
begin
 do
  for each a in A do
    request from a:
      set of possible starting times S_a
      pheromone-matrix T_a
      load-profile L_a
    choose one s out of S_a with Eq. (3)
    adjust T_a with Eq. (4)

    add L_a at s in the
       intermediate solution
  end for each

  choose best solution so far

  for each a in A do
   adjust T_a  with Eq. (5)
  end for each

 until convergence

 agree on best schedule
end
```

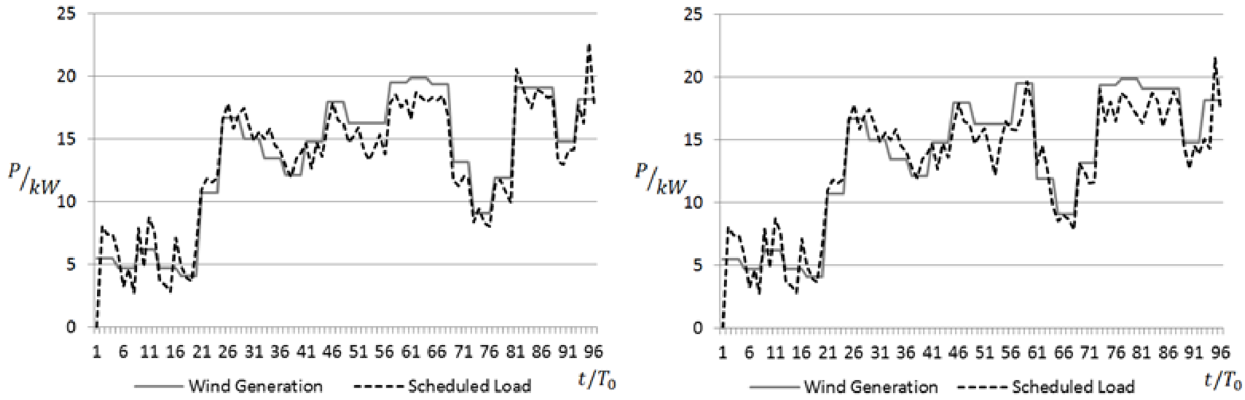

Fig. 4: Scheduling of dynamic loads towards a forecasted wind generation. Initial planning (left) and intraday adaptation (right). Forecast changes at time 50.

After each ant of a colony has built a path through the graph, a global pheromone update is performed:

$$\tau_{cd} \leftarrow \begin{cases} (1-\rho)\cdot\tau_{cd} + \rho\cdot\Delta\tau \\ \tau_{cd} \end{cases} \quad (5)$$

The upper case is performed when (c, d) is on the best route, the lower one otherwise. ρ is the global pheromone evaporation parameter with $0 \le \rho < 1$ and $\Delta\tau$ is described by

$$\Delta\tau = \frac{1}{I_{best}} \quad (6)$$

I_{best} is either the iteration best cost of operation (of the whole system) or the global best.

In Listing 1 the behavior of an Ant, optimizing the list of Agents, is described in pseudo-code. It can be seen that creating intermediate solutions with the chosen starting times is an important step as the Ant proceeds through the graph. Knowing the cost of the intermediate configuration until $a_i \epsilon A$, the Ant is able to calculate the costs of adding the load a_{i+1} at all allowed starting times of a_{i+1}, choosing one out of S_{i+1} according to Eq. 3.

5. Evaluation

To demonstrate the approach with the MAPE-K loop, 100 domestic households using the described ACS were simulated. The device configuration of the residential area is stated in Tab. I and is based on the statistical distribution of these devices in Germany [29]. The devices were chosen because of their dissemination, their relatively high demand for power (compared to other household appliances) and the likeliness that consumers will accept a slightly altered usage paradigm. As non-controllable loads (light, consumer-devices, etc.) are not interesting for Demand-Side-Management, their influence is not considered here.

The two semi-automatic device-types have slightly different power demand curves (see Tab. II) with an operation time of almost 2 hours. Each device was parameterized with a semi-random starting time based on the operational probability and an allowed delay between 0 and 6 hours.

The aim in this scenario is the demand-optimization of the shiftable consumers in order to use the projected generation of a wind power plant more efficiently and to reduce the external purchase of energy. The simulated wind power plant is an ENERCON E-30 with the wind data from Hamburg, Station Finkenwerder at the 16.09.13. In order to match generation data and the residential demand, 10% of the power rating were used for the optimization of the shiftable devices and appliances, so mean generation and mean demand are almost equal. Demand exceeding the power rating was priced with $v_{k,high} = 1.0\ per\ kW$, while the low price was $v_{k,low} = 0.1\ per\ kW$. The parameters for the optimizer were determined empirically: $\alpha = 4,\ \beta = 1,\ \rho = \varphi = 0.1,\ \tau_0 = 10^{-6}$

In Fig. 4 the initial day-ahead scheduling is shown (left). Note the period from 68 to 81 where the generation is quite low. During the operation of the system, the monitoring and analysis components senses a sudden change of the forecast at time 50 and the period of low generation is now from 60 to

Device	Type	Number
Washingmachine	Semi-automatic	95
Dishwasher	Semi-automatic	64
Electric heating	Fully-automatic	4

Tab.1: *Consumers in the residential simulation*

73 (Fig. 4, right). The cooperative planning by the Agents adapts towards the new schedule, using their knowledge about their available shifting potential and the new forecasts. The mean deviation from the schedule rises from 15.12% with the original planning to 18.06% with the adapted schedule.
Tests show that even when the planning horizon is very short, e.g. just a few minutes in advance of the change, the system adapts through the ACS very fast towards a nearly optimal scheduling.

6. Conclusion and Future Work

In this paper we proposed a distributed Ant-Colony based self-optimization approach for Demand-Side-Management. Both, the implementation of the Ant Colony System as a meta-heuristics for the optimization as well as the developed distribution concept of the algorithm were described. The distributed algorithm was integrated as a cooperative planning step into the MAPE-K feedback loop from the Autonomic Computing approach. A self-optimizing Demand-Side-Management system that is able to adapt its day-ahead planning to sudden environmental changes was realized. This results in an adaptive rescheduling of the consumers in case of sudden conditional changes. The introduced simplified market-model is almost compatible to the IEC61850-7-420 scheduling, just adding prices to the model in order to enable an optimization based on economical considerations.

A case study was evaluated where a day-ahead planned schedule needed to be adapted to a changed wind generation forecast in order to optimize the load of distributed consumers to the power generation of a wind power plant. The results

t (in ¼ h)	Washingmaching (in W)	Dishwasher (in W)
0	100	80
1	2000	2000
2	900	80
3	100	80
4	100	80
5	300	2000
6	50	300
7	0	150

Tab.2: *Power demand of the washing machine and dishwasher (Source: [29])*

showed how the system was able to adapt its scheduled load in a self-optimizing fashion to the changing environmental condition, resulting in an optimized load schedule.

Future work will include further case studies with more sophisticated producers and consumers and also different events that require a self-optimizing adaptation of the planned schedule. In addition, a realization of the proposed self-optimization algorithm with the SodekoVS [30] approach is planned. In this context, an adaptive switch of planning algorithms based on the changing environmental-, markets-, or grid- conditions is envisioned. At the moment, all these conditions are reflected in the centrally generated power-curve and the price-model. The dynamic exchange of sensor data between these domains would allow a fully self-organizing system.

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Open Energy Exchange - A new way of social energy networking

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Abstract: The energy transition to (fluctuating) renewable electricity generation requires advances in infrastructure, efficiency, and demand response. Infrastructure is expensive, and users are hesitant to uphold or shift energy reduction, as shown by the limited success of energy saving contests on social networks. In addition, legislation changes slowly. We therefore suggest the integration of automatic demand response based on user preferences to foster a voluntary bottom-up alignment of supply with demand. The framework introduces a geo-location dependent social network in which energy consumers can choose a renewable energy plant in their neighbourhood, which shall drive the energy consumption of their connected home appliance. Incentives and rewards are given based on a gamification approach. A hard- and software prototype has been implemented.

1. Introduction

Governmental organisations, network operators and utilities are in need of sustainable and future-oriented energy management solutions to cope with the rapid evolution of the energy system.
A set of governmental measures and their economic and technical impacts has coined the German term “Energiewende” (energy transition) into the English language. One of the lessons learned in this context are the consequences of a missing involvement and information of the general public, which has to accept rising energy costs and the installation of new energy infrastructure.
Even though the private households only contribute 29% to the total electricity consumption in Germany [1] they are located close to the problematic areas in the grid and may thus be incorporated in fluctuation-compensating- and grid-stabilizing-strategies. To convince people to take part in these measures, awareness for the problem has to be established and a strong incentive is to be given while addressing the fear of loosing their informational and decisional freedom.
One way of dealing with this is the active involvement of the individual energy consumer. Social networks are an established tool to attract young and technology affine people and to exploit the potentials of gamification lying therein. *Welectricity* [2] and *Opower* [3] are examples of social network based energy saving contests, in which users can compare their energy usage to others and rally for the lowest energy consumption with their peers. While *Welectricity* relies on a proprietary and closed social network, *Opower* is a facebook plugin and thus addresses potentially more users. Despite limited success, these approaches have not achieved their expectations, which is ascribed to the burden of manual data entry and its dependence on time and discipline of the individual customer. This is also suspected as the reason for *Google*’s withdrawal of a comparable product [4]. While some users did enter their energy usage statistics of their own accord and no devices were switched by a third party (thus ensuring informational and decisional freedom), the given incentive was too low for the repetitive and time consuming work.
Changers.com [5] takes a different and more successful approach to the matter. The core business is the marketing of small photovoltaic solar panels with a recent shift towards the smartphone-app-based tracking of energy-efficient mobility. Both the panel and the activity tracker are connected to a proprietary social network. People are rewarded with statistics on their CO_2 savings and so called re-coins which can be traded into carbon certificates. As their users locations and energy production patterns are tracked, *Changers* does impair with their users informational freedom. The incentive given in return is the absolution in form of a measured reduction of the individuals carbon footprint.
This article presents the *Open Energy Exchange* (*OEEX*) as a concept that extends the idea of

involving the user. By operating flexible household appliances automatically dependent on nearby renewable energy production, the user is rewarded in a similar fashion as successfully demonstrated by *Changers*. To relieve the user of tedious and time-consuming manual tuning, a smart plug equipped with additional sensors is automating the measurements and activation (on/off).

The system is designed to be simple to allow non-experts to modify and apply the technology. By scaling the simple technology and the number of small energy consumers it shall foster the bottom-up demand response in an unregulated niche. Furthermore, it is meant as a flexible tool for scientists to test behavioural flexibility assumptions and demand response innovations [6] by extending the open source smart plug with their own concepts.

The paper is structured as follows: Section two describes the main principles of the social energy networking approach; afterwards (in Section three) a focus is laid on the software part of the project, giving information on the server and firmware implementation. The hardware is delineated in Section four, followed by an outlook on promising future work and a closing conclusion in Section six.

2. Social Energy Networking

The core of the *OEEX* approach is a geo location based social network. Within this network an energy consumer is given the possibility to virtually connect its household appliance to a renewable energy producer. This connection is established via a “following” relationship as known from services like *Twitter*. This means that for example the users’ fridge will “follow” the solar power plant selected and shift as much load as possible into times of the according plants renewable energy production. In contrast to Renewable Energy Certificates, which provide market segmentation and price discrimination but are prone to ’greenwashing’ [7], the ’following’ concept aligns the real power flows in the network by increasing the correlation between supply and demand. To facilitate the selection of an appropriate producer, nearby renewable energy plants are displayed as symbols on a map. When clicking on such a symbol, a social media profile giving personal information and a little story on the plant operator and its plant is displayed, as depicted in Fig.1. This shall enable the user to build up a personal relationship to the origin of the energy she consumes. When the user has found its preferred producer, she just clicks the “I like that plant” button in the profile displayed and its appliance is already set up.

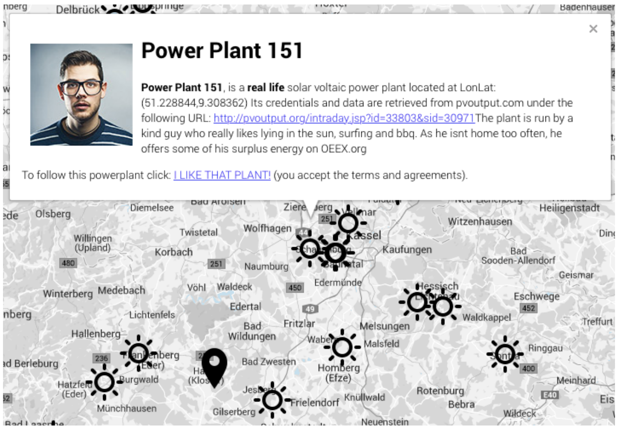

***Fig.1**: Geo-located social media profile*

After this short setup the user can access statistics on the carbon savings achieved and other related performance indicators, as for example the degrees of global warming prevented or square meters of ice saved in Antarctica. Albeit these numbers are small, they answer why this alignment matters.

Other features of social networks, like user interactions, valuation systems or comparison tools may be implemented depending on user feedback.

The advantage of the approach can be seen in the constant generation of a good – green – conscience without the burden of manual work. The user can easily access the information at a fingertip on his mobile phone, but is not required to do so. Next, consider the informational and decisional freedom under this approach. The operation strategy of the device (e.g., a fridge) is determined by a smart plug that submits measurements online and receives a recommendation in return. The decision is made locally, but some information is revealed to request a recommendation.

3. Software

The current OEEX software framework is based on the following pillars:

1. The **Server Frontend** serving User and web-service based plant interaction.
2. The **Sever Backend** hosting a database containing user and plant data as well as all logics and heuristics for user feedback and plant control.
3. The **Spark Cloud** service enabling device discovery and configuration by means of a web-service interface. As the service is only used

upon device registration it will not be described any further below.

4. The **Device Firmware** acting on the underlying appliance based on simple, fail-safe heuristics for on- and offline operation.

The Server Frontend, Backend and Spark Cloud may be subsumed under the term *OEEX*-Cloud, as depicted in Fig.2. The connected smart plugs communicate via https-connections with the Server Backend, which will generate switching advices as a function of the followed producers power availability.

3.1. Server Frontend

The Server Frontend features a lean and intuitive website explaining the underlying concepts in a brief and non-technical fashion, boiling it down to distinct bullet-points. It can be found under the web-address: http://www.oeex.org. Technically interested users who want to join in the *OEEX* universe find building instructions for the smart-plug's circuitry and hardware as well as software downloads and setup instructions. As no user trails have been performed so far the data displayed are wildcards, based on data gathered from open data sources.

3.2. Server Backend

The *OEEX* key enabler is a backend containing an SQL database and simple yet powerful algorithms to match power and demand while considering marginal conditions set by the user or arising from technical requirements of the underlying appliance.

The database contains general device and user information as for example user IDs, social media profiles and device descriptions building the base of the social network implemented. Inter device and user relations and interactions are stored as well, enabling a live or retrospective behavioral analysis.

Besides these analyses the backend calculates statistics on carbon reductions upon user request issued by means of the Server Frontend. As the connection to the smart plugs is based on an asynchronous information transfer triggered by a device request towards the server, the switching advices in form of a reference signal are only calculated on request as well. The reference signal represents the expected excess of energy produced by the target generator that is 'followed' by possibly several smart plugs. The signal can be distorted by device thresholds and restrictions, as for example the minimum on and off times to preserve a fridges' compressor or the maximum and minimum internal temperature to preserve the stored goods.

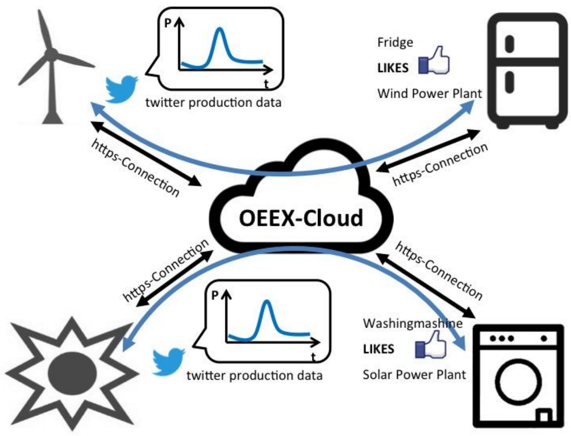

***Fig.2**: OEEX system design principles*

3.3. Firmware

By choosing the Spark Core integrated micro-controller board as the heart of the system an easy wifi-connection mechanism via the TI CC300 Simple Link wifi chip is at hand.

After connecting the device to the wifi, it attempts to join the *OEEX* cloud and will operate in offline mode until it receives information, that it is associated to a user account and an energy producer.

While in offline mode the device operates between preset boundaries, with a heuristic aiming to accomplish as few switching operations as possible. The thresholds may be altered by the user online after associating the device to its' particular account. While featuring this fail-safe behavior the device constantly tries to (re-)connect to the cloud.

When connected to the cloud it switches into an online-mode, gathering data and reporting it to the *OEEX* cloud. In return it receives a reference signal, which is taken into account when deciding to switch the underlying appliance.

4. Hardware

With the rise of smart meter and home automation technology a multitude of remote switching and power measurement solutions is at hand. However none of these allows for an easy integration of further measuring and switching points, as for example a temperature sensor in a fridge or an actuator to start a washing machine. Furthermore does the variety of different providers with proprietary protocols and APIs enhance complexity to a non manageable level. Here, we present a low priced smart plug, which shall be deployable in every household with an internet connection and an accompanying WIFI-router without the need for a central hub as found in many home automation solutions. By using off-the-shelf microcontroller- and sensor-boards, the effort for hardware-engineering, assembly and testing is held down while still offering space for future expansions.

This is also the reason for the considerably low part count of only 19 pieces without the case. At the time of writing the price is below 100€ for all components with a prospect of dropping even lower. Besides the Spark Core Microcontroller Board as the heart and brain of the device, the following components shall be mentioned:

The AC/DC converter "RECOM RAC05-05SC" has been selected, ensuring a stable operation and expandability for more energy-intensive sensors and actuators. An Allegro ACS714 Current Sensor break out board is used to measure the electricity consumption of the device itself and the connected load. The connected load may be switched by means of a relay. External components are linked by means of a One-Wire bus interface, enabling daisy chaining multiple sensors and actuators, and facilitating later expansions for the development of tailored solutions (e.g., the switching of a washing machine via a servo, charging an electric vehicle with voltage control or monitoring a water heaters temperature and water-level). The connection of sensors is established via a 3.5mm headphone jack for reasons of pricing and robustness. A Maxim DS18B20 temperature sensor is connected, allowing to control a fridge or a water heater.

Circuit Diagrams, Eagle-CAD board layouts and detailed part lists with vendor information as well as plans for a 90x90mm acrylic glass case can be found on http://www.oeex.org or in related work [9].

5. Outlook

The proof-of-concept prototype presented above may be refined for valorization. On the server side, the user workflows can be streamlined for simplicity. With regard to the upcoming smart home infrastructures as for example Apples' HomeKit, a standardized communication and API could facilitate the explotiation of existing sensors and actuators. At the same time, initial end-user trials would be very valuable to indicate users' needs and gather information on the usage patterns, e.g., to improve the quality of service and user loyalty. Energy producers may be attracted to join the system, if analysis and evaluation tools are enhanced, which would also elicit the societal benefits of the system.

6. Conclusion

The *OEEX* system concept merges social- and energy networks, giving non-experts the power to participate in the green energy revolution. The platform aspires to be used as a tool for research and innovation in collective demand response in the distribution network and below, which has been identified as a key priority in smart grid research [8].

The open source smart plug facilitates testing innovative demand response solutions, such as voluntarily following distributed renewable energy sources. It is based on a client-server architecture, deploying streamlined heuristics and simple hardware which is made openly available. By utilizing a standardized bus system and open hardware it is extensible to a wide range of applications.

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Reliable operation of energy storage units in the power grid – an analysis of existing requirements

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Abstract: Energy storage systems are one of the most important components for realization of the future energy supply system. They are especially important for the effective integration of highly fluctuating electrical energy produced by RES. This article considers and analyzes different German legal and political frameworks as well as technical rules for integrating energy storage systems into the power grid and providing their cost-efficient operation. Possible points of discussion regarding the regulations for energy storage units for different frameworks are given.

1. Introduction

Electricity generation by renewable energy sources (RES) has gained greater importance in recent years. The goal of the federal government of Germany is to increase the amount of renewable generators by 80% by 2050. However, the stochastic character of energy generated by RES can have a negative influence on the security of the power supply and on power grid stability. In order to avoid such negative effects, corresponding adjustments in the power network infrastructure must be carried out. Alternatively, energy storage systems can be integrated into the power grid. In fact, energy storage systems are one of the most important components for the realization of the future energy supply system, especially for the effective integration of highly fluctuating electrical energy produced by RES.

Energy storage systems can be used in all sectors of the power grid. For example, they support big power plants during the scheduled load changes. For the transmission networks, energy storage systems provide:

- electrical power during power outages, and
- system services (e.g. compensation of reactive power for voltage stability or provision of balancing power for frequency stability).

For the distribution networks, the energy storage systems make congestion management possible, help maintain voltage stability and power stability, and make it possible to create virtual power plants.

On the consumer side, energy storage systems support the security of power supply, which is especially important for critical loads.

This article presents and analyzes different legal and political frameworks as well as technical rules regarding the integration of energy storage technologies into the power grid and to provide their cost-efficient operation. Possible points for discussion regarding the regulations for energy storage for different frameworks are presented here.

2. Legal and political frameworks

This section presents an overview of different legal and political regulations in Germany with regard to the conditions of energy storage integration and participation in the power grid.

a) *The Renewable Energy Act (EEG2014)*

The EEG includes the directive for the integration of RES into the power grid and for the providing of their economical revenue. The EEG aims to increase the amount of renewable generators and to make them a more competitive alternative to conventional power generators. The EEG 2014 defines storage systems as power units that can store energy produced exclusively by RES for an intermediate length of time and then transform it into electrical energy as needed (§5.1 sent. 2) [1].

According to §11, network operators are obligated immediately and as a priority to purchase, transmit and distribute the entire amount of available renewable energy. When the network operator regulates the renewable generator, he is obligated to compensate the corresponding RES operator for 95% of lost revenue; if the lost revenue is more than 1% of the annual revenue, the compensation rises to 100% (§15). Thus, the energy storages can be used by network operators in order to minimize such compensation costs.

Moreover, the EEG also offers financial benefits. According to §2.2 EEG2014 all new renewable generators are obligated to use direct marketing. Direct marketing is defined as the sale of produced renewable energy to third parties, except in cases where the energy is consumed in the immediate vicinity of the power plant and is not transferred through the power network [1]. In direct marketing the operators are entitled to the so called market premium. The traditional fixed EEG remuneration is applied except for the new small generating units (installed until 01.01.2016 with maximal power of 500kW and after 01.01.2016 with maximal power of 100kW) and except for the cases of failure on the part of the direct marketer. A fixed feed-in tariff is still the norm for exist renewable generators that have not switched to the direct marketing and if their 20-years remuneration period has not yet expired.

The market premium model is the dominant model used in direct marketing (§19.1.1). In this model, the operator of a generating unit can receive the remuneration in the form of a market premium in addition to the revenue from its own marketing of electricity. The market premium is determined as the difference between the fixed feed-in tariff and the electricity price, which is calculated using a reference value based on the average electricity price for one month, as determined by the electricity market (e.g. EPEX SPOT) [4], [2].

Immediately saving electricity in an energy storage system before feeding into the grid does not occur with direct marketing. But, EEG remuneration is possible when the stored energy is discharged and then fed into the network under conditions according to §19.1 and §19.4 of the EEG.

With regard to energy storage, §19.4 of the EEG determines that the remunerations should also be applied for the electrical energy fed-in to the power network from the intermediate energy storage. The remuneration is equal to the amount that the renewable generator receives without intermediate saving of electrical energy. The total remuneration is valid for 20 calendar years plus the year when the power plant was taken into operation (§22). This rule about obligatory remuneration is not applied to energy storage losses and electrical energy that is marketed as balancing energy.

Moreover, the EEG presents the network security guidelines. The central point here is the feed-in management according to §14, which enables network operators to disconnect certain renewable generators or cogeneration power plants from the power network under certain conditions, i.e. in the case of network bottlenecks (or in order to avoid it). Small PV systems can be disconnected only as a secondary measure. Thus, energy storage can be applied to avoid the feed-in management of renewable energy sources.

The EEG also provides for an exemption from the EEG apportionment for the electricity from energy storages. According to §60.3 the energy storages, that provide intermediate storage of electricity and its later feed-in into the power network, are excluded from the EEG apportionment.

The relevant points regarding energy storages considered in the EEG are [1]:

- priority grid connection (§8),
- right to remuneration (§19),
- prohibition of marketing for remunerated energy as balancing energy (§39, §80),
- mandatory direct marketing of energy (§2.2),
- exemption from the EEG apportionment for the electricity from energy storage (§60.3).

A possible discussion point regarding EEG regulations of energy storage systems is the development of strategies for balancing group management for energy storage systems. This point considers:

- working out the remuneration guidelines for energy saving depending on various energy generators,
- realization of market models for energy storage systems that store the surplus renewable energy from the power grid in order to ensure the basic power generation,
- usage of stored renewable energy as a balancing energy during critical network situations.

b) *Energy Management Law (EnWG)*

The next law considered in this paper is the Energy Management Law (EnWG) [4]. The goal of this law is to ensure a cost-effective, efficient and user friendly supply of electricity and gas.

The EnWG under §3.15 classifies energy storage systems as power units and, under §3.31, only defines gas storage systems. Thus, an energy storage system can be determined as a power unit, which is able to store energy and to later release it.

The important aspects for energy storage that are considered in EnWG, are [4]:

- non-discriminatory grid connection conditions (§17.1, § 17.2)

- obligation for energy storage with a rated power of at least 10MW to adjust the required active and reactive power for the transmission system operator (TSO), (§13.1a),
- exemption from the general grid connection obligation for generation units, also in conjunction with energy storages in the case of covering their own consumption (§18.2),
- the operators of energy storages are obligated to publish their technical characteristics and technical descriptions of their network connection in the internet (§19.1),
- exemption from network charge for electrical energy storages that were installed after 31.12.2008, and which will begin operation during the 15 years after 04.08.2011. Such an exemption is limited for an operation time period of 20 years (§118.6). The requirements here are the continued electricity feed-in into the power network, and the maximal load must deviate significantly from the simultaneous annual total peak load of all consumers.

A point for possible discussion here is the fact that the EEG and the EnWG pursue different objectives (the EEG provides the remuneration for RES while the EnWG ensures a cost-effective and reliable power supply). The other point to be discussed is the obligation for every energy storage system to participate in adjusting the required active and reactive power for the TSOs.

c) *Other Regulations*

The System Service Ordinance (SDLWindV) regulates technical requirements, especially reactive power compensation, for wind turbines at the grid connection point. Wind turbines that were installed before 01.01.2009 can claim the system services bonus if they fulfill the requirements of SDLWindV according to EEG2009/2012. Thus, if the energy storage system is installed between the power network and the wind turbine, it is necessary to fulfill the requirements of either an energy storage system or an associated inverter in order receive this bonus. The regulation on electricity feed-in to and consumption from the electricity supply grid (StromNZV) presents the rules for access to the power supply network. The Electricity Grid User Charge Ordinance (StromNEV) defines the guidelines for the formation of network charges, that are limited by the Incentive Regulation Ordinance (ARegV). In addition to the exemption from the network charges according to the EnWG, it is also possible to influence the network fee via StromNEV. The timely usage of an energy storage system can help an electricity consumer reduce its electricity consumption (and as a result that of its network operator). If the consumer does so then, according to the StromNEV §19.2, the network operator must offer individual network charges to this end-consumer, which take adequately into account the specific usage behavior of the grid customers. However, these individual network charges must be at least 20% of the regular network fee. More network support from the consumer side leads to a decrease in individual network charges. Thus, the use of energy storage systems can significantly decrease the network charges [7]. Individual network charges (see Fig. 1) are also offered when large amounts of electricity are purchased, if the following conditions are fulfilled (§ 19.2 StromNEV):

- the consumer's electricity consumption is more than 10GWh/year, and
- the number of operational hours is at least 7000 hours/year.

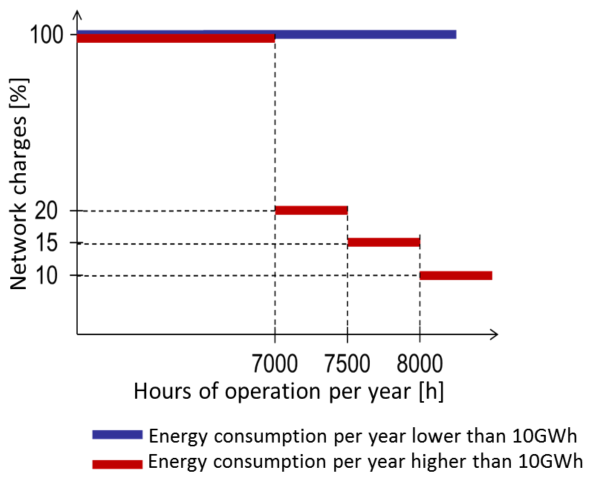

Fig..1*: Reduction of network charges for large electricity consumers*

With regard to the StromNEV, the following aspects can be discussed:

- moderately decreasing network charges for large consumers, which can be determined through simulations,
- extending the exemption of network charges to energy storage systems,

- considering energy storage systems as a separate kind of technology instead of as a consumer.

The Electricity Tax Act (StromStG) regulates the formation of electricity taxes. The main aspect of the StromStG that effects energy storage systems is the amount of electricity tax that the electricity consumer has to pay (20,50 €/MWh). And, because energy storage systems are considered to be consumers, they are also taxed. At the same time, electricity from renewable energy sources is tax free. For a possible discussion, the following points are proposed:

- exemption of electricity taxes for energy storage systems (particularly when storing energy from RES),
- avoidance of double taxation of energy storage systems,
- consideration of energy storage systems as a separate kind of technology instead of as a consumer.

d) *Components of Electricity Price*

A precise consideration of the main components of electricity price helps to assess correctly the impact of the exemption from some of these components. As an example, the electricity price for private customers in Germany for May 2014 will be analyzed. The values mentioned here are averaged values and can vary depending on region and electricity supplier.

It can be seen that the biggest portion of the electricity price comes from electricity production and distribution, and is about 25% depending on the electricity market. The second largest component is network charges, which accounts for about 21% of the total price. This fee is for the use of the power network during the electricity transport and distribution. The electricity tax and Value Added Tax (VAT) together compose another 23%, and the EEG fee is about 21%. The EEG fee is required to compensate for the additional costs of network operators, which occur from the increased price for electricity from RES. The remaining almost 9% is composed of different apportionments and taxes. The biggest part of which is the concession fee (about 6,33%), which the energy supplier pays to the utility for using of the public infrastructure. The remaining fees and taxes include: a cogeneration levy, which serves to promote the cogeneration power plants; the apportionment according to §19.2 of StromNEV for compensating the deficits from reduced network charges for specific electricity customers; the offshore apportionment to compensate the distortions that occur during the grid connection of offshore wind turbines; and the apportionment according to §19 for the regulation of disconnected loads (AbLaV) to cover the costs of interruptible loads, which are used to maintain the system reliability [3].

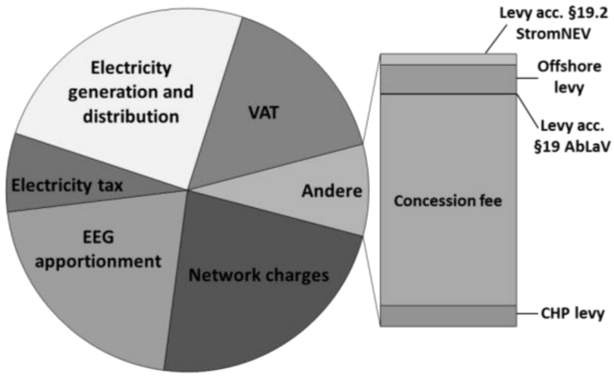

Fig..2: *Components of electricity price 2014 according to [3].*

Furthermore, there are various possibilities for special exceptions for different components of the electricity price.

Thus, the following exemptions or reductions of the EEG apportionment should be mentioned:

- According to EEG §60.3 the exemption of the EEG apportionment can be made for electricity that is stored in an energy storage system and will only be used for re-supplying the power network.
- Different versions of the EEG present different privileges for the self-consumption electricity from RES. Thus, according to §61 EEG2014 the exemption from the EEG apportionment can be made in the following cases:
    - if a self-supplier of electricity is not connected to the utility network (isolated power plant) or
    - fully supplies itself with electricity and uses no facilitation for the energy surplus, or
    - it is a small self-supplying power plant (with parameters up to 10kW and up to 10MWh per year, which will not change over the next 20 year period).
- According to §63, the EEG apportionment can be reduced for electricity intensive consumers and track railways.

According to the EEG §61.1 and §61.2 the electricity purchased from RES and cogeneration power plants has reduced apportionment, which will be increased until the year 2017 from 30% up to 40% of EEG apportionment.

As for network charges, they are levied in accordance with §3 StromNEV for power network usage in order to carry out electricity consumption. Network charges are calculated for each used network level and passed on to the operator of the corresponding low-level network. According to §15.1 StromNEV the network charges are not applied to the feed-in electricity. According to §18 StromNEV, the network operator of the network that the electricity is fed-into charges the operator of the distributed power generators fee that corresponds to the avoided network charges.

3. Technical frameworks

In addition to the legal and political frameworks, there are also technical conditions that need to be considered.

a) *Transmission and Distribution Codes*

Transmission Code 2007 (TC2007) presents the conditions and rules for high and extra-high voltage networks [5]. TSOs are obliged to ensure the secure and constant electricity supply according to the TC2007. Furthermore, they are responsible for the balance between electricity supply and demand. The task of the TC2007 is to ensure the following system services [5]:

- voltage stability due to reactive power management (TC2007 §3.3.13.5),
- re-establishment of power supply due to:
    - island operation capability (§3.3.14.2),
    - black start capability (§3.3.14.3),
    - concepts of power network rehabilitation (§3.3.14.4),
- system/operation management due to the 5-stage plan for frequency regulation (TC2007 §7.3.4):
    - 49,8Hz – alert the staff and usage of still available generator capacities according to the TSO; dropping of pumping;
    - 49,0Hz – instantaneous load shedding of 10-15% of the network load,
    - 48,7Hz – instantaneous load shedding of a further 10-15% of the network load,
    - 48,4Hz – instantaneous load shedding of a further 15-20% of the network load,
    - 47,5Hz – disconnection of all generating power plants from the power grid,
- frequency stability (provision of balancing power).

Distribution Code 2007 (DC2007) describes the certain minimum technical specifications for medium and low voltage networks, namely for distribution system operators (DSO) [6].

Considering the TC2007 and the DC2007 the following points for possible discussion can be mentioned:

- the possibility to use the energy storage as a means for realizing system services,
- allowing system operators to operate the power generators, in order to ensure the system security,
- sub-division of storage capacity according to its application purposes.

As mentioned above, energy storage can participate on the balancing energy market by providing balancing power. The TSO is responsible for balancing the power (namely using primary, secondary and tertiary balancing power) according to EnWG §12.1, §13.1.2. TSOs are prequalified to use all types of control power in the control area in which the relevant technical unit is connected (independent of voltage level). The prequalification requirements are presented in the TC2007. For energy storage the following guidelines are important:

- According to the TC2007 Annex D1, the priority task of energy storage, independent of its current schedule (e.g. transaction on the energy exchange), is to ensure primary balancing power. The corresponding TSO shall provide a concept for this.
- According to the TC2007 Annex D2, dynamic operation is typical during the phase of secondary balancing power because of the permanent power imbalances. Therefore, energy storage should also provide the dynamic operation. Thus, the pooling concept for the supplier is possible. The pooling can be controlled either by signal or by technical units.
- Pooling is also possible during the tertiary balancing power (according to the TC2007 Annex D3). For participation here energy storages shall have the minimal value of

1MW. The operational availability for providing the entire service must be 100%.

b) Other technical directives

The grid connection and operation of the energy storage (or energy storage system) shall comply with the following technical guidelines [8]:

- VDE-AR-N 4101 – Requirements on meter panels for electrical power plants in low voltage networks,
- VDE-AR-N 4105 – Generating units in low voltage networks – technical minimum requirements for connection and parallel operation of generating units in low voltage networks,
- TAB 2007 – Technical Grid Connection Guidelines for connection to low voltage networks,
- TAB 2008 – Technical Grid Connection Guidelines for connection to middle voltage networks,
- VDE|FNN – Guidelines for the technical/ operational realization of feed-in management,
- Technical guidelines for generating units in middle voltage networks,
- ENTSO-E-Network Code for Requirements for Grid Connection Applicable to all Generators.

Additionally, the FNN-Guideline "Grid Connection and Operation of Energy Storages in Low Voltage Networks" gives some technical requirements for distinction of energy storage according to operational modes [8]:

- Energy consumption mode – energy storage system is charged from the public or customer-owned AC network. In this case the requirements of TAB 2007 is applied;
- Energy supply mode – energy storage system is discharging to the public or customer-owned AC network. In this case, it is considered as a generating unit, thus VDE-AR-N 4105 and Technical Grid Connection Guidelines of network operator (TAB NS) are applied;
- Island grid mode (maximal permitted durability of interconnection to the utility network in this mode is smaller than 100ms) – in this case, energy storage is disconnected from the public AC grid, is charged from and discharged to the customer-owned AC network. Here, the Technical Guidelines "Emergency power generators" are is applied.

4. Conclusion

This paper provides an overview of the main frameworks – both political and technical – that are relevant for the effective and successful connection of energy storage to the power grid as well as its further cost-efficient operation. Moreover, this paper presents points of possible discussion or adjustment that can be done in the existing frameworks, when considering energy storage as a new participant in the power grid. An extension of the existing technical and political frameworks is needed in order to operate the storage system both cost effectively and technically effectively in the future.

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