DISSERTATION

Automated Buildings as Energy Storages

Using the thermal capacity of commercial buildings as energy storage by introducing model based decision strategies into existing building automation systems

Submitted at the
Faculty of Electrical Engineering and Information Technology,
Technische Universität Wien, Vienna, Austria

in partial fulfillment of the requirements for the degree of
Doktor der technischen Wissenschaften

under supervision of

Em. o. Univ. Prof. Dipl.-Ing. Dr.techn. Dietmar Dietrich,
Institute of Computer Technology
Vienna University of Technology, Austria

and

Univ.Prof. Dipl.-Ing. Dr. Wilfried Elmenreich
Institute of Networked and Embedded Systems
Alpen-Adria-Universität Klagenfurt, Austria

by

Dipl.-Ing. Klaus Pollhammer BSc.
Matr. Nr. 0126339
Breitenfurterstrasse 378/3/28
1230 Wien

5th of February 2016

Kurzfassung

Durch die verstärkte Einbindung erneuerbarer Energieträger wie Wind- und Solarenergie steht die Energieversorgung und –verteilung vor neuen Herausforderungen. Durch die nicht gänzlich prognostizierbare Einspeisungsprofile dieser Energieformen tritt die Problematik der nur begrenzt verfügbaren Energiespeicher für elektrische Energie stärker zutage als bisher. Diese Herausforderung und weitere, wie die Einbindung der Verbraucherseite durch Einsatz von Kommunikationstechnologie, wandeln das Energieversorgungsnetz in ein so genanntes intelligentes Netz oder Smart Grid. Der Ausgleich des Fehlers zwischen Prognose und realer Einspeisung erneuerbarer Energieträger ist durch das Fehlen von mittelfristigen Speichertechnologien bislang nur mit Hilfe des Einsatzes von Regelenergie beherrschbar. In dieser Arbeit wird die Möglichkeit untersucht, inwieweit Gebäude für Lastabwurf-Szenarien verwendet werden können und welche Voraussetzungen dafür notwendig sind. Unter der Annahme, dass ein Verschiebe- und dadurch Speicherpotential bei funktionalen Gebäuden besteht, wird zu Beginn der Untersuchung ermittelt wie viele solcher Gebäude mindestens notwendig wären, um den Windprognosefehler für ganz Österreich auszugleichen. Es werden die Anforderungen hinsichtlich Kommunikation und Funktionalität an funktionale Einheiten (Demand Response Controller, Gebäudeagent) aufgezeigt, welche notwendig wären, um die elektrische Last funktionaler Gebäude als Verschiebepotential nutzen zu können. Diese Einheiten sollen ermöglichen, dass auf Basis eines vorhandenen Gebäudeautomationssystems Last verschoben werden kann und so Speicherkapazitäten in den physikalischen Vorgängen des Gebäudes (z. B. Temperatur der Luft) für das Energiesystem aktiviert werden. Eine funktionale Struktur für solch einen Demand Response Controller wird eingeführt und die darin enthaltene Entscheidungseinheit wird untersucht und Möglichkeiten evaluiert, wie mit Hilfe selbst-adaptiver Modelle dieselbe Konfiguration für unterschiedliche Gebäude verwendet, sowie auf Änderungen in der Gebäudephysik im laufenden Betrieb reagiert werden kann. Mit Hilfe von Simulationen und Experimenten wird die Machbarkeit des vorgestellten Lösungsansatzes belegt. Es wird gezeigt, dass durch die Aktivierung von Gebäuden und ihrer enthaltenen Verbraucher und Speicherkapazitäten eine gänzlich neue Perspektive im elektrischen Energiesystem aufgezeigt wird. So kann eine Möglichkeit zur mittelfristigen Speicherung von Energie - die Verschiebung von Energieverbrauch von Gebäuden - dem Energiesystem zu Ausgleichszwecken zur Verfügung gestellt werden. Ergebnisse zeigen, dass mit Hilfe des untersuchten Ansatzes - Verwendung funktionaler Gebäude als Lastverschiebepotential - in Kombination mit der Einspeisung erneuerbarer Energieträger eine beinahe zur Gänze prognostizierbare Einspeisecharakteristik erreicht werden kann. Dies ist durch den Ausgleich des Prognosefehlers möglich. Erneuerbarer Energieträger können dadurch großflächiger eingesetzt werden und damit verstärkt genutzt werden – ohne zusätzlich Regelenergie für den potentiellen Ausgleich bereitstellen zu müssen. Simulationen einer funktionalen Implementierung des Demand Response Controllers zeigen darüber hinaus, dass eine Umsetzung der vorgestellten Kommunikationsstruktur mit Smart Grid-Controller und Gebäudeautomationssystem möglich ist. Ebenso zeigen Experimente, dass die Umsetzung eines selbst-adaptiven Temperaturprognosemodells selbst auf einer sehr leistungsschwachen Feldeinheit eines Gebäudeautomationssystems möglich ist.

Abstract

Stronger integration of renewable energy sources like wind or solar power to the power infrastructure leads to new challenges for the power grid. Renewable energy sources tend to follow a non-fully predictable generation profile a characteristic that increases the problem of having only limited possibilities to store electric energy. Challenges like the mentioned one as well as a stronger integration of the load side through communication links between all entities lead to a transformation of the power grid into a smart or intelligent power grid. Due to the lack of mid-term storage technologies the compensation of the prediction errors of renewables is only possible through the provision and activation of balancing energy. The presented work investigates the hypothesis that buildings as a whole can represent a potential for load shedding and which requirements have to be met to activate buildings as demand response storages. On the supposition that buildings have electrical load shedding potentials the work starts with an analysis how many buildings would be necessary to fully compensate the prognosis error of wind power generation in Austria. Requirements on communication and functionality for a functional unit (Demand Response Controller, Building Agent) are formulated. This functional unit is supposed to activate the load shedding potential of commercial buildings for the smart power grid through influencing already existing building automation systems in said commercial buildings. In this way it is intended to exploit different physical processes and parameters inside the building (e.g. air temperature) as temporal buffers for load shedding – and therefore storage – potential for the energy system. Workflow and functional structure of a demand response controller are presented and the included model based decision unit is analyzed. A new way to not only simplify the necessary models but also adapt certain model parameters on-the-fly through self-adapting mechanisms is outlined. It is shown that, with the help of self-adapting models, changes of the building physic can be faced and covered without changing the simulation model itself. Simulations and different experiments show the feasibility of the approach. The activation of buildings and its internal devices as active nodes in a smart grid brings a new perspective into smart grid applications. Buildings that act as load shedding units can be used as medium-term storages that can be utilized for balancing scenarios. The results show that with the help of buildings as demand response storages or load shedding units in combination with renewable energy sources a fully predictable generation profile can be generated. In further consequence renewable energy sources can become a fully predictable energy source and because of that (until now) necessary balancing energy for back-up is not used any more. The proposed functional unit to make this approach feasible – a so-called Demand Response Controller – is simulated and successfully evaluated. Additional experiments prove that the developed self-adapting temperature models for buildings can be implemented on low-profile field devices of a common building automation system. In conclusion it is shown that the presented communication hierarchy and structure that connects Smart Grid Control Unit and Building Automation with the help of said Demand Response Controller can be used as intended.

Danksagung

Eine Dissertation zu schreiben ist eine einsame Sache, meist sitzt man alleine vor seinem Bildschirm und versucht aus den Erkenntnissen die richtigen Schlüsse zu ziehen oder – noch schwieriger – diese in klarer und logischer Form schriftlich darzulegen. Umso mehr braucht man die zahllosen Menschen um sich, die einen ermuntern, aufheitern, anspornen, unterstützen oder in sonst da sind. Aus diesem Grund haben natürlich die verschiedensten Leute Anteil daran, dass diese Arbeit nun genau so aussieht wie sie eben aussieht.

Beginnen möchte ich bei meiner Danksagung mit den Personen ohne deren Betreuung diese Dissertation gar nicht zustande gekommen wäre – Professor Dietmar Dietrich, ohne dessen Unterstützung und Ansporn diese Dissertation wohl im Sand verlaufen wäre – Professor Wilfried Elmenreich, dem ich besonders dankbar bin, dass er sich kurzfristig bereit erklärt hat diese Dissertation als Zweitbetreuer zu übernehmen und Friederich Kupzog, ohne den es die Energy&IT-Projektgruppe und somit die Grundlage dieser Arbeit nicht gegeben hätte (und dessen erster und letzter Dissertant aus dieser Projektgruppe ich möglicherweise bin).

Außerdem gebührt meinen Kollegen aus den Forschungskonsortien der beiden nationalen Projekte „BED – Balancing Energy Demand with Buildings“ (Haus der Zukunft Plus, Nr. 822235) und „OREANIS“ (Neue Energien 2020, Nr. 818880) sowie dem Fördergeber selbst Dank für die erfolgte Unterstützung.

Des Weiteren möchte ich mich bei allen ehemaligen Kollegen vom Institut für Computertechnik für die langjährige, gute und tolle Zusammenarbeit und die gemeinsamen Mittagessen bedanken, insbesondere bei allen Mitgliedern der Projektgruppe Energy&IT (Georg, Thomas, Marcus, Mario, Alexander, Pavlos, Eva), Martin, Michael, Bernhard und Jan und all den unzählig anderen. Hervorheben hier möchte ich meinen lieben Kollegen Friedrich Bauer, der mich nicht nur bei all den administrativen Belangen nach Kräften unterstützt hat sondern auch immer unterstützt hat, wenn es einmal nicht so gut lief. Dank gilt auch allen von mir betreuten Studenten, dass sie meine Begeisterung für das Thema teilen konnten. Ich möchte zu diesem Teil abschließend schreiben, dass ich ohne die aktuellen und ehemalige Mitarbeiter des Instituts und die Kontakte und Freundschaften, die ich schließen konnte nicht derselbe wäre.

Eine Dissertation zu schreiben ist mit nichts zu vergleichen und ist im Nachhinein betrachtet vor allem eine Lektion in Selbstdiziplin. Man sucht sich das Thema selbst aus, arbeitet alleine und selbständig daran und hofft Bestätigung dafür und darin zu finden und all das auch irgendwann abschließen zu können. Die Arbeiten daran und rundherum begleiten einen über lange Zeit, während das Leben um einen weiterläuft. Man nimmt das nagende Gefühl „etwas“ tun zu müssen und „weiterzumachen“ mit wohin man geht, zu (beinahe) jeder Zeit, immer im Bewusstsein es sich selbst ausgesucht zu haben und all das selber zu wollen. All die Sorgen, Ängste und Zweifel die einen belasten, aber auch Meilensteine und Erfolge die erreicht wurden prägen natürlich auch das private Leben und Umfeld. Aus diesem Grund möchte ich ganz besonders meinen Eltern und meiner Familie für all die Unterstützung und Geduld bedanken. Genauso möchte ich mich bei ihnen bedanken, dass sie mich immer wieder gefragt haben wie es vorangeht – und all meinen Freunden, dass sie genau das nicht gemacht haben. Beides habe ich als Ansporn gesehen und als besonders wichtig empfunden.

Besonderer, spezieller und unendlicher Dank geht an dieser Stelle an Elisabeth, die mich in all der Zeit mit Liebe und Geduld unterstützt hat und manchmal ertragen musste. Du warst nie ungeduldig, hast nie gedrängt oder gezweifelt – du warst einfach immer da, danke dafür. Insbesondere gebührt dir Dank dafür, dass du mir gerade in der Endphase der Arbeit die wichtigen Zeitfenster freischaufeln konntest, in denen ich die letzten Änderungen und den Feinschliff durchführen konnte. Ich kann es nicht oft genug sagen, aber hier muss es einfach sein: Ich liebe dich.

Danke auch unseren beiden Prinzessinnen, die zwar noch (länger) nicht wissen werden wie sie dazu kommen aber nichtsdestotrotz für mich mit dieser Phase meines Lebens untrennbar verbunden bleiben werden. Schön, dass es euch gibt, ich liebe euch beide.

Zu guter Letzt stellen ich fest, dass ich – im Nachhinein gefragt – nicht noch eine Dissertation schreiben würde, aber trotzdem froh bin es getan zu haben. Ich habe die Zeit an der Universität als Student, Projektmitarbeiter und Lehrender sehr genossen und vermisse sie manchmal bereits jetzt.

Klaus Pollhammer,
Jänner 2015

Table of contents

1 Introduction

Future building automation systems will not only be influenced by data that is generated and processed inside the controlled building but also by stimuli that are generated from the outside. One possible representation of this outside world is the energy infrastructure in which the building is embedded. The first parts of the chapter give a brief overview on the main scientific challenges for power generation and distribution. How automated commercial buildings can become an integral part of the future smart power grid will be formulated as the main research question in the following part. The main tasks and challenges which have to be solved for using all kinds of building automation as energy control systems and fulfill supporting tasks for the smart power grid will be pointed out in the last part of the chapter.

1.1 Energy and the environment

Energy shortage and efficient use of existing energy forms are and will be important topics for economy and science now and in the near future. Different causes for this development can be found, but increasing costs for energy and a changing awareness for the environment may be the most prominent ones. Therefore, innovative and effective strategies for reducing, for example changing and optimizing the energy consumption of all kinds of consumers are needed.

The term *energy* mostly stays for different energy carriers (gas, fuel, oil, etc.) or different manifestations of energy like electrical energy or thermal energy. Every country and society is strongly dependent on energy in its various forms starting from fossil energy sources like coal, oil or gas to so-called renewable energy forms like water, wind or solar power. Each of these energy forms has its own advantages or disadvantages concerning its availability, transportation and utilization. Quality and efficiency are the main restrictions for the usage of one specific energy form but they all can be used for “producing” thermal or electrical energy to cover the demand of people.

In our society, nearly everything is powered by energy. Our cars run with fuel, our mobile phones need electricity for charging their batteries and our buildings need thermal energy for heating. Electricity is one of the main sources of energy and the dependence on electrical energy still grows with the upcoming success of electrical powered cars, the stronger usage of electrical devices and the (relatively) ease of transportation. Although the predicted boom for electrical powered cars was not really visible in Austria for the year 2009 with only 6 registered electrical cars [VCO09, p.9]. It is expected that the ratio of electrical vehicles will be between 12 and 31% of the total number of registered cars in the year 2030 [VCO09, p.14]. Independent of the actual rate, this development will increase the overall demand of electrical power even more.

With the increasing need for electrical energy the role of electrical power generation will play a more vital role than it has today and that has to lead to higher amounts of generated energy or a more efficient infrastructure. Power plants that could be used for expanding the power generation can be divided into two groups. On the one side there is the conservative choice of building fossil fuelled power plants which use all kinds of fossil fuel e.g. oil, natural gas or nuclear power. On the other side various different technologies exist which are based on so-called renewable resources like solar radiation, wind or water. The big advantages of the renewable resources are that they are highly available and free to utilize (especially solar radiation and wind) although the transformation ratio is still not optimal (in 2015 commonly available photovoltaic panels have an transformation efficiency of about 21-22% [34]).

From an environmental point of view it would be preferable to confide only on renewable energy carriers. Referring to [Nit00, pp. 64-66] renewable energy sources have helped to decrease the emission of climate effective substances like CO_2, CO, Methane and nitric oxide. The authors make clear that the emission of these substances can be decreased by using renewable energy sources but the amount is depending on the energy carrier mix on the generation side. Following the calculation the CO_2-reduction by using renewable energy in Germany can be up to 20 301 790 tons per year [Nit00, p. 66].

In addition to these calculations using renewable can help to decrease the dependency on fossil energy carriers. While most countries or societies do not have problems to get access to wind power or harvest energy out of solar radiation, only few countries have enough fossil fuels to cover their own demand. Following [IEA08, p. 228] the biggest part of the oil production is situated in the regions of the Middle East, Europe/Eurasia, North America and Africa.

Based on various causes power generation at the moment cannot be based solely on renewable energy forms like water, wind, solar, tidal forces or geothermic heat. One of these causes - surely not the only one - is that the technology in some fields still is in a very early stage of development (especially tidal power and geothermic heat). A more challenging problem is coping with prediction errors. Already established technologies like power generation with wind, sun or water (the best known and oldest renewable) are strongly dependent on outer circumstances like location and weather. Solar radiation and wind power tend to have fluctuations and their accessibility cannot be guaranteed. Water power is not subject to short term variations like wind and solar power but highly dependent on appropriate locations for building power plants. Nevertheless also water power generation is strongly influenced by climate factors like precipitation and the time of the year.

Compared to many other countries the situation in Austria regarding renewables is a gifted one because of the possibility to cover a fairly big amount of the total energy generation with water power plants and other renewables. In the annual report for 2009 of “Statistik Austria” the percentage of renewables compared to other energy carriers is stated with 25.3% for the year 2006 [Sta09]. This includes all different energy carriers and includes both electrical energy generation and thermal energy generation. A detailed illustration of the values taken from [Sta09] is given in Figure 1-1.

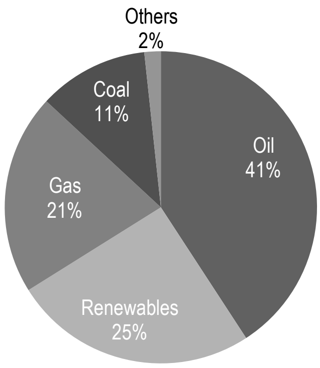


Figure 1-1: Usage of energy carriers in Austria, 2006 [Sta09]

Data from the year 2013 [Sta15] indicates that in 2013 a total of 67716 GWh of generation power was installed in Austria. About 60% (40963 GWh) were water power plants while 15% (10264 GWh) were Wind/Solar/Geothermic and other power plants. The remaining power was either produced by conventional power plants or imported. The referenced source quantifies the overall power consumption (including import/export and pump-storages) for 2013 with 69613 GWh.

But with the stronger integration of renewable power sources into the infrastructure, different and unintended effects occur on the generation side of the power grid. In previous times the energy grids were planned and built in a hierarchical way. The overall structure of the "classical" power grid is: on top of a tree-like structure are *1-n* power plants, which generate electricity. The generated electricity is transferred via power lines to the consumers. The transport grid may be structured in subsections which differ in their voltage level. These levels decrease starting from the power plant at 380 kV down to 400 V (phase to phase voltage) on the consumer side [Reb02, p. 696]. Some larger consumers may be connected even directly to the transport grid. Regarding to these requirements the infrastructure of the grid is dimensioned for generation on the top level and consumption on the lower levels. So the power stream always "flows" from the top to the bottom where the power is used.

Renewable energy forms force the structure of the power grid to change. The difficulty of finding well suited locations for the renewables leads to the situation that energy is mostly not generated in places where it is really needed, and so the generated energy is induced in the nearest available section of the power grid. This point of injection may or may not the top level of the transportation grid. That is why the formerly (more or less) one-point-of-generation grid changes to a multiple-point-of generation grid.

A comparison between the recent and the future structure of the grid is shown in Figure 1-2. The structure of the power grid is shown with the generation at the top level, the different transportation layers beyond and the consumers at the lowest level respectively some industrial consumers connected to higher levels. It is also shown that most of the renewable generation (here symbolized by wind generators) would input the generated power not on top. The figure illustrates the change in the structure of the power grid, each newly built wind generator or other highly distributed generators that inject the energy on the lower voltage levels of the distribution grid could have an impact on the voltage levels on the connected transmission lines.

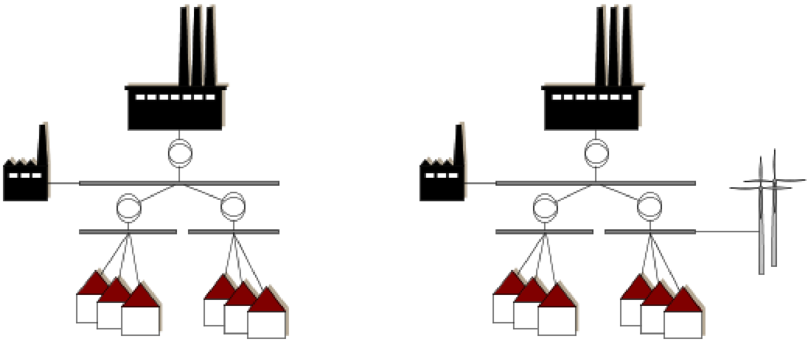


Figure 1-2: Recent structure of the power grid compared to new structure

Following the development of the "Austrian Consumer Price Index" during the last 10 years two main developments can be observed (see Figure 1-3). The figure shows the development of the specific costs on the basis of the costs in the year 2005 (=100%). On one side the costs for living, water and energy were rising steadily and are now about 30% higher than in the year 2000. On the other side the prices for information interchange showed a development in the opposite direction and were in 2009 about 30% lower than on the beginning of this century. [3]

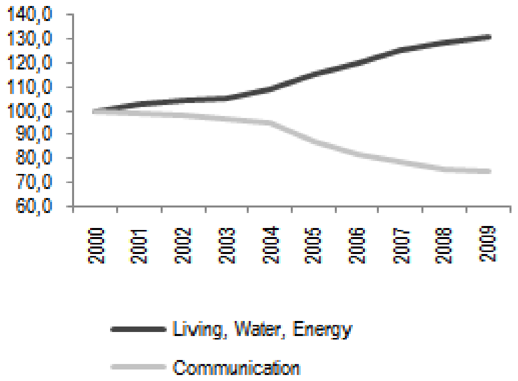


Figure 1-3: Development of Austrian Consumer Price Index 2000-2009

With this increasing gap between communication and energy prices the necessity for new strategies on managing energy demand and generation gets bigger. The inclusion of communication and information exchange is one possibility to introduce new strategies like automated demand response or active communication grids [Kup11]. New communication, management and control strategies have to be found and included into the infrastructure to handle these totally new requirements which are needed by tomorrow's power grids. The following subchapter will give a short overview of how the introduction of communication and control into the power grid will force strong changes and transforms the power grid into a "smart power grid". These changes are the cause why also the consumer side of the power grid will change dramatically and new ways of managing and controlling this part will be necessary.

1.2 The smart power grid

As mentioned before the power grids are evolving from a strongly hierarchical structure into a new form. The strong division line between producers and consumers of electric energy as seen in the classical power grid cannot be drawn anymore, because each node inside the grid could show the characteristics of a consuming or a generating device or even both. This is not only because of the stronger distribution on generation side that leads to power insertion at nearly every level and point of the power grid.

Also the formerly mere passive consumer side is changing rapidly. Installed photovoltaic panels induce energy at the place of the generation which can be also on low voltage level. There might be situations when not all of the energy is needed that was produced in this way for example in summer holidays when nobody is at home. The additional power cannot simply be injected into the power grid, because unexpected high voltage levels would occur, that could harm the connected devices which may not be suited to this situation. Therefore management and control of generation devices is needed. With possible generation on each roof instead of a few distributed power plants (or even wind parks) that can become a severe problem for the distribution grids. The communication and management of networks with many distributed nodes leads away from classical energy engineering to information- and communication technology (ICT) tasks like the synchronization in distributed networks.

When more and more communication technology is introduced into the infrastructure of power grids, this influences not only the often mentioned distributed generation of electricity. Grids could be planned in a new and fundamentally different way. The generation was regulated by either increasing or decreasing the produced amount of electricity, depending on how much energy was needed by the consumers. But with the integration of ICT the coordination and control of the grid is not limited any more only on controlling the generation side. By introducing communication between all participants of the power grid it becomes possible to influence and manage the consuming devices. This situation makes the management of the grid more challenging by introducing a new variable into the calculation. The main objective of managing a power grid is, that the difference between generation and consummation needs to be always zero [Heu07, p. 67]. In this case the power grid is balanced. With the lack of adequate storage technologies the generated amount of power always has to be consumed entirely. Today it is only possible to influence the generation side, so if a power shortage occurs the generation has to be increase to meet the demand. By influencing the consumer's side too, a power shortage can lead to a different situation. For example if the generation cannot be increased, there exists the possibility of decreasing the demand. Another possibility would be to increase the generation and decrease the demand. This last approach of decreasing the demand is followed by various projects, for example IRON [Roe05] or KNIVES [Han07].

One of these new strategies is the so-called demand side management (DSM). The idea behind DSM is that in critical situations for the grid, for example if too much energy is used and generation cannot fulfill the demand, some of the consumers are taken off the power supply. The main concept of DSM is pretty simple but the main problems of it are shown in implementing a real working system. Some of the main questions here are the following ones. Which devices can be shut off? How often can devices be switched off? How do device coordinate their switching? In terms of usability the last question is surely the most important one. Two main problems are found here. First, if lots of devices are switched simultaneously either on or off, the stability of the grid can be even more influenced, than it was before its DSM functionality started to operate. And second, the amount of communication that is necessary to coordinate a big number of devices cannot be underestimated, not to mention the speed that is needed to coordinate such a distributed network in the short time that is necessary to stabilize a power grid. As shown in [Bra06, p. 56] the total potential of DSM for all Austrian households is up to 1600 MW in winter and 700 MW in summer. This potential cannot be neglected, but working solutions and implementation to use this hidden capability are still rare. In addition to that it has to be said, that the referred work only estimates the potential for DSM for households whereas the possibility of using DSM in the area of commercial buildings is not considered at all.

The author of [Kup08] has shown in his work, that it is possible to solve the communication overhead problem by not using real time communication at all. In his work it is shown, that the coordination between the devices could be minimized to an amount of a few messages each week. During this communication phase the devices communicate with a central server and are assigned a priority. After that there is no communication at all between the different nodes, but each of them gets information about the grid-stability by observing the frequency of the power grid. If big changes in this frequency are detected by the devices it could be seen as an indicator for too high or too low demand. If the frequency goes down, it is indicated that the connected load is too high and the generation cannot cover the needed amount of energy. If this situation happens the devices are switched off in a controlled way one after another. This is possible because the different devices have their assigned priorities and know therefore how fast they have to react. With this mechanism the author shows that it is possible to solve the problems with amount and speed of communication. It is possible to implement DSM in that way. Especially with the usage of devices that are fulfilling slow and not time critical processes this functionality can be very effective. In his work the author shows that there are various examples for such processes like pumping processes in a purification plant or thermal processes like in refrigerators.

But there remain lots of difficulties and problems and the solution for the communication problem developed by [Kup08] is just one step further to a really “smart” grid. Even if each and every possible device (at least the ones where it is easily possible) is connected to the grid via power supply and communication, there are still unsolved problems. One question for example is the benefit that consumers are getting for helping to make the power grid more flexible. New business models for paying back this surely big option have to be found.

Another problem is the not solved question of scalability. If all possible controllable devices or consumers are connected via communication or control lines either to a central grid coordinator or are managing their behavior in a different way that means an enormous amount of communication. The grid coordination would have to keep track of the behavior and status of each and every device that is connected with the grid. With the additional coordination of every single device the grid coordination would include a great amount of micro-management. The communication regarding the coordination therefore would need a scalable, layered structure with different layers of abstraction. On the highest levels the grid coordinators could communicate in a more abstract way. The control events would not have to include specific commands for specific devices (or device groups) but more abstracted commands. For example could a very simple message include that the consummation is too high and there should be an action (i.e. switching off some devices) at the consumer side. The implementation how many and which devices have to react should not be of interest for the coordination and management of the power grid.

This leads to the main idea behind this work. It will be shown, that building automation systems could be used as coordination, management and control layer between the grid and the devices. All building automation systems have the possibility to communicate not only with the installed devices inside the automated building but also with the outside. This can be used for example to display the status of the system on the internet but it is not restricted to this. The next sub chapter will give a short introduction in the possibilities how today's building automation systems are capable to act as energy control systems inside a building.

1.3 Using building automation as energy control system

Building automation systems are still not as widely spread as it was predicted when they were developed for the first time. The author of [Rya89] predicted in the end of the eighties a fast development and that in a very near future every building, apartment and house will be fully automated with benefits for all inhabitants. Now, nearly 20 years after the first open standards for building automation were available - the first public review of the BACnet-standard was in 1991 [1] - the vision of having all buildings totally automated and controlled by building automation systems is still very far away. The causes for this situation should not be topic of this work, but high prices for the components of such systems and the installation may be one side of the problem, were the other side is surely the difficulties with using the systems. Most systems still cannot be given the attribute of being user-friendly and easy operable although this issue was already pointed out by [Rya89]. In addition to these points it also cannot be neglected that the interoperability of devices can be a problem, although a minimum interoperability is gained by introducing open standards. For example the LonMark International, developer of the LonWorks standard, solves this problem by defining generic functional profiles for different devices and describing them with mandatory and optional Standard Network Variable Types (SNVTs) [Die01, p. 43]. These functional profiles guarantee that devices of different manufacturers can be used together in one installation without major changes in the firmware of the devices.

A great number of today's commercial buildings (office buildings, hotels, hospitals etc.) have installed building automation systems that control very different parts of these buildings from heating and cooling, to lighting or security devices. Various control strategies handle the different functions such a system is fulfilling. The main objectives for these systems can be very different, for example they could keep an eye on the inside temperature and hold it stable during the day or control the lights. One main benefit is that a building automation system also observes the building during the hours in which it is not in use and can react on events even during this time. A building automation system that was installed to be able to prevent fire or another safety-critical task fulfils its assignment 24 hours each day for the whole year.

For the task of optimizing the temperature inside a building the automation system gathers information about all kinds of environmental parameters from temperature inside and outside the building, to solar radiation or the current location of the people which are working or living inside the building. All these parameters are observed by, using a close-meshed network of distributed sensors. The characters of the sensors are depending on the main task of an installed building automation system and can vary from simple temperature sensors over complex weather observation systems to totally different kinds of sensors like occupancy sensors or even the connection to an information network like the internet.

A primary goal of most building automation systems is to make the workflow inside the building cheaper and more efficient by increasing the user comfort [Kas05]. Although a big amount of building automation systems are installed to control the HVAC (Heating, Ventilation & Air Condition) devices of a building, the main objective for installing the systems is the more easy way to observe and control these devices. The systems are installed for simplify the task of managing big buildings and their heating and cooling infrastructure. Optimizing the energy consumption of the building (and the installed devices) is mostly an enjoyable side-effect, but nearly never the main objective.

But this is not understandable at all. In [Fis09, p.72] it is stated, that with the help of weather prediction and the activation of thermal storages inside buildings up to 30% of the energy could be saved. With this estimation it is even less understandable why facility managers do not use the big potential that lies in using building automation for saving or optimizing the energy consumption of buildings.

One possible answer to this question can be that it was not really necessary to save and optimize energy so that there was no need to use building automation systems for this task. It cannot be said that the different systems do not allow energy management and optimization in an easy way. At least two different implementations of building automation systems already allow this kind of control, respectively BACnet, a communication protocol for management, application and field level, and ZigBee, a wireless solution. Both systems include mechanisms to execute active energy management and energy management mechanisms. The specific parameters and requirements of both systems are summarized in [ANSI07] and [Zig08] and will be subject in the subchapter 2.3.3 of this thesis. In this part of the work the two technologies should only outline, that even with state-of-the-art technologies it is possible to control buildings in an energetically efficient way, but implementations that are more than prototypes are still missing.

So while it can be said that the different building automation systems are capable of monitoring, managing and influencing different kinds of devices inside a building the main challenge is to find usage scenarios that lead to a benefit for the users, operators and maybe the surrounding environment of a building. Especially interesting in this regard is the question if there are ways how the operational processes inside a building can be influenced by outside stimuli intentioned to enable a building’s load shifting ability. That would lead to possibilities to perform demand side management not only with single devices like fridges or heat pumps but with entire buildings.

1.4 Task and challenges

In the previous sections a short overview of the current situations in the power infrastructure and the building automation is given. In most cases power infrastructure and building automation would be treated separately. In the past the field of power generation and transportation with its high voltage levels and the microprocessor-based technology of building automation had no real common ground to each other. With the stronger inclusion of communication and control mechanisms into the infrastructure of the power distribution even these fields which formerly were far away can come together in new and innovative ways.

The work will focus on the task to connect the two fields in such a new way and outline how new impulses in one of the two fields can have unforeseen effects on the other one. It shall be shown how both fields can make benefit through a stronger (communication)-connection between each other. One main result of this thesis will be a solution how the thermal storage capacity of different automated buildings can be bundled and used as a sort of distributed energy storage that could be used by the power infrastructure to stabilize it. To achieve this goal communication between the buildings and the power grid has to be established and strategies have to be developed how the building automation systems can store energy inside the buildings and how this potential can be provided to the power infrastructure.

A question will be how big commercial buildings like office buildings, schools, hotels and various others can provide important functionalities for the energy and power infrastructure. The main approach will be to use newly installed or existing building automation systems for communication and control of the whole building. The goal is to find ways and possibilities to use the thermal processes that exist inside every building for storing energy and activate this functionality for the superior energy distribution infrastructure. Therefore it will be necessary to find ways and interfaces for buildings to communicate with other nodes of the power grid to coordinate their common consumption.

In small amount a potential for storing energy exists in nearly every building. Only in big commercial buildings this opportunity is technically feasible because of the often existing automation system and the bigger amount of possible storage capacity. The existence of building automation systems is important because with these systems no new systems for energy management are needed. It would be very difficult and expensive to newly install a system like this in a building with an inhomogeneous heating and cooling infrastructure like an apartment building. This thesis will therefore focus on commercial buildings with existing automation systems to show, what is possible without the need of installing totally new systems.

After storing the energy inside the automated buildings respectively inside the thermal processes of a building, it should be used by the power infrastructure for executing peak shifting and demand side managing. An essential role in this approach plays the building automation system. It should be used for both: controlling the devices inside the building and communicating with the outside infrastructure. Seen from the outside the automated building simply acts as one active consuming node which has the possibility of storing a specific amount of energy. It therefore acts as a virtual storage device. Inside the building the installed automation system would control the devices (especially the cooling and heating system) and changes the operating points of the whole system to fulfill the requirements which were given from the outside.

A challenge that has to be solved is the question of interconnecting different installed building automation systems inside one building. Even though widespread information of very different aspects of the situation of and inside a building is available for different systems, these systems are not able, or not allowed, to provide their own knowledge to each other. An example for this situation might be that the security system of a building knows very well which rooms are not occupied (or should not be occupied), but the heating control system does not have this information. The technical aspect of interconnecting different protocols or technologies can be seen as an engineering task and is not part of this work. The crucial task that has to be solved is to find ways how the information of the systems can be shared, without giving too much detailed information to each other. This is important; otherwise the people that live and/or work inside the buildings would get a feeling of being observed by their automation system.

That brings up one more important point which cannot be neglected and will also be an important point in this work: The comfort of the people that are living or/and working inside the focused building should not be affected at all. That is very important to support a later implementation by increasing the acceptance of the system. So, if the automation system tries to store thermal energy inside the building, the living and working environment of the occupiers should be comfortable and livable at all points of time.

Another aspect that is known, but will not be directly part of this work will be the question of developing new business models and monetary benefits that fit for the upcoming situations. It has to be taken care of the situation that formerly consuming nodes now take over special responsibilities for the grid coordinated. This has to be rewarded in one way or another and for that totally new business models have to be found. This thesis will show how the steps to reach this situation can look like, but the question about the business models has to be solved, once the smart power grid is established.

The main questions the work will focus on are if and how buildings can be used as energy storages by controlling their inside energy flows with, either newly installed or existing, building automation systems. Furthermore the question of how to activate the thermal processes through building automation systems will have to be solved and example implementations have to be developed. For that strategies and mechanisms have to be found that use distributed control networks for save, reduce and shift the energy consumption of the connected devices and influence the controlled physical processes. The decision mechanisms on how and when the situation allows the usage of the thermal capacity as storage have to be found.

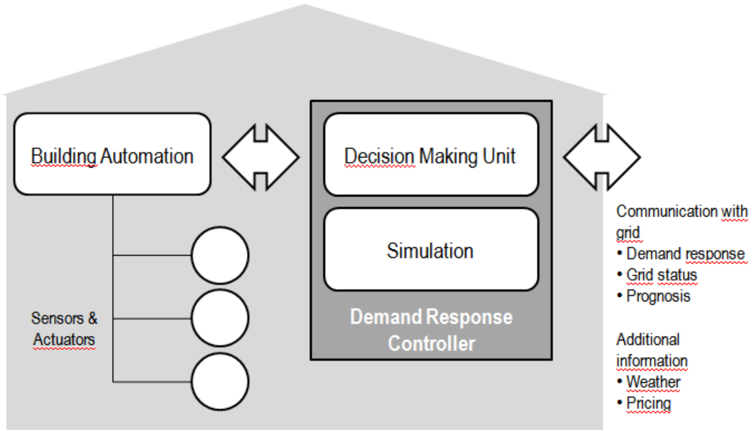


Figure 1-4: Demand Response Controller

Therefore possibilities have to be evaluated and compared on how the building automation system could make such decisions based on the measured data. This decision has to be based on the internal circumstances inside the building and therefore a model-based approach will be followed. One issue here has to be to find a simplified model of the thermal relationships inside the building that could be processed within the building automation system. Such a model is needed for a correct prediction of the behavior of a building without the need of a full-scale thermal simulation. Nevertheless is important to ensure the correctness of a simplified model and compare its precision with the results of thermal simulations.

An important part of the work will evaluate the possible introduction of a so-called Demand Response Controller into the whole process. A detailed illustration of the most important parts and its position in the communication process is given in Figure 1-4. This entity should either provide communication with the outside world (the smart grid or other information providers) or the communication with an existing building automation system. It should take responsibility for making the decision if a building's internal processes can be momentarily used for storing energy or not. For making this decision on one hand a "Decision Making Unit" will be needed with a specific rule set for this task and a model-based "Simulation Unit" for getting information about the possible behavior of the building. The decisions made by the corresponding unit should take the requirements and necessities inside the building into account. Every decision made should be based on the predicted behavior provided by the simulation unit that holds a model based representation of the buildings physical structure and internal processes.

The resulting Demand Response Controller has the advantage that it can be easily included into existing systems and provides the ability to encapsulate its functionality into a single entity for a later retro-fitting or update of buildings.

2 State of the art and related work

One main goal of the proposed work is to provide a possibility on how two different fields of technologies - namely the field of energy generation and distribution and the field of building automation - could be linked for forming new types of interaction between buildings and the power grid. In this respect new ways of solutions and applications should emerge that could be used for benefit in different ways. Because of the diversity of the technologies the following chapter is divided into three main parts, each dealing with one of the technology areas, its specific state of the art and recent work and development in that field. The parts start with the state of the art in the respective field and after that followed by an outlook on recent work and new developments in the respective areas, focusing mainly on technologies for storing energy, communication protocols in smart power grids and the development of energy management techniques for building automation systems.

2.1 Power grids and energy distribution

Electricity is one of the main energy sources of our society. Although the first tests regarding the conversion of different energy forms to electricity and the distribution of electrical energy were made at the end of the 19th century the technology behind cannot be seen as old or outdated. The system itself and its entities do resemble their ancestors although various new technologies and possibilities still lead to an ongoing evolution of the power grid. The last years brought a stronger integration of so-called renewable energy sources what has led to serious challenges for managing and stabilizing the power grid.

Smart power grid initiatives propose that the next evolutionary step of the power grid will lead to a stronger introduction of communication and information technology into the power infrastructure because of the required coordination of the distributed renewable generation units. New concepts and inputs for research and development can be achieved by merging electrical grid and information infrastructure and by opening up new possibilities of managing the power grid. On the other hand these technologies enable to look a step further down the road where aggregated virtual power plants and virtual storages can be seen on the horizon.

The following subchapters will introduce the layout and structure of the recent power generation and distribution infrastructure with a closer look on the challenges the integration of renewable energy sources bring to the grid management. This is followed by a description and discussion of different concepts for storing energy. The following chapter highlights diverse research initiatives in Austria that focus on smart grid implementation and applications that were published in recent time. The chapter is closed by an outline on how load management and load shedding mechanisms could be implemented by active buildings, and showing one of the starting points the presented thesis is based upon.

2.1.1 Electrical power generation and distribution

In existing power grids the primary and secondary control of a power grid's frequency depend on the existing surplus of generation devices. The stability paradigm for electrical power grids is that the difference between actual demand and generation has to be zero at all times. If the demand is too high the generation side cannot support the need which leads to instabilities just as it is the case when too much energy is introduced by the generation side. An indicator for both situations is a change of the power grid frequency. If the generation is to low and/or the demand is too high the frequency drops significantly beyond its target value of 50 Hz (in Europe). A significant rise of the grid frequency occurs if the amount of consummation is too low for the offered energy. An illustration of an exemplary progression of the power grid frequency during a period of about 45 minutes measured in Vienna on the 11th of March 2015 can be seen in Figure 2-1. The illustration shows how the frequency values oscillate around a target value of 50 Hz.

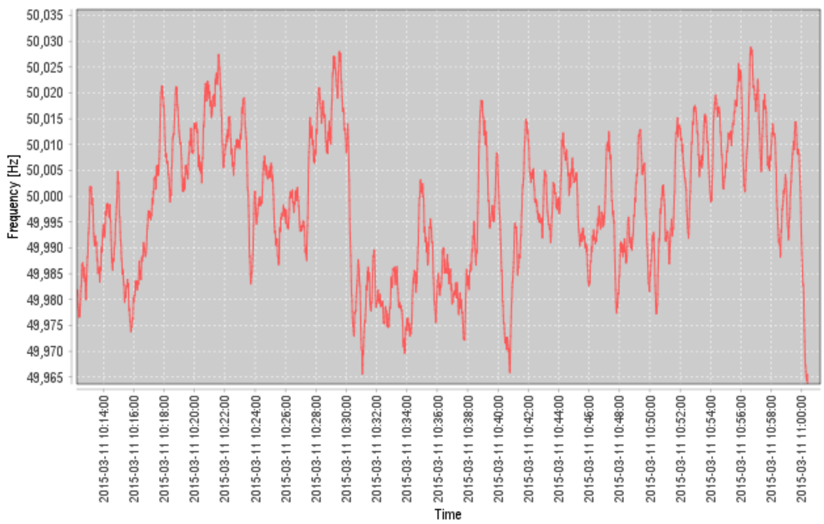


Figure 2-1: Progression of grid frequency, measured in Vienna on 11th of March, 2015

As outlined in various works [Heu07; Reb02] the power grids are structured hierarchically and it can be stated that the theory behind electrical power generation and distribution has not changed for many years. On top of the power grid's hierarchy the electrical power is generated out of primary energy sources. In its electrical manifestation the energy is transported via various levels of transportation and distribution grids with voltage levels from 380 kV to 400 V [Reb02, p. 696] to the consumers (phase to phase voltage), where the electricity is "used". During this usage the energy is transformed and the power is used for keeping up or starting different processes. The target energy form is depending on the process (kinetic, potential, heat etc.). As physical processes can never be without losses a certain amount of the energy is lost and transformed into unwanted energy forms, mainly heat.

Electrical power generation in traditional form is based on the transformation of kinetic energy into electrical energy through the use of generator coupled turbines. How the needed motion is achieved can be very different, either from various processes for heating and accelerating gases (e. g. coil, oil, nuclear energy, sun, geothermic) to the usage of natural potentials like the energy of the wind power or the inherent potential energy of water in water reservoirs and tanks that is released through turbines.

Most traditional energy generation techniques (except water power) are based on thermal based power generation. These processes are scalable and with a continuous support of raw material the power generation the generation of electricity can be guaranteed. In contrary to these advantages one of the main disadvantages is that the processes tend to produce various emissions that are environmental active (e.g. CO, CO_2).

In comparison to traditional power generation, generation units that use renewable energy sources have the main advantage that the energy carrier is renewable or regenerates. In addition to that sun, wind or water depending processes produce fewer emissions than thermal power plants. The factors that make the renewable less attractive for the generation side are the fluctuations in the main energy source and the lower predictability. The frequencies of the fluctuations in the generation profile can be quite different. While the operators of water power plants normally can expect a constant flow of water with only seasonal fluctuations, the strength of solar radiance, tidal forces and wind power can change (even several times) within minutes. Renewable devices have to be included in large numbers (because of a low energy gain) and bring instabilities into the grid, because certain amounts of energy cannot be guaranteed in the same way traditional generation is able to.

In addition to their already described disadvantages renewable energy generation has higher requirements on the location and has to be included into the existing grid structure. This structure, once hierarchically planned with huge generation units on top of the hierarchy and the costumes on the bottom.

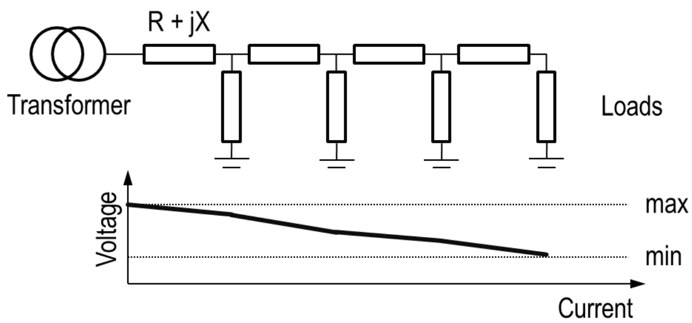


Figure 2-2: Progression of the voltage level along a power line without generating units

To support this structure the transmission lines are dimensioned that the voltage level is always decreasing. The upper and lower voltage limits for a transmission line are depending on the number of consuming nodes that have to be powered and the expected voltage drop that is caused by the length and the specific admittance of the line. The voltage level has to stay within its limits. With only consuming loads along the transmission line the voltage level will drop and reach its lowest value at the end of the line. Therefore no unexpected high voltage levels can occur if the transmission line is construed correctly. Figure 2-2 illustrates this case and includes a schematic on how the voltage level drops along a transmission line.

With only few predictable and controllable generation units the voltage level can be held inside the allowed limits by regulating the voltage level on the input point of the sub-grid or transmission line. If a greater number of renewable and not totally predictable energy sources are included the situation could become challenging for the regulators and could lead to situations in which the voltage levels cannot be guaranteed any more. In cases of power surplus (e.g. all wind-generators operate at their maximum output rate) the upper limits have to be ensured as well as in the opposite case of power shortage.

But not only big numbers of generating units can become a challenge for a transmission line. The following example illustrates that such a scenario can also occur with only a single generating unit. In Figure 2-3 two voltage scenarios on the transmission line are illustrated. In both cases it is assumed that a generating unit is located at two different places along the transmission line. Scenario 1 (blue voltage graph and generator) assumes that the unit is located after the third grid segment. In this scenario the voltage is well inside the limits. In the other case (red voltage graph and generator) the generator is located only one segment nearer to the transformer. If it is injecting at the same rate as in the scenario before, the voltage limits level will over the maximum boundary.

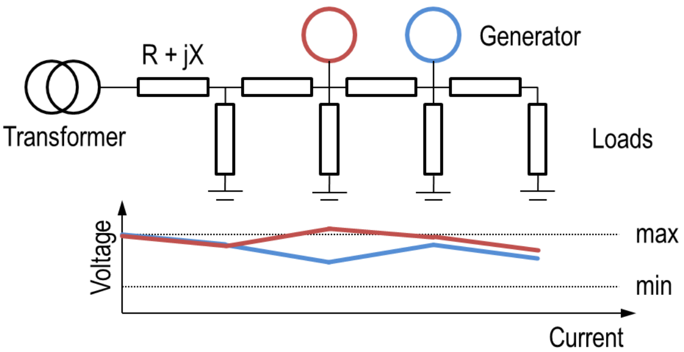


Figure 2-3: Progression scenarios of the voltage level along a power line with one generating unit

To avoid such scenarios and ensure the voltage limits for transmission lines mainly three possibilities exist for making the injection by renewables possible. The first one would be to strengthen the transmission lines by installing new transmission lines that are capable to resist higher voltage levels. This possibility has the disadvantage that the power lines would be much stronger than needed during most of the time and is therefore not really profitable.

A second possibility is to coordinate and manage the input of the renewable energy sources by intelligent control systems. In times of possible too high voltage levels the generation sites are coordinated accordingly. In this case the distributed units have to be connected via communication channels to exchange information. This approach is followed and researched by national and international projects, for example “IRON” [Roe05] and “DG DemoNet” in Austria [Sti11] and “KNIVES” in

Japan [Han07, Min09]. This scenario has the advantage for the power grid operators, that the limits are ensured. For the operators of the generation units on the other side this has both advantages and disadvantages. The (financial) advantage clearly is that the generating units can be allowed to inject energy at all. The main disadvantage is that in most cases of high energy (enough wind etc.) not the possible total amount of generated energy can be injected into the power grid which is a financial disadvantage for the operators of such units. Especially in situations in which the highest profit for a generating unit can be expected, this is reduced due to external circumstances.

The third possibility includes the creation of local energy storages that are able to either store a surplus of energy or provide energy if the local generation is too low. With storage nodes in the local networks the workload of transmission lines can be lowered. How certain storage technologies can be used and be implemented is described in detail in the following subchapter.

2.1.2 Energy storages

The (in fact) not existing ability of the grid to store energy leads to a challenge for the operators. Altering the time of generation always brings the necessity of altering the consumption at the same time. This is based on the implicit need of always keeping the balance between generation and consumption. Storages could somehow make this challenge a lot less demanding as even short time storages could highly increase the flexibility of the operator. A possible storage has to fulfill various requirements not only affecting the technical feasibility but also depending on environmental and economic circumstances. In [Heu07, p. 52] the following main requirements for electrical energy storages are listed:

- Low specific cost per kWh
- High lifetime
- Big number of charge and discharge cycles
- High level of efficiency
- Minor losses through discharge
- Low maintenance costs
- Simple installation and control
- Low specific requirement on space per kWh
- High environmental sustainability

According to the given list, various challenges have to be faced for successfully implementing energy storages. Various technologies seem to take this challenge but most of them are still far away from being efficient and/or cost efficient. Processes that are used for storing energy are based on the exploitation of specific physical or chemical phenomena. Depending if a transformation is necessary, the storage processes can be divided into direct and indirect storages.

The indirect storage processes are based on a transformation of electrical energy into another energy form. The transformed energy is stored and if needed retransformed back into electricity. The specific details of these transformation processes in combination to the effectiveness of the storage define the effectiveness of the whole process. Some transformations may be possible, but not very effective and therefore not usable for the storage of electrical energy. The most common types of electrical energy storages are listed in [Heu07, pp. 52-56]:

- Water storage (pump storage)
- Air pressure storage
- Fly Wheel
- Battery storage
- Hydrogen storage
- Capacitor-based-storage
- Superconductive Storage
- Thermal storage

Of the described technologies water and pump storages have fairly the highest market presence. They can be seen as well established and highly profitable. Advantages of this storage type are the well-established mechanisms, the high efficiency and a possible big but still well scalable storage capacity. A drawback for pump storages is the strong dependency on local circumstances. Pump water storages can only be built if the water supply and the slope support the construction. It is for example not possible to build pump storages near the shore where they would be needed for buffering the fluctuations of big scale off-shore wind generation. [Heu07, pp. 52-56]

Storages based on air pressure use big underground caverns (often old mines) to store compressed air. During peak times of generation air is pressured up to 70 bars and in high load times the air is decompressed. In comparison to pump storages the air pressure storage is less dependent on location by a similar scale of capacity [Heu07]. Following [Ras11] the given overview on this storage type can be seen as relevant also today.

Fly wheel storages use the kinetic energy stored in a rotating mass. For charging the storage the rotation of the wheel is accelerated through an electrical motor which is used as generator through discharging phases. The technology is known for quite a while (compare article about fly-wheels in [Gen82]) but the last years brought steady optimization of the technology.

Battery and capacitor based storages are usable on smaller scale for encapsulated devices and systems. The cause is that the installation and development of battery storages that are able to support the power grid with its specific constraints lead to challenges of size and power. Nevertheless some of these systems were realized, for example an actual installation was used for stabilizing the power supply of the city of Fairbanks, Alaska/United States of America. In [McD04] the outlines of the systems are named by having a size of 118.9 x 7.9 x 4.5 meters and consisting of four battery strings that can provide an initial discharge rate of 27 MW for 15 min, eventually expanded to a rate of 40 MW / 15 min.

Table 2-1 includes a detailed overview of different storage technologies and their main applications taken from [Bar04]. As shown, energy storages can fulfill a variety of different tasks inside the power grid. In [Bar04] an overview on different storing techniques and their abilities is given. While some of the energy storages are useful for short-term storing of energy (like different types of capacitors) and can therefore be used as spinning reserve (flywheels, pumped hydro) others are more suitable as long-term storages e.g. for smoothing weather effects (large hydro storages). Especially interesting for the approach that should be presented in the following chapters is the column labeled "Heat or Cold Store + Heat Pumps", as buildings and their assigned devices like heat pumps are exactly within the main focus of the thesis. According to the table it can be assumed that devices like heat pumps (and implicitly the capacity of the supported buildings) could be used as storages for periods of about 20 minutes to days.

Table 2-1: Storage Technologies and Applications [Bar04]

Full Power Duration of Storage	Applications of storage and possible replacement of conventional electricity system controls	Biomass	Hydrogen Electrolysis + Fuel Cell	Large Hydro	Compressed Air Energy Storage (CAES)	Heat Or Cold Store + Heat Pump	Pumped Hydro	Redox Flow Cells.	New And Old Battery Technologies	Flywheel	Superconducting Magnetic Energy Storage	Supercapacitor	Conventional Capacitor or Inductor
4 Months	Annual smoothing of loads, PV, wind and small hydro	X	X	X									
3 Weeks	Smoothing weather effects: load, PV, wind, small hydro	X	X	X									
3 Days	Weekly smoothing of loads and most weather variations	X	X	X	X	X	X	X					
8 Hours	Daily load cycle, PV, wind, transmission line repair	X	X	X	X	X	X	X	X				
2 Hours	Peak load lopping,	X	X	X	X	X	X	X	X				
20 Minutes	Spinning reserve, wind power smoothing, clouds on PV		X	X	X	X	X	X	X	X			
3 Minutes	Spinning reserve, wind power smoothing of gusts		X				X	X	X	X			
20 Seconds	Line or local faults, voltage and frequency control, governor controlled generation							X	X	X	X	X	X

Following the conclusions of [Bar04] it is safe to say that establishing a system that would allow using this type of devices for storing or shifting energy be seen as plausible according to state of the art assumptions. Since the given reference is not the most actual it can be considered that the given amounts of storage times are higher today (based on assumed development in the fields of building insulation and the overall increase of efficiency of heating/cooling systems). [Ras11] underlines again that the given overview can be still seen as accurate today as it also categorizes hydrogen, pumped hydro and compressed air storages as technologies with "large capacities", while different types of batteries are categorized as "medium" and flywheels and the different capacitor-types as "small".

2.1.3 Smart grid initiatives in Austria

Over the last years an active research community focusing on smart energy grids has formed in Austria. Two reasons for this development can be identified. The central position of Austria inside Europe's UCTE power grid leads to special requirements regarding energy transfer as the power generation can be highly dependent on the geographical location (e.g. strong wind generation in north sea). Another reason for the high awareness of grid operators and energy providers for the requirements of distributed renewable energy sources can be made out in the total absence of nuclear power plants inside Austria's power infrastructure. The (historical) very high ratio of hydro power plants inside Austria's energy mix helps to raise the awareness for the necessity to provide a flexible and secure infrastructure for European partner organizations as well as costumers while increasing the ratio of renewable energy sources even more. Austria's grid operators and energy providers had to face the requirement of including renewable energy sources at the location where they can be found instead of where the power is needed. It can be assumed that this is why the operators could easier anticipate the demands of a smart power grid in this regards. With the help of different national funding programs a strong community built over the last years and a number of (interchanging) research groups and national model regions formed to tackle various challenges inside and develop different solutions for the smart power grid.

Another main stakeholder for research projects in this area can be named by the Austrian technology platform for smart grids which was first introduced in [Lug09]. The initiative is still active and [20] may show a spotlight on the more recent projects and activities. The platform tries to support mainly the target of providing energy generation and distribution in a sustainable way. For reaching this goal it connects the different stakeholder groups for using synergies and strengthens the cooperation. Additional targets are pointing out possible paths to overcome obstacles in the way of smart grid realization and increase the research and development rate on this topic. It seeks to bring all the existing main sources of competence in these fields and all the different stakeholders together and form a unified platform for research and development as well as find a common understanding of the roles and solutions a smart power grid could provide.

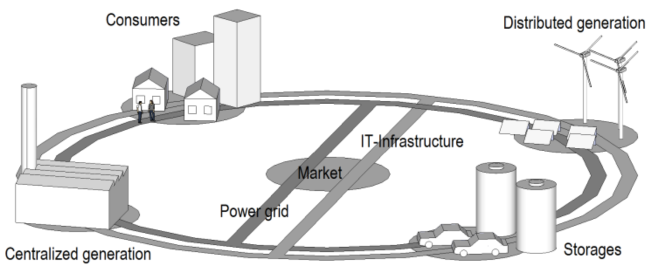


Figure 2-4: Proposed structure of a smart grid following [Lug09] and [20]

The Austrian technology platform has published a roadmap that lays out necessary future research and development paths [21] which is currently in revision and will be updated within a short time. The first edition includes also a structural outline of a smart grid in which the cooperative and parallel nature of communication and energy infrastructure is outlined (see also Figure 2-4). The proposed structure should show how both domains, communications and energy, are equally important to form a smart power grid as both infrastructural connections interconnect the various entities and help to build new and innovative applications and solutions. The importance of the technology platform becomes obvious when the main results of the last time in the research field are traced back to the specific project teams seem to consist mainly of participants and members of the technology platform.

In Austria most research projects are clustered inside several model regions that focus on different aspects of the smart power grid. Different communities, grid operators, research groups and facilities and local power generation providers have formed various consortia in these regions to deal with certain aspects of smart energy grids. To point out just some of these regions here is a small list including the most active smart grid research and model regions in this area, as listed in [Pol13]:

- Smart Grids Model Region Salzburg
- Smart Distribution Grid Biosphärenpark Großes Walsertal
- Smart Services for Linz
- Smart Community Großschönau
- Pioneer Region for Smart Grids in Upper Austria /
- Smart Infosystems Vöcklabruck
- Smart Microgrid Murau
- Experimental community Eberstalzell

The given overview in brings to notice that the regions and flagship projects are not located in a small area but distributed evenly over whole Austria. It therefore is obvious that the smart grid is not only a main topic of a single region or university but a main part of the Austrian research endeavors, a main result of the Austrian funding efforts in this area. [Pol13]

The applications and solutions that were developed are as diverse as the whole topic. The different approaches and viewpoints lead to unique and specialized solutions that on the other hand can all be seen as part of a common solution and very promising results for a "real" smart grid. A detailed comparison of the different viewpoints and applications can be found in [Mei13].

The solutions and studies are widespread and include a variety of application approaches. So called "User/Costumer-in-the-loop" approaches involve the human costumer and try to change their behavior with different incentives (e.g. with different details of information about energy consumption/prices). [Sch11, Ger11] include the description on a study that focuses on the question what amount of information feedback is needed (and in which form) to change the behavior of energy costumers for optimizing the behavior in respect to the power grid's requirements.

Other applications have the lack of storage capabilities inside today's power grids in focus. The idea behind these approaches is to connect entities and devices to the smart power grid to either directly or indirectly exploit their capability to store different forms of energy. One prominent concept in this context is the inclusion of electrical vehicles (and their batteries) as active units/nodes. Their demands on the power grid (DC charging can lead up to 50 kW peaks [Kam10]) in combination with the (mostly) uncoordinated times of the load process can lead to high peaks of load at unexpected points of time. The approaches focus on coordinating the load cycles of the cars as the AC/DC transformers in the cars do not allow a re-injection of electricity to the power grid. The projects based on cars as controllable entities focus on communications and interfaces [Kup11_2, Fas13], driving behavior and load strategies [22] as well as the combination of smart households and electrical vehicles [23]. The other main concept includes the introduction of communication connections to buildings and to be more specific to the building automation systems that control these buildings. As the presented work is heavily focused on this specific area a more detailed analysis of this area can be found in chapter 2.1.4.

The question of forming virtual entities by connecting different (or similar) units to act as one virtual unit can also be found in the Austrian research environment. Depending on the required operational area these field studies include the connection of single units like the pumps of a purification plant up to large scale integration of household devices to form demand response storages. These field studies always focus on the approach that the "normally intended" operation must not be influenced and therefore management entities (in this case based on SCADA) have to oversee the operation of the system. A broad spectrum of projects that include aspects of this approach can be found in [Leb11, Kup06, Kup13, Sta07, Kol13].

While most presented projects do include some sort of field study this is not possible with every development and research project. Due to costs as well as security and safety constraints not every new method can be evaluated in a real world environment. On the other hand "pure" simulations (for example [Sch12]) often do not allow extensive and universal test cases that include every possible scenario. For these situations a simulation environment is being developed by SIEMENS AG and TU Vienna that is able to emulate different parts of a smart grid as well as support "hardware-in-the-loop" approaches to co-simulate a smart power grid while testing new and innovative components [Ein12, Deu13].

While these approaches all introduce new methods or components the presented projects all include a high rate of already implemented solutions that are either still in experimental phase or to their way for bigger scale testing environments. This mainly included "functionality" questions on how certain entities of the smart power grid interact. The Austrian research community is aware that not every question regarding smart grids is already answered, let alone asked. Future projects can be made out that focus on some (until now) underrepresented research issues. One of these issues is the question on how to introduce privacy and security intro the smart grid by design. Consummation and generation data is highly value and different information could be derived from this data (e.g. conclusions if the inhabitants of an object are present or not) and the protection of it therefore of great importance – especially when first smart grid solutions start to make their way from experiments to solutions. In this regard the envisaged research paths include a holistic information platform for smart grids that should include all actors, domains and applications [Kie11, Jun12]. In a related project the security issues of smart grids are directly made out and strategies for handling cyber-attacks are highlighted [Sko12].

The different players and stakeholder that take roles inside a smart power grid come (naturally) from different domains and application areas. Therefore the solutions and models can all be seen as valid solutions within a greater smart grid, but due to the non-homogenous origins of the solutions compatibility or even interoperability between the solutions has to be a main issue. This realization was not only made inside the Austrian research community, but also in international bodies. The question of specified technical reference architectures for smart power grid is for example included in a request of the European Commission [24]. On this behalf first resulting reports can be pointed out by CEN-CENELEC-ETSI including first proposals for this issue [25, 26]. Other international bodies of standardization and regulation presented first guidelines and approaches for the said reference architecture, e.g. in the US [27] and Germany [28-30].

In conclusion to this part can be said that the smart grid evolves fast as the development is driven from different stakeholders with a very healthy mix of approaches and views. Nevertheless the vision of a universally interconnected smart grid is still far away as the different approaches still lack of a unified point of view. As small as the country Austria is, the research community in this field is heavily interconnected and therefore the chance is high, that not different closed island-solutions will emerge but a solution for an open smart grid architecture that supports all different applications and solutions.

2.1.4 Load and demand side management

In energy engineering the term load management is used for describing the approach of influencing the consuming devices or nodes. Different techniques and mechanisms can be used for influencing the load. It has to be said that all of the described technologies were developed and are used for achieving different goals. Some are used for decreasing the load in times when the grid balance is destabilized, others are used for so-called peak-shaving and especially storage centered approaches are used for getting more out of existing infrastructure (keeping the voltage levels inside the limits).

[Pal11] gives a (still valid) analysis on different approaches as well as challenges and difficulties of demand response and demand side management. It starts with a categorization of demand response approaches, dividing them in (increasing) energy efficiency, (altering the) time of use of devices/nodes, physical demand response (with and without rebound-effects) and enabling new ways for getting a higher spinning reserve in the grid. Here the authors also point out, that changing the behavior of the demand side does not automatically reduce the overall consumption but can even lead to higher consumption due to "rebound-effects" and possible losses through leaks and similar on-site limitations. The discussion goes on by pointing out different ways to categorize demand side management possibilities. It is shown that different ways to categorize such attempts can be found. One way would be based on the activation interval (incentive-based demand response versus time-based demand response), another could be if the used incentive is market-based (tariffs, price-signals) or based on directly on physical parameters (grid status, emergency signals). It is pointed out, that especially market-based signals can hardly be quick enough to generate incentives in short order.

In [Pal11] it is stated that real load shedding never can be realized via market/price incentives alone. The analysis part is followed by an in-depth discussion of demand side management and how to utilize its advantages. Most notably the authors propose the usage of "Energy Controllers" at the demand side for managing the (sub-)devices of a specific energy consumption node. It is also pointed out, that the best case scenario would be to increase the overall energy efficiency (minimize losses, optimize insulation). Beside a summary of demand response experiments and its possible impacts, the authors also focus on approaches of distributed spinning reserve as proposed in the projects IRON [Roe05], DG DemoNet Austria [Sti11] and [Han07, Min09]. The last points covered are a number of information on demand shifting, loads as virtual storage power plants and communication protocols for load management. The authors miss the opportunity to include a deeper analysis of communications protocols, as only IEC 61850, OpenADR and BACnet are mentioned and found sufficient for the application. For a more detailed analysis if these protocols already fit all the requirements compare the chapter 2.2 and 2.3.2.

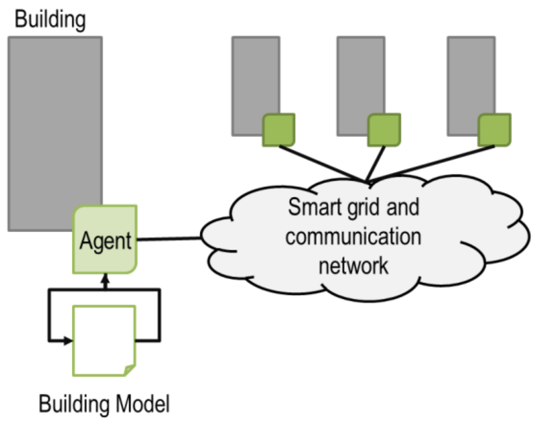


Figure 2-5: Buildings connected to the smart grid via agents according to [Pal11]

Especially interesting for this work is the outlined application structure, as it proposes the usage of building agents for brokering the specific time schedule of a building in respect to the demand response necessities of the smart power grid (compare also illustration in Figure 2-5). The mentioned agent's functionality is based on building models and depends on internal energy controllers that are able to switch devices for changing the load profile. The authors point especially out, that evaluation projects (namely Building to Grid-B2G [33]), may produce data to support the proposed structure. The described decision model is heavily influenced by the BACnet load control object (see [ANSI07] and also chapter 2.3.2).

The authors of [Pal11] (as well as the B2G project) miss the fact that the proposed structure for including buildings inside the smart energy grid lack of certain flexibility. The building models are a mere idea or concept and far from being well-defined as well as the building agent's functionality. The work gives an overview, or generic model proposal, but not a specific implementation strategy. This is especially evident at the lack of models for the building model. The presented works will also try to shed light on this specific challenge and propose solutions for the workflow of the building controller as well as the question on how to introduce certain flexibilities into a static simulation model.

2.1.5 Buildings as active nodes – a conclusion

The seamless integration of buildings inside a smart power grid can still be seen as ongoing challenge. Buildings should and could act as active nodes by either increasing their overall energy efficiency, or (at least) adapt the load profile into a more "grid-convenient" profile (avoid peaks in times or shortage, shift high demand periods into times of energy surplus).

One general requirement that seems obvious, but still has to be solved is, that every building that is able to offer its internal storage potential to an outside smart power grid always has to exchange various information with it. This information does not need to contain the information about the actual state of the storage (is it possible to take in more energy or is it full). Simple commands like “shut off” or “shift” would also do the trick. In general it can be assumed that if more information is available at control nodes, a more complex and well-adjusted management strategy could be implemented that would enable a building to act more “grid- friendly” than another building that does not exchange the same amount of information.

Inside the building also a (centralized or decentralized) control infrastructure has to be found, that is able to control the main energy consumers. This infrastructure has to fulfill the role of a communication layer that understands the various commands that are submitted by the power grid coordination unit and translate decides about the proper reaction and bring the content of the command into action. It is important that the commands sent by the power grid are understandable for different systems that could be installed into the house. That is important to bring as much buildings that are equipped with building automation of whatever form and type to support the power grid. On the other side is this important because the smart power grid coordinator does not need to know how different devices like different HVAC systems have to be addressed or how certain scenarios are implemented inside the building as long as the effect on the energy consumption is as expected.

Building agents especially have to understand certain incentives from the smart power grid and translate them into the building control domain. Some examples for this process for control signals that could be generated by the grid for stimulating an intended behavior at its subordinates are included in Table 2-2. The last row especially shows that even simple example commands could be implemented very differently. While in the first case the energy consumption is not decreased but only shifted, the second case leads to a real reduction. Both suit the need of the power grid in case of only one command during a longer time – but a difference and evaluation has to be made if commends are frequent and come more often.

Table 2-2: Interpretation of smart grid commands by a building agent

Command (Smart Grid)	**Command (Building Automation)**
Power shortage	Changing working point of devices (reduction of power consumption)
Power surplus	Changing working point of devices (to increase power consumption)
Possible power shortage in n seconds (Peak reduction)	Increase power consumption to avoid it in n seconds or Be prepared to reduce the consumption in n seconds

At last stands the point that a building agent that is able to fulfill the upper examples also has to be able to simulate or predict the behavior of specific measurement parameters inside the building. A building automation system always acts as management and control entity for specific parameters inside the building (humidity, temperature etc.). The smart grid introduces “new” limits or boundaries in which these parameter values should be found, or to put it in a different way: it introduces new decision variables in addition to the established ones.

Therefore a model for simulation is needed, that is able to describe the parameters in question in correlation with the new inputs. Most existing proposals miss any detail of this model and do not give requirements such models have to meet. As the power grid is a highly complex and dynamic system the simulation of all connected building (even if it is executed in a distributed way) could lead to high demands of computational power. Here a trade-off between simplicity and complexity has to be found, as highly detailed building model can easily stress even more powerful processing devices. This point especially will need to be focused on in the presented work as solutions on this point cannot be found.

2.2 Communication inside a Smart Energy Grid

When talking about the smart energy grid one main specification is always the inclusion of communication channels to connect the different players and stakeholders within such an energy grid. These communication channels are necessary to exchange operational and administrative data between the different entities. To specify the communication side of the smart energy grid several (sometimes diverse) targets have to be met that bring different requirements for the protocols as well as for the underlying physical communication channel.

Operational data could be the submission of measurement data from a remote metering device as well as weather information (measurements as well as forecasts) or the information of new tariffs. One main requirement operational data has on the operation is to support the submission of data in a structured way, may it be single values or time series. Administrative data could include meta-information about a node for example if it is a generation node or a load, a storage unit or some other entity that takes part in the general smart energy grid (for example grid operators or regulators). As diverse as the different players is the information that is exchanged may be the data. Therefore data, operational and administrative, has to be human- and machine-readable. In addition every communication channel has to be secure, flexible and reliable. To support nodes and devices of different vendors both protocol and communication channels have to be standardized in an open way.

The communication between the (smart) power grid or another central source of management and control signal is one crucial challenge for connecting buildings or similar nodes as distributed storages to the grid. But not only those nodes have special requirements, in fact every communicating in a smart power grid has special needs and necessities that have to be met.

Without communication channels (however) they are implemented it is simply not possible to execute any demand side management at all. While there seems to be a consensus on the fact that communication is necessary it is heavily depending how the requirements on the demand side management communication are defined. In [Kup08] two different communication modi are used. One direct, uni-directional and fast, implicit one (= a frequency measurement determines if load reduction is needed or not) and a slower one on a not so fast and unreliable GSM channel. While the first one normally would not be defined as communication channel it fulfills in the described setup the important task of submitting the information about the power grids actual status. This shows how minimal the information exchange can be. Mostly the communication will be more substantial, exchanging commands in a well-defined format, ensuring a certain level of security and quality of service.

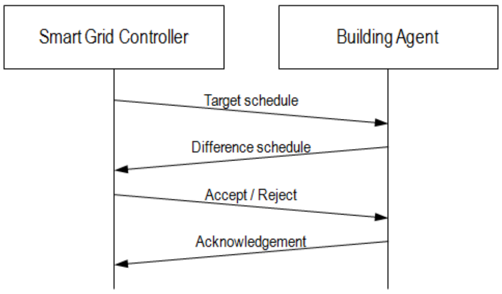


Figure 2-6: Possible communication scheme [Gam11]

One possible communication scheme is defined in [Gam11] where possibilities of communication between smart grid controllers and building units are examined. Figure 2-6 illustrates a possible communication scheme that could be used to broker the load schedules of a specific device/unit. The example alone includes 4 different exchanged messages with various types of messages. On one hand "schedules" are exchanged, as well as messages that include acknowledge/reject data. This short example of one stage of a brokering workflow shows how diverse the payload in a smart power grid could be.

The first part of the following subchapter focuses on a general description of the challenges while the next part introduces several protocols that are specifically outlined as "smart grid protocols" either explicitly by their developers or implicitly by their abilities. The last part includes an evaluation and comparison of these protocols based on a set of parameters.

2.2.1 Smart grid protocols

Within the following chapter a collection of different protocols should be highlighted that are suitable for communication interchange within a smart power grid. It should especially highlight why and how each of the protocols suits the intended purpose and what possible applications it would fit best.

2.2.1.1 Session Initiation Protocol – SIP

The Session Initiation Protocol or SIP is a session management protocol for establishing communication links between different user agents (the endpoints) over IP (Internet Protocol) based networks. It mainly is intended to work together with other protocols that handle a full communication link, for example to establish a conference call between Voice-over-IP clients (the domain it is probably most used in). A typical addition to SIP would be the Session Description Protocol (SDP). Within the whole communication protocol stack the SIP/SDP combination would be between the applications layer and over the TCP and UDP protocol layer that would handle the further communication.

According to a white paper of the SIP-Forum [11] SIP suits the need of demand response applications (one of the possible applications within a smart power grid) because of its most defining features:

- **Powerful push architecture:** The ability to provide an event-based architecture in which the participants could "subscribe" to different states of any event, as well as any change in the states of any participants. The opposite of this would be a pull-architecture. In cases of a smart grid scenario a push-architecture would enable all units to announce a change of properties by themselves whereas a pull-architecture would need a dedicated unit that triggers an information exchange.
- **Easy Firewall/NAT traversal:** According to [11] the biggest problem with firewalls is that different services may use dynamic (changing) ports. This is avoided by most firewalls. SIP uses one dedicated port (5060) for either UDP or TCP and therefore no random ports have to be opened.
- **Highly scalable:** In [11] it is stated that SIP supports millions of subscribers.
- **Customizable demand response Event Packages:** SIP supports special event architecture for submitting different types of packages. Packages dedicated for demand response can be implemented without altering the base abilities for achieving minimal interoperability.
- **Capability based:** SIP is able to support participants that use only a subset of all abilities. [11] gives the example of residential and commercial units in a demand response application that use different subsets of the overall supported capabilities.
- **Multiple events per participant:** One participant is able to subscribe to different demand response events at the same time, making it possible for single nodes to subscribe to different grid services.
- **Network optimized:** Multicast and singlecast support as well as different group-level-addressing mechanisms ensures network load reduction if necessary.
- **Partial notifications:** Only those parameters are sent out, that have changed.
- **Opt-out, Opt-in:** Different applications based on implicitly defined units as well as the possibility to specifically join or leave applications by the units themselves.
- **Demand response package discovery:** When implemented a participant can query and discovery new packages of this special type (for example for demand response purposes).
- **Transport secure:** SIP can be transmitted over TLS (Transport Layer Security, formerly known as SSL, Secure Sockets Layer) or other similar protocols.
- **User security:** According to [11] SIP supports different methods for ensuring the security of the different users.
- **Participant groups:** A cluster mechanism can be used to include a number of nodes or users that act as one virtual unit inside the application.
- **Common identity for multimodal communication:** For all different modes (events-based application, transaction based application,…) only one identifier is needed for each unit.
- **Single User to N device(s) mapping:** SIP supports the concept that one single user may possess different devices within the network. This could be needed to model the relation between the person that pays the bills (or earns the money by generating electricity) and his/her different units within the network.
- **Reliability:** Different routing mechanisms help to provide a high reliability. SIP supports alternate path routing one path fails as well as application level retransmission if transport layer retransmission occur as well as dynamical locating of participants.

- **3rd party payload friendly:** SIP is able to encapsulate “foreign” packages as payload. This is especially important if higher level applications are dependent on their own special data format while they want to gain benefit from SIP’s advantegs.
- **Richer presence state:** SIP does not only support the two states of a client being “online” or “offline” but also state of being “loaded” or “empty” (for storages) are thinkable and already supported.

All this points could lead to the assumption that SIP is the optimal and only necessary protocol inside a smart power grid. But it has to be pointed out again clearly: SIP can never be the only communication protocol, as it is intended to support higher-level protocols. One possible candidate for providing this “high level” communication is named in [11], where it is stated that the combination of SIP and OpenADR can be seen as ideal solution for demand response applications. Therefore a detailed description of OpenADR is included in chapter 2.2.1.3.

2.2.1.2 Smart Energy Profile 1.1

The Smart Energy Profile is an addition to the ZigBee PRO wireless communication protocol and can be seen as an addition to the ZigBee protocol stack. In this regards it can be compared with similar extensions or application profiles like the Home Automation Profile, Telecommunication Services, Health Care or other application profile stacks for ZigBee. At the time of the writing of this work the actual version of the Smart Energy Profile is still 1.1 although the versions 1.2, 1.3 and 2.0 are under development and partly published. Therefore the still more common version 1.1 will be the one that will be discussed here. Some details of the basic ZigBee protocol as published and standardized by the ZigBee Alliance (official webpage: https://www.zigbee.org) will also be part of the following overview to give a basic outline on the features of ZigBee and if they seem especially important for smart energy grids.

General information about ZigBee

ZigBee (the latest version of the standard is called ZigBee PRO and published 2007) itself is an industrial wireless communication standard operating in the ISM (industrial, scientific and medical) frequency areas which lie around 868 MHz in Europe, at 915 MHZ in the USA and Australia and additionally at 2.4 GHz in most areas worldwide. The maximum data-rates lie between 20 kbit/s (for the 868 MHz band) and 250 kbit/s (for the 2.4 GHz band). The physical network layer and the medium access control (MAC) layer are based on the IEEE 802.15.4 standard. The protocol itself is intended to have a low power consumption profile and cover distances up to 100 m (line of sight). As network topologies star-like or tree-like or mesh-networks are supported. The protocol supports 128 bit symmetric encryption and large numbers of nodes.

A typical ZigBee network consists of three different types of node devices:

- **ZigBee Coordinator (ZC):** Acts as single bridge to other networks and first device in the tree-like network structure. It stores different management data of the network as well as security keys.

- **ZigBee Routing device (ZR):** On one hand the ZR acts as end node and is therefore able to operate as data source or sink as specified within the application. On the other hand is also able to route messages through the network.
- **ZigBee End Device (ZED):** Least powerful device, acts as data source or sink and relies on ZR or ZC nodes to send and receive messages.

The main functionality of ZigBee applications is defined by different application profiles. These profiles should ensure that devices of different manufacturers can communicate or are at best even fully interoperable. The application profile is a standardized framework for specific applications (e.g. Home automation, Smart Energy and others). The ZigBee Alliance has standardized several different profiles – called public profiles. New devices have to use public profiles to certify their compliance.

The Smart Energy Profile (SEP) guarantees the interoperability of products for monitoring, controlling, displaying and automating electricity usage and generation. The public profile id of the Smart Energy Profile Version 1.1 is 0x0109. Version 1.1 itself is backwards compatible to devices that implement SEP V 1.0.

Smart Energy Principles

Based on the main ZigBee principles different application profiles can be used to provide an especially tailored environment for different solutions that are still standardized. One of those is the smart energy profile that mainly is based on the following principles [Zig08]:

- **Demand response of devices through utility company:** Devices with high electrical loads should be controlled from the smart energy infrastructure.
- **Real time data display:** Information of the actual consumption for the customers. This should give incentives for the costumers to reduce the energy. Sometimes this approach is also called “Human-in-the-loop”.
- **Intelligent appliances:** Built-in energy awareness of certain consumer devices. These smart devices should automatically reduce or delay their consumption. Common examples would be dishwashers and washing machines.

Smart Energy devices

For building an effective environment the smart energy profile defines the following devices that act within said network [Zig08]:

- **Energy Service Portal (ESP):** Acts as coordinator and one is required for each network.
- **In-Premise Display (IPD):** Shows important data to the costumers/users. This data can be e.g. the actual power consumption as well as archived data. No specification on the actual display of the data is given in the Smart Energy specification.
- **Metering Device:** Measures and records as external device or built-in component of energy meters. The data is sent to the utility company via the ESP.
- **Load Control Device:** Allows the interfacing of the communication network to units with high power consumption. It therefore acts as actor for demand response scenarios with units that are actually not able to do so.

- **Programmable Communicating Thermostat (PCT):** Thermostat that is able to act as controllable load in a demand response scenario with the utility company taking over the control in certain situations of too low or high energy generation. The specification includes the possibility for the users to override the automatic control through manual inputs.
- **Prepayment Terminal:** User interface to provide the possibility to pay for certain amount of power in advance. Possible use-cases could be camping-sites, but also scenarios comparable to pre-paid tariffs for mobile phones are possible. Displays the actual balance information. The actual payment could be realized via credit card or coin input.
- **Smart Appliance:** See also "*Smart Energy Principles - Intelligent appliances*" one page above as the "smart appliances" are nothing else than the implementation of the defined principle.

Network structure

The smart energy networks built on base of the described devices and principles could be as simple as one coordinating node (Energy Service Portal / ESP) that on one hand coordinates a wireless network of sub-nodes of different types and on the other hand is connected to the energy-network and therefore the utility company. In this case the utility company would also provide and control the network on user-level [17, p. 21]. A more complex approach could be a utility company controlled network that bridges with a customer private network. In this scenario the private area is controlled by an energy service portal (ESP) while only the bridging device is registered in the home area network (HAN) controlled by the utility company. The customer home area network with all its devices acts as one virtual device in this case [17, p. 24]. A third scenario could be that the different private home area networks are not directly connected to a network controlled by the utility company but embedded into a so-called neighborhood area network (NAN). The main energy service portal of this network would take care of the connection to the utility company [17, p. 25].

In all these three cases the utility company acts as smart grid controlling unit, introducing the high-level application commands as well as deciding the overall strategy.

Security

The implementation of the Smart Energy Profile (SEP) also requires a certain standard of security. In SEP V1.1 two different security principles are required – data encryption and user authentication. The security itself should ensure protection against intentional and non-intentional interference. As energy networks need high security standards SEP includes additional security measures compared to standard ZigBee (ZigBee PRO).

The security principles of ZigBee PRO include

- Unique network 64 Bit-IDs for reliable identifying every network
- Dynamic channel arbitration for avoiding collisions by selecting channels with low activity
- Random IDs for transmission
- 128 Bit symmetric encryption (AES) for all transmitted messages
- Trust center based key-management for providing random network keys and pre-defined keys for secure identification of nodes.

In addition to the described security measures the Smart Energy Profile also includes the possibility to generate unique application-dependent keys. Every application in a network has a unique key for providing the security of its communication links.

2.2.1.3 OpenADR

The development of OpenADR (Open Automated Demand Response) started directly after an energy crisis in California caused by market manipulations and the shutdown of pipelines in 2002. The specification is freely available, for example through [13]. As direct answer on shutdowns and unexpected cost variations a stronger inclusion of the power consumption side, mainly through demand response mechanisms was the declared main goal of the specification. Within the specification of OpenADR the definition of Demand Response follows those of other federal institutions, like the US Federal Energy Regulatory Commission. It defines Demand Response in [14] as:

[Demand response is an] *"action taken to reduce electricity demand in response to price, monetary incentives, or utility directives so as to maintain reliable electric service or avoid high electricity prices".*

OpenADR was designed to provide data models for sending and receiving demand response signals from different utilities, system operators or clients within a smart power grid. The data model itself was developed to provide the possibility not only to be human-readable but also for building or industrial control systems. These systems have to be adapted in a way to take actions depending on demand response signals for introducing fully automated demand response applications with the power infrastructure. Being based on an open specification OpenADR supports a flexible infrastructure design on all parts of the network.

The specification in [13] names the following defining features as integral parts of OpenADR:

- **Continuous, Secure and Reliable:** An continuous, secure and reliable two-way communication with servers and clients receiving and acknowledging demand response signals.
- **Translation:** Translation of demand response event information to internet signals. The signals are intended to be used in fully automated applications, connecting different facilities and stakeholders (Energy Management and Control Systems, lighting, etc.)
- **Automation:** Machine-readable information for the implementation of fully automated and pre-programmed demand response strategies.
- **Opt-Out:** This option includes that a participant could ignore or override specific event signals if the intended action would not be desired at the specific time.
- **Complete Data Model:** A model that includes all possibly relevant data for an energy infrastructure (price, reliability, activation signals, etc.)
- **Scalable Architecture:** An architecture that could be fit on different sized infrastructures.
- **Open Standards:** The technology is based on open standards like Web services or SOAP (Simple Objects Access Protocol) that build a fundament for the communications model.

In addition to that, the specification names the following points as main benefits of OpenADR:

- **Open Specification:** Open protocols in terms of "non-proprietary" should provide a standardized possibility to implement various different events for coping with demand response requirements.
- **Flexibility:** Independence in terms of implementing platforms and implementations as well as interoperability and end-to-end provide a flexible overall system.
- **Innovation and Interoperability:** OpenADR should encourage a technology that is able to evolve while still being interoperable. This should reduce technology operation and costs for maintenance, besides stranded assets and obsolescence in technology.
- **Ease of Integration:** Other technological fields should be easy to integrate, for example common Energy Management and Control Systems (EMCS), or centralized lighting solutions or any other system able to communicate via Internet signals (for example XML).
- **Remote Access:** This option should provide the already mentioned opt-out paradigm as well as the possibility to override functions through participant web portals acting as graphical user interface for the human operators for providing information about standard demand response related operations and interact with the appropriate systems.

Upcoming development of OpenADR will be focused on the stronger integration of industry standards and the standardization organizations of these standards. This should help to harmonize the different data models in use. The evaluation of different demand response strategies for homes, large and small commercial buildings as well as in industrial facilities is also in the future focus of OpenADR development. [13]

In addition to the given points the specification of OpenADR [13] also includes use cases and requirements for demand response automation servers based on OpenADR as well as whole automated demand response architectures. A more detailed outline on the whole protocol and intended use and implementation of OpenADR can be obtained in said specification [13] for the present view its main characteristics of being open, interoperable, easy to integrate and specially designed to include smart grid applications should be brought up one more time. In addition of being based on XML and therefore being human and machine readable adds to the abilities of being easily integrated and understood by different clients.

2.2.1.4 DNP3

As part of the SCADA (Supervisory Control and data Acquisition) protocol family the Distributed Network Protocol (DNP3) is intended for data transmissions in a point-to-point scenario. The transmission technology can be either serial or over IP (Internet Protocol) as it was specifically designed for communication links between different types of devices for data measuring and control. The protocol itself is commonly used in the domain of electricity and water distribution. In both domains one typical scenario is that operator stations communicate with and monitor a number of substations. The substations themselves may be intended to gather information from even lower layers of the hierarchy or transmit control messages for powering on and off different parts of the network. DNP3 labels computers in the control domain "master" while each node in the field level is called an "outstation".

Both master and outstation are designed with a layered communication structure in mind having the DNP3 Link Layer directly over the communication medium, the so-called DNP3 Pseudo Transport Layer next, an Application Layer and the “User’s layer” on top of the stack. The User’s Layer connects to the outside world by providing different input and output options (both digital and analog) for measuring with and controlling of different units (see Figure 2-7 for an illustration). The protocol itself follows an opened standard which ensures that different vendors could implement units that could communicate over DNP3. While the lower three layers (Link, Transport, Application) are predefined by the standard, the “User’s layer” is the place where vendor-specific applications are allowed. [16]

A DNP3 network supports 16 bit wide addresses (up to 65520 unique units). The network layout is defined by either one-to-one connections or one-to-many. A master is always taking over the role as network coordinator triggering its outstations with request-response demands in a periodic order (round-robin scheduling). It is possible to build up tree-like structures in which an outstation takes over the role of sub-master in a specific sub-network. These structures are intended to build up networks in which a number of sub-masters act as data-concentrators for its subordinate nodes.

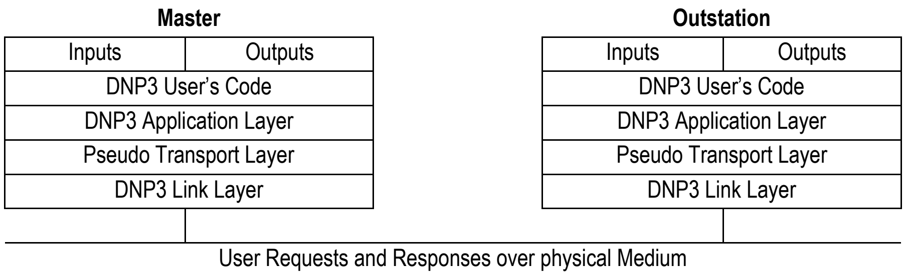


Figure 2-7: Communication layers of DNP3 [16]

The protocol itself supports also different classes of event-reporting. Events, in comparison to so-called static data, are defined as changes of state of different variable values. A node can be configured to report such events by themselves to the master. For these events three different priorities or classes (high, medium, low) can be defined. The data that can be transmitted over DNP3 follows a structured object-based approach which should provide future extensibility as well as flexibility for different application scenarios.

Security

Security was not included in the first versions of DNP3 as the initially planned application domain was located solely in private and closed networks without external access. Big distances between the facilities and the necessity to use open access networks like the internet to bridge these distances brought the requirement of securing the DNP3 links in later versions. In 2007 a new version of the standard was published that addresses the high security requirements an open communication over the internet brings to DNP3 and its application domain [15].

The application layer is therefore extended to include counter-measurements against spoofing, modification, replay and eavesdropping attack scenarios. So any scenario that includes the unauthorized access, changing or intercepting data should is tackled. The specific mechanisms for avoiding these scenarios are in DNP3:

- **Initialization:** Master and outstation open a unique session for every data exchange. Basis for this mechanisms are public keys that are known by all communication partners.
- **Periodic identity check:** After a period of time (from 20 min to 1 h) master and outstations verify their identities. During this checks a new session keys are generated and shared.
- **Critical function code requests:** Critical functions that demand for example write access require an additional authentication by master and outstation. This functionality includes a challenge-response authentication triggered by the node that should grant access to the critical function. Before executing the action, it sends a challenge including encrypted random data to the counterpart. This counterpart answers with the same data encrypted with the addition of the valid session key. This mechanism authenticates the node as a valid communication partner.

Encryption in DNP3 is using Hash-based Message Authentication Code (HMAC) comparable to a secure checksum mechanism. The underlying calculation is based on private and public knowledge (message data, unique challenge generated data and secret keys) that should only be available to master and outstation providing secure message transmission and message integrity.

The key management is based on pre-shared keys that are exchanged between master and outstations. The exchange may be manually, automated or even by configuration or setup of the devices. Each session is secured by periodical generated session keys.

Smart Grid functionalities

It has to be said clearly that no explicit smart grid functionalities or mechanisms are included in the DNP3 protocol specification. Nevertheless, specialized applications could be developed that make use of DNP3 and implement a smart grid use case, although no demand response mechanisms or specific possibilities to transmit timelines for exchanging load profiles are inherent parts of DNP3.

2.2.2 Evaluation and comparison

Some of the abilities, drawbacks and requirements of the different protocols are highlighted in detail in the respective subchapters. The following will contain an overall evaluation and comparison of the protocols should give an overview on which protocols seem best suited for communication exchange for smart power grids. As the described protocols are due to their different nature and intended usage not directly comparable a first part will focus on the definition of parameters that provide the necessary abstraction while a second part includes the conclusion of this evaluation.

2.2.2.1 Evaluation parameters

The following evaluation parameters are used to evaluate the protocols. They are defined in a way to focus on the main requirements the communication in smart energy protocols may have. A short description is given why the category was chosen for the evaluation process.

- **Interoperability**
  The smart grid as it is proposed in most scenarios consists on a large variety of different users and stakeholders, represented by a diverse multitude of units. A way to connect all different parts not only in a communicational way but also in terms of functionality is surely one of the main challenges for the development of a stringent infrastructure. In fact [Wan11, Fan13] name the challenge of interoperability one of the big questions on developing a smart power grid. For the protocols this requirement brings the challenge (in the best case) to support communication from and to units on an equal level as well as communication between different levels of the (communication) hierarchy. IP (Internet Protocol) is often seen as the main communication protocol of today's technological solution, mainly because of its high availability on different kinds of platforms. Especially with different SCADA (Supervisory Control and data Acquisition) systems introducing IP as a way to send messages between abroad plants to avoid the introduction of dedicated networks, IP has become a valid way also in critical installations, even if some adaptations are required according to [See12]. Regarding the interoperability of a protocol's payload the way to go seems in the direction of using XML (Extensible Markup Language) for the introduction of machine-to-machine communication. First steps of including XML into smart grid applications can be seen, for example in [Tar12]. A valid way to evaluate a protocol on its qualification for smart grid applications in terms of interoperability would therefore be its support for IP and XML.
- **Scalability**
  A crucial ability for a smart grid communication is the requirement of managing a large number of different nodes and their communication interchange. This is mainly a question of routing, short round trip times and the avoidance of packet losses. In [Wan11] it is estimated that alone 120 million IP nodes will communicate in a smart power grid. For establishing a reliable communication with a high quality of service the principles of scalable routing (outlined for example in [12]) have to be implemented. Scalability is as much a question of big numbers of nodes as well as a question of efficient routing and communication of these nodes.
- **Security**
  Like in every other communication network security has to be an integral part for communications in a smart energy grid. Even more because the quality of the data (load consumption profiles, load control information, etc.) as well as the communicating nodes (most prominently units for power supply) depend on absolute security because of their vulnerability for different kinds of cyber-attacks. Referring [Pall11] the availability, integrity and confidentiality of the data has to be ensured at all times. On protocol side especially the integrity and confidentiality of the communication can be ensured while availability is more a question of the underlying transmission network. Integrity and confidentiality can be forced by mechanism of authentication and encryption and therefore these questions will be part of the evaluation.
- **Extensibility**
  The question of backwards compatibility is especially important on new emerging fields of technology. In these areas new developments are emerging in faster pace and backwards

compatibility, which is just another term for extensibility, ensures that once integrated parts of the whole system are still available if the technology, in this special case the protocols, change by adding, for example, new additional features.

- **Demand-response ability**
  Demand-response, in different manifestations [Han07, Kup08, Tar12], can be seen as one of the most prominent mechanisms a smart power grid should include. Alone the possibility of altering the load side of an energy infrastructure may be one of the driving forces for developing smart energy grids. Protocols for these networks therefore have to (at least) support this application or provide dedicated features for it.

In the following subchapter these defined categories will be used to highlight the main features of the already presented protocols. The categories themselves were chosen and defined in a very lose way because of the different natures of the protocols. More specific categories would have led to the problem of not providing enough comparability between the protocols at all.

2.2.2.2 Conclusion

In the following part the protocols will be compared according to the categories defined in chapter 2.2.2.1. An overview of the results will close this part of the discourse.

Interoperability

In terms of interoperability it will be assumed that if the protocol in question is able to exchange data over IP (Internet Protocol) and XML (eXtensible Markup Language) it is able to offer interoperable services between different units. Although this alone would not guarantee any interoperability "out-of-the-box" it would make any attempt of connecting two different services/nodes a question of mere protocol translation on application level than technical feasibility.

One of the initial design ideas behind SIP (Session Initiation Protocol) was to provide an ability to communicate over IP. Together with the option to send a message body that is encoded with XML SIP can be named as interoperable in the way it was defined. Applications and setups that implement ZigBee Smart Energy Profile 1.1 do not follow the requirements of being interoperable in the defined way as it does not communicate over IP and does not encode the data with XML. OpenADR on the other hand may or may not be used in IP based networks; the standard itself does not define the carrier. The data itself is encoded in XML per definition. Therefore OpenADR will be seen as interoperable. Being developed as purely point-to-point and serial protocol DNP3 may not be the most obvious candidate to meet the given requirements for being interoperable, but the last additions to the standard brought support of long-distance communications over IP. Nevertheless DNP3 still does not use XML; therefore it is only partially interoperable.

Scalability

It was established that scalability is mainly a question of managing big numbers of nodes in a single network. SIP, often used in Voice-Over-IP applications, is able to manage ten thousands of user sessions with only a single server. ZigBee Networks that implement Smart Energy Profile applications are able to manage hundreds of nodes in mesh-networks managed by one coordination device. One of the first applications that implemented OpenADR 1.0 was a server solution by Honeywell

(Akuacom DRAS server) and supports up to 100.000 clients. At last with DNP3 it is possible to use thousands of devices with only one master station. As all networks support nesting and implanting different layers through subnets all can be named highly scalable.

Security

ZigBee Smart Energy Profile, SIP, OpenADR and DNP3 define different security mechanisms within the standards. Not all of them can be used all the time as some are depending on the usage and application. Nevertheless all of the presented protocols can be named secure within their own application domain.

Extensibility

SIP is per definition extensible via the addition of headers, parameters, methods and even bodies without altering the main protocol. ZigBee Smart Energy Profile, like other application profiles of ZigBee, can be extended to build special profiles. New features can be added in this way. The protocol features of OpenADR can be extended more or less without problems as it uses XML, which is extensible from the get-go (eXtensible Markup Language). The object-based approach of DNP3 is also fit for updates.

Built-in demand response ability

DNP3 and SIP are not explicitly developed for smart energy grid communication and therefore do not include any implicit mechanisms for supporting demand response. A smart grid application that should be designed around the usage of one of the protocols out would need to include its own implementation of this feature. Per se that is possible and feasible, but the development effort would be higher to provide the ability to fulfill demand response applications on base of DNP3 and SIP. In addition to that SIP depends on the usage of an additional protocol as it is intended to be used as session initiation protocol (for more details see also the chapter about SIP).

OpenADR and ZigBee Smart Energy Profile both include mechanisms for supporting demand response. ZigBee SEP does include two different application clusters that support this mechanism: the DR&LC (Demand Response and Load Control) cluster and the Pricing cluster. The first goes in the direction of directly control and influence the load via explicit control commands while the pricing cluster depends on the idea of giving indirect incentives (like high prices in some periods of time) and hope that either specialized and automated devices or the human operators of the load decide to reduce the energy consumption. OpenADR on the other hand is designed as event-triggered environment to pass control or meta information (pricing, weather forecasts, etc.) to the nodes.

Conclusion and summary of the evaluation

The four protocols that were evaluated were mainly chosen out of reasons that references state their ability to act as communication platform for smart power grids. Out of the given information none of the protocols can be considered as the one and only single solution for smart power grids.

Table 2-3 summarizes the main points according to the defined classifications. Taking the already included abilities to support smart grid applications ZigBee SEP and OpenADR have to be considered the better suited protocols for smart grid applications. Especially their ability to support demand response applications have to be pointed out once more. One advantage of these two protocols here is that they were clearly designed with the smart power grid as main application domain.

SIP and DNP3 are the least fitting choices for smart power grid but that can be pinned down mainly to the fact that they were not intentionally designed for smart energy grids. An interesting point in this regards is given in [11]. The authors point out that a possible usage of SIP in smart energy grids could be to provide the session initiation in a scenario were OpenADR is used for the message body. This can work out as OpenADR is not bound to any communication method and it would bundle the advantages of SIP and OpenADR together and can be considered a valid option.

Table 2-3: Overview on evaluation of communication protocols

	Interoperable	Scalable	Secure	Extensible	Demand response
OpenADR 1.0	Yes (IP, XML)	Yes (100000+ clients)	Yes (TLS)	Yes (XML based)	Yes (Special demand response event messages)
DNP3	Partly (IP)	Yes (1000+ nodes)	Yes (Encryption, key-management, TLS)	Yes (Object based design can be modified)	No
Smart Energy Profile 1.1	No	Partly (100+ nodes)	Yes (Encryption, key management, trust center)	Yes (Private applica-tion profiles possible)	Yes (Special applica-tion clusters for DR)
SIP	Yes (IP, XML)	Yes (16000+ sessions)	Yes (TLS, IPSec, HTTP Digest, S/MIME	Yes (Messages / headers adpatable and extensible)	Partly (In combination with OpenADR)

Some more advantages of the single protocols that should be specifically pointed out are:

- SIP is not per se totally unqualified for Smart Energy grids, in combination with OpenADR it still could be an option for the session initiation process.
- ZigBee Smart Energy Profile includes the most “complete” solution for communication in smart energy grids as it provides everything from the communication channel up to the application profile “out-of-the-box”. The drawback here is that it is still defined on base of IEEE 802.15.4 (WPAN – Wireless Personal Area Network) and is therefore more suited for the costumer area. A backbone (wired) network would therefore be also needed to make multi-area-installations possible.
- OpenADR provides the most flexible approach as it is extensible per definition and not bound on a specific network/transmission technique. But that can also be a drawback as a reliable communication still has to be designed for each and every application.

In summary it can be said, that at the moment, there is not one protocol or protocol family that can be named as the perfect solution for every smart grid application. Nevertheless are there a number of possible protocols that are valid candidates to be used inside this domain. Some of them are especially designed for the application profile a smart grid has on its communication side and cannot be seen as experimental anymore. Therefore it is a safe assumption that the formulated requirements for a smart grid can be met with the right choice during the implementation. A reliable, secure and flexible communication in a smart energy grid is therefore very feasible and it seems not necessary to expand on this point within the presented thesis any further.

2.3 Building automation

The development of open standards for building automation started more than 20 years ago [Die97] while first models for automation hierarchies can even be traced back to the year 1982 [Sau11, p.37]. The development of BACnet (Building Automation and Control Network), which is considered to be one of the first standardized building automation systems, began 1987 [Kas05]. Compared to electrical power generation and distribution the field of building automation systems is still a relative young technology. Within the following chapter it is tried to give an overlook over the different systems that are used for building automation, new developments in the field of building automation and how the different technologies for building automation support the management, control and optimization of energy usage in buildings for enabling buildings in the surrounding smart energy grid.

2.3.1 Building automation systems

Data connections between different computers were established since the first days of computer science. Because of the relatively low number of computers, these networking approaches were far away from today's networks but single connections between single devices. With the evolving development and the easier accessibility of microchips - mainly because of their decreasing costs and sizes - computers became a solution for more and different applications. In addition to the higher propagation of microchips their increasing computational and, more important, networking abilities, lead to new possibilities of interconnecting computers and building up data networks. Today millions of participants share information and data over different, world spanning networks.

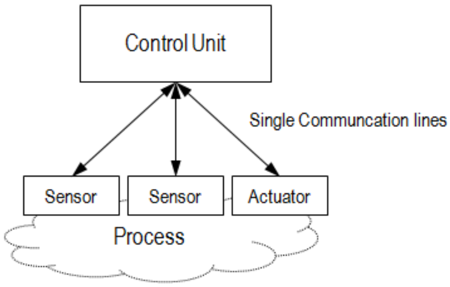


Figure 2-8: Structure of a centralized system for process automation

Beside the exchange of data the idea of control and management of technical systems and processes with the help of interconnected computerized devices came into focus. The automated control of processes was first implemented through so-called centralized programmable logic controllers. In this concept one device takes over the control and management of technical processes or small parts of bigger processes. The controller gets data from distributed sensors and makes its decisions on the basis of this data. After that the controller sends its commands to actuators (i.e. motors, valves, switches) that act on behalf of the sent commands. The structure of such a centralized system is illustrated in Figure 2-8. In the described concept neither the sensors nor the actors have any computational power, all the calculation and decision-making mechanisms are situated at the central controlling unit. Centralized control of processes leads to clear hierarchies and data-flows with the drawback of increasing complexity, inflexibility and costs [Die01, p. 19]. Especially the integration of new nodes or the replacement of old nodes can lead to a change of the whole control program, or even the entire control device.

With the decreasing costs and sizes of microchips it became possible to integrate more and more computational power into the nodes. Therefore it was possible to integrate microchips into the distributed nodes for purposes of pre-processing the measured data inside the sensors or taking over some of the control mechanisms inside the actuators. The increasing processing power of the nodes was followed by a total decentralization of the control networks for process automation. Inside these networks no specialized controlling devices are needed, the process is controlled through distributed mechanisms that are executed by the distributed devices. Following the approach of a decentralized intelligence, there is no need of a central programmable logic controller [Die97, p. 2].

In decentralized control systems the devices still gather information about the system, for causes of parameterization and managements, but the control of the technical processes lies in the hand of the nodes that are directly affected by these processes. The structure of such a distributed control system is shown in Figure 2-9.

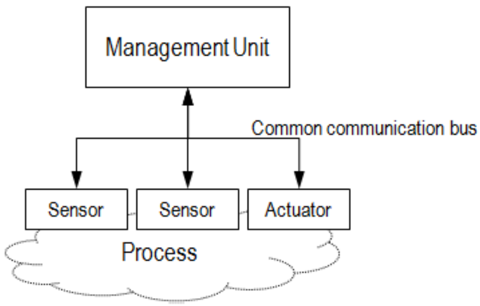


Figure 2-9: Structure of a decentralized system for process automation

The applications for decentralized control networks can be found from the military field, cars, airplanes and industrial processes to buildings [Die97]. Nearly everywhere where control is needed it could be achieved through a distributed approach. Although the applications have very different requirements regarding communication, security, availability and quality of service, the decentralization of computing power and the ability of controlling devices that are physically and logically distributed is the key idea behind all distributed control networks.

The first applications for automation networks had an industrial background, with simplifying the task of discrete manufacturing [Sau11, p. 35]. And with the different and complex processes that have to be controlled inside buildings, distributed control networks found their way in this new domain. Buildings include different application domains for distributed control networks. These domains include climate control, visual comfort, safety, security, transportation, one-way audio, energy management, supply and disposal, communication and information exchange, miscellaneous special domains [Sau11, p. 39]. A general description could include that building automation systems should optimize the processes and workflows inside a building, increase the comfort and living/working standard of its occupiers and make the building safer.

It seems to be a well-known fact, that some of the requirements a building automation system has are not as strict as for industrial automation or automotive automation systems. In most cases costly hard-real-time ability is not needed for building automation systems, for the simple reason that processes in buildings do not need certain reaction times. A lighting-control delay of 0.1 s or a reaction time 10 s for heating control is not a big problem [Die01, p.29-30]. Even if some data is getting lost during the transfer, most applications would not really care. The main exceptions for these statements are surely the safety-systems (fire-alarms). But there are several other requirements building automation systems have to fulfill [Kas04; Nov08, p. 4]:

- interconnecting a large number of nodes
- robust physical channels
- large physical network structures
- providing flexible network management and engineering tools
- low costs
- scalability
- parallel processing
- safety and security

Systems that are used for building automation are based on the idea of decentralizing the calculation power of its elements and controlling its different assignments through distributed mechanisms. A single building automation system can include up to some ten thousands of nodes. Following [Sno03] the biggest installation (at that time) in Europe, the LeCoeur Défense office in Paris, includes 17000 nodes. But this number can only be seen as spotlight, in 2001 the authors of [Die01, p. 19] mentioned a number of 50000 nodes for one building automation system and predicted a rise of this number to 500000 or even 5000000.

The development of open standards for building automation started in the early 80s with industrial automation [Sau11, p.37] and found its succession with the development and release of BACnet, EIB and LON about 10 years later [Sau01; Die01; Nov08, p. 21]. Beside the two ones already mentioned KNX (formerly known as EIB) is a third prominent open systems. The ability of being open is one of the key factors for the success of these three systems. In comparison to closed or proprietary systems which are developed by single vendors, an open standard can be implemented by everybody. This ability helps to keep the systems alive by allowing a bigger number of companies, developers and other stakeholders to be part of the development process and influencing new versions of the standard [Loy01].

Although BACnet, LON and KNX have different histories and primary application domains, there are some general features they share. They all are primary developed for wired, event-based communication on different types of media, where the communication follows the rules of CSMA (Carrier Sense Multiple Access). While BACnet and LON support various kinds of network topology (tree, star, mesh), KNX is stricter by only supporting tree-like topologies. With some efforts it is even possible to enable cross-system communication and interaction, for example between BACnet and LON [Bur04] or between BACnet and KNX [Gra07].

2.3.2 New developments in building automation

With the release of open standards for wireless communication networks by the IEEE in the years 1997 (IEEE 802.11 - WLAN) and 2003 (IEEE 802.15 – Bluetooth, ZigBee etc.), also the development of automation and control systems got new inputs. From this time on the next step in the evolution of building automation systems seemed to include wireless transmission techniques. The ideas of increasing flexibility of the network structure and topology and maintain an easy expendability through the inclusion of wireless communication connections brings new ideas into the development. In the meantime at least two of the three big open systems for building automation showed approaches of including wireless transmission into their collection of physical media. In [Par07] an approach is presented how BACnet could be extended by a wireless data link layer through the usage of ZigBee (mainly the transmission over IEEE 802.15.4 wireless physical layer).

While in [Par07] only a possibility of including wireless connections into the existing BACnet system is described, KNX is one step ahead. KNX RF was presented as the official wireless extension for the KNX system. Compared to wired KNX it represents a totally new subsystem and includes a different addressing scheme and more restrictive connection schemes. In difference to wired KNX no *n-m* connections but only *1-n* connections are possible [Rei07]. Although the possibility to use wireless connections in LON is mentioned in scientific literature [Rei09] and even some commercial products can be found [18, 19] it is not possible to give exact parameters due to the lack of scientific valid references that include the required information.

Besides the advantages of increased flexibility and easier installation the development in the wireless-direction brings different challenges to a wired installation. One of the main issues to be solved is the question of having a physical medium that is easily accessible, open for everybody and without boundaries of any type. Therefore network security is one of the basic paradigms for any wireless communication protocol. It has to be ensured that only authorized participants can take part on the communication. A second problem the open medium brings is that there exist no physical network boundaries (except the range of the senders/antennas). It has to be avoided that a nearby installation of the same network protocol interferes with a system. It never should be possible that one device of system A suddenly controls another device of system B. In KNX RF this challenge is solved by the introduction of a new addressing scheme [Rei07].

The topology control of wireless networks has to ensure that all nodes can communicate with all other parts of the network. Accessibility issues like the problems of exposed and hidden nodes have to be solved, as well as special types of routing (hop-by-hop) and the support of mesh-like topologies. If the network also requires the inclusion of moving nodes it has to be ensured that mechanisms for real-time topology refreshing are included as well.

Another task that has to be addressed in wireless networks is the energy supply of the wireless nodes. Regardless what the specific tasks of the single nodes are, they all need some sort of energy supply, at least for communicating with the control network. Different approaches come up for solving this challenge. The inclusion of long-living batteries into the sensors and actuator nodes or a wired energy supply is one solution. With the help of different concepts the lifetime of batteries can be increased drastically. Falling into this category for example are so-called wakeup-sub-circuits. These compare the measured value with a target value and if it exceeds specific boundaries it activates or wakes up other parts of the devices, presumably the ones that would need the most energy if activated the whole time [Ham11]. Another possibility is included in the (proprietary) EnOcean system by including energy harvesting techniques into switches and sensors. The small energy gains lead to a lack of security and quality of service because all messages are transmitted in plain text and on a best effort paradigm.

2.3.3 Energy control with building automation

Independent of the technical details like the connection type or communication paradigm of a building automation system the main issue always is the intended functionality. Different domains can be controlled by the various systems from security and safety over lightning to the heating and ventilation subsystem. The various building automation systems are mostly capable of controlling multiple domains, although due to historical reasons some of them might be specialized in certain domains while others were added later.

One question still remains: how do the systems support the specific domain of electrical energy control and the management of the demand of the controlled devices? The following part will give a short introduction how two different but nonetheless established automation networks are implementing this specific application domain. While one of them (ZigBee) introduces a very detailed model the other one (BACnet) holds on to a simplistic paradigm. Both approaches are valid and therefore the following part will give a spotlight on the highlights these two automation systems have in the domain of active energy and load control.

The main issues for a building automation system that should be used for energy control and management are the same as for other demand control systems. One big issue is the need of highly trustable security mechanisms. Especially the information on the demand of certain units can be seen as private and therefore the secrecy of the submitted information must be guaranteed to all time. That is one side of the security problem the other is the risk of intrusion and the intended and malicious change of control signals.

The two systems that will be investigated are BACnet and ZigBee. BACnet, being a long established communication protocol for all different functionality levels of building automation (management, application and field), can be safely named a “classical” solution for automation in building. ZigBee, first presented well after the year 2000 includes especially the advantage of being wireless with a wide spectrum off possible application areas.

To include the possibility to control a measure the energy consumption of nodes in a BACnet network was first standardized in an addendum of the ANSI/ASHRAE standard in 2007 [ANSI07]. It describes for the first time a "Load Control Object Type" for BACnet networks and defines it as: *"a standard object type to allow a standard means for providing external control over load shedding"* [ANSI07]. The standard additionally includes all requirements and capabilities of this object type.

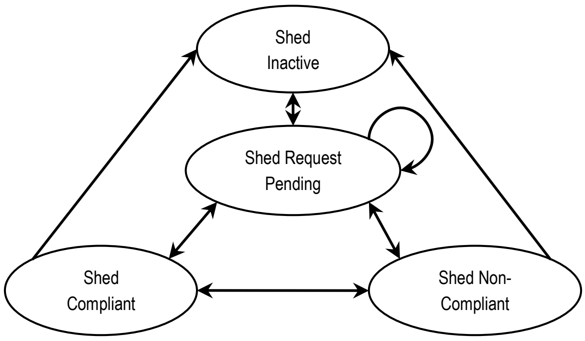


Figure 2-10: BACnet Load Control Object – State Machine [ANSI07]

Following [ANSI07] the usage of the Load Control Object can be described with the help of a state machine that includes for different system states and the transitions between those states. Figure 2-10 shows an illustration of the mentioned state-machine. The two states "Shed Inactive" and "Shed Request Pending" can be named the "main" operating states. Either the ability to shed is inactive or a request is pending. The other two states show the intended abilities of either follow the request ("Shed Compliant") or "opt-out" and delay or neglect the request ("Shed Non-Compliant"). There is no specific design rule or implementation outline to be followed, the standard only defines these four states and what they should be used for. The Load Control Object itself can be additionally used for introducing hierarchically orders of nodes for building up more complex dependencies between different nodes. This can help to structure the system to build up an application scenario from field to management level. The practical usage of the presented theoretical approach for energy management is still very limited as the functionality of the Load Control Object covers only the functionality to switch a device on or off or suspend such a switching. There is no standardized functionality planned for more complex interactions for example the exchange of consumption profiles for negotiating different usage scenarios or similar approaches. Solutions that implement such features can therefore be considered not interoperable as every subsystem would look differently and solve the same issues in a different way. While the approach gives maximum freedom for everybody who implements load shedding in a BACnet based network, it will lead to a multitude of different and not compatible solutions for the same question.

ZigBee as second example follows a very different approach. Chapter 2.2.1.2 already gave a detailed look onto the "ZigBee Smart Energy Profile" (SEP) for comparing its principles with other smart grid communication protocols. In general it can be said that SEP is more specific in terms of energy management and control than the presented BACnet approach. The BACnet addendum [ANSI07] is only describing one additional type of profile for representing a device in the network while SEP describes a whole system layout complete with communication principles, data format and network layouts [Zig08]. Because of this the following part will only shortly summarize the parts of this standard that can be compared with the outlined BACnet abilities. For further information on the "Smart Energy Profile" including its specified abilities for pricing, measurement and other domain specific application scenarios see chapter 2.2.1.2, respectively [Zig08].

Inside SEP, load control is covered by the "Demand response and Load Control Cluster". It defines a server-client system architecture in which the server is responsible of generating "Load Control event commands" for all units that can provide load control. An example here would be a thermostat that is able to temporarily lower or switch of its load consumption. A difference to BACnet here is that the design of SEP supports different device nodes and their special abilities by design. While in BACnet it has to be decided before the whole system is designed how a node reacts (if at all) on a load control request, in SEP this is already part of system design.

ZigBee SEP introduces hierarchical control signals of different urgency levels ("Criticality Levels"). While the lower levels are defined as being voluntarily, which means that every unit can decide to either obey the order or "opt-out", the higher levels are defined as mandatory. These mandatory signals are defined for planned outages, emergencies or service disconnects. BACnet does not have such a fine granularity in its commands and it seems that there are no "mandatory" signals at all as every unit can either follow the requests or ignore it. In ZigBee all units inside the system have to follow the system design to be part of the energy management environment while BACnet tries to build up a system that supports device nodes that are able to follow such requests and "old" ones that do not support this functionality.

Summarizing this analysis it can be stated that the BACnet standard only includes only the protocol, its technical background and requirements while ZigBee SEP defines a whole system environment from physical layer, to protocol to application layers and even covers specific use cases and example scenarios. Regarding ISO/OSI reference model both systems can be located in the layers close to the application itself, but neither can be named an application on its own. ZigBee SEP is clearly not far away from being a whole application stack on its own, but it still is just a base system that is depending on a specific implementation for each system. It includes a wide range of functionalities for supporting different applications for smart energy management while BACnet only provides the most minimum support and barely can be seen as "Smart Grid Ready".

One of the defining abilities for smart grid applications - the ability of performing load shedding actions (therefore included the ability to support the measurement and interpretation of demand information) - is already part of both systems. BACnet for example supports this function since the revision of its standard in 2007. ZigBee on the other side has introduced energy management to its pool of profiles. This "smart energy profile" supports the introduction of energy management setups for different applications. These applications can be the measurement and control of the energy demand in a house to the interconnection and control of different sites in a village to the support prepaid solution where the demand of specific consuming units is measured and compared to a pre-paid amount. The support for smart energy solutions is much more specific than in the very general BACnet solution. Both automation systems are good examples for the actual development in this application domain and cover the whole spectrum of possible soltions (minimum solution – full fleshed out solution) very well.

2.4 Discussion and conclusion

On the side of the energy grid various technologies and algorithms how to get the problems of fluctuating voltage levels and grid frequency under control are or were under development. One main field of research is how to integrate storage technologies into the electrical power grid as storages are considered to be one solution for a widespread introduction of renewables into the energy grid as well as a solution to grid-bottleneck problems. While big sized solutions like pump storages are well established, small sized solutions that could compensate the voltage fluctuation in the low voltage distribution grids for short periods of time are still lacking.

Various approaches from storing the energy in the rotating masses of flywheels or in the batteries of devices like electrical powered vehicles are still not ready for the mass market. So the question of possible short-time storing or buffering of energy is still not solved. Solutions are necessary that make it possible to include energy storages in the distribution grid similar to today's integration of generation or consummation nodes. In addition to the not established technologies for implementing energy storages the control algorithms for distributed storages for energy are still under research.

Control and information exchange and automation in buildings is not as wide spread as it was predicted when the electronic building automation systems were initially released. Still there exists an amount of building classes where building automation systems are widely used. The systems for the control of the heating, ventilation and air-conditioning subsystems in commercial buildings are one of them. The inclusion of wireless transmission technologies into the building automation systems brings also new impulses into the play. Energy applications and profiles are developed for various building automation systems and this development shows that the ability of performing energy applications in buildings for controlling and measuring the energetic behavior of devices will be part in the future spectrum of possible building automation applications.

Taking into the operational layers of building automation system (management, automation and field layer) into account it can be said that most are able to communicate with the outside. In all cases it is possible to introduce gateway-nodes associated with the management layer that are able to communicate within the system and beyond its borders. Different incentives can trigger actions inside a building automation system; performing actions based on the energetic behavior of its devices is one possibility.

It is still a question how this ability could also be utilized from and for the outside. The functionality and workflow of the building automation systems of commercial buildings are dependent on various incentives. While nowadays these incentives are coming either from the inside (sensors e.g. for temperature, occupancy, humidity) or the outside (weather information, calendar information), there is no cause why these incentives could not involve other dynamic information like energy tariffs or commands to reduce the overall energy consumption coming from communication and information channels. The idea is that buildings (if their resources allow it) shift their energy demand for short time periods. Innovative optimization processes for building automation systems could be designed not only to optimize the way the processes inside one building but optimize the processes across the boundaries of various buildings or whole districts. The combined processes in various buildings could then be exploited as controllable units for the energy grid and could take demand side management to a new dimension.

For that an intermediary abstraction layer has to be developed that represents the building and its possible functionalities in terms of the energy shifting potential to the outside (namely the power grid) and supervises the inside processes to act the way that is needed. In Figure 2-11 the position inside the communication process of such a gateway and its most important requirements is shown.

These requirements can be summarized and described in the following way: First it has to enable the exchange of the most important data between power grid and building automation. In that regard it has to understand a possible load shifting request of the power grid and translates it that the building automation understands what to do (for example alter a set-point or change a time-schedule). Or it has to activate processes that could profit from different external data (weather forecast, energy pricing information) or other incentives that could lead to the necessity of load shifting. This leads to the second requirement – it has to be able to act inside the building automation system as other nodes that fulfill similar tasks, like operator-terminals that also provide the ability of changing the internal parameters. And the third main requirement is that different buildings that may or may not have different abilities in terms of internal capacities should be acting and communicating in a similar way.

For the smart grid such buildings should provide one communication interface and understand the same commands and requests. Therefore such a gateway has to give an abstract and standardized representation of the internal (storage) processes to the outside. In addition such communication gateways do also need to have the ability to make the decisions if a building can act as active node for the power grid at a specific point of time or not (either as energy source or sink). The option to opt-out from every scenario has to be provided. If the smart grid sends a load shifting request it is necessary that this decision is made. It cannot be expected that the building automation itself is able to do that and therefore the appropriate unit has to be located also in the communication layer between building automation and smart grid. In any case it can be assumed that for the power grid it always is a benefit if any units follows its commands at all - in comparison to the actual situation in which no load unit actively can do that.

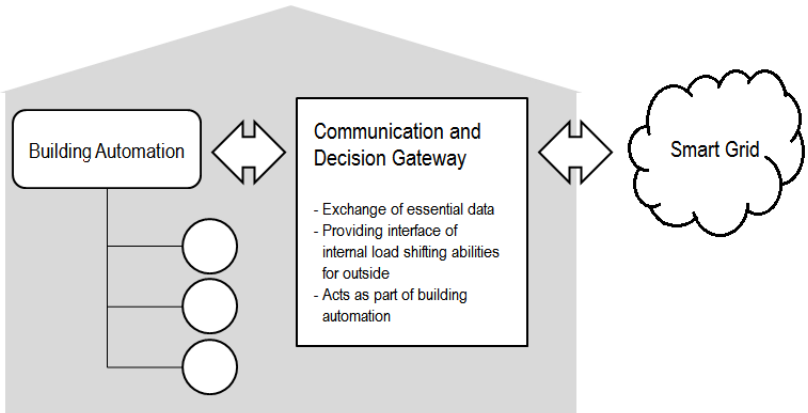


Figure 2-11: Operational requirements for gateway between building automation and smart energy grid

The question of communication inside the smart energy grid itself can be seen as better evolved than all other parts of the presented scenarios as was shown in chapter 2.2. Different communication protocols and networks are available, some of them even intentionally designed for the requirements of a smart energy grid. These would include all at the moment thinkable use cases for communication scenarios and therefore need no further evolutionary step. The question of which smart grid protocol to use will be therefore not part of the presented work.

In summary it can be said that all of the mentioned parts are well described: the thermal processes in buildings, the necessity of storages for the grid to include more renewable energy, the knowledge how virtual power plants or virtual storage power plants should and could act in a smart power grid and the technologies of building automation. The question is how to combine them in a way that not only newly built buildings but also the actual stock of automated commercial buildings can retrofitted and activated as storages for the power grid. This last point would increase the chance tremendously to achieve a certain critical mass to really make a difference. The presented work therefore has to mainly focus on the following questions:

- What are (realistic) requirements a smart power grid could have on buildings as active nodes?
- Are there possible application-scenarios in which a small number of such nodes can really make a difference?
- How could demand side management with buildings work?
- Which processes inside buildings are possibly exploitable as energy short time storages?
- How have existing building automation systems be adapted to fit the defined requirements?

3 Reducing wind prognosis error with buildings as demand response storages

From the power grid's perspective a building can be seen as collection of a number of consumers. Different devices that consume power can be found inside them. The used power forms vary from electrical to thermal power. Beside the new passive house standards, more and more buildings exist that even have installed active power sources like electrical or thermal solar collectors. Also small-scale electrical wind turbines have already been developed in different forms. Therefore the power grids cannot treat buildings as a mere collection of consumers anymore but have to take into account that a generation of (especially electrical) power happens on the building's side. So buildings can be seen as combined generation and consummation unit, not different to storage units, which are able to consume and inject energy into the grid.

This chapter will give a solid estimation on the possible potential a group of commercial buildings - able to act within a demand response scenario – can have inside a smart power grid. In the end it will be shown that with a greater number of such buildings it should be possible to nearly eliminate the discrepancy between the 24 h-prognosis of the wind-generation and the real generation profile. In addition a comparison of different scheduling mechanisms is covered in a second part of the chapter to complete the picture on the usage of demand response storages.

3.1 Buildings as energy storages for the smart power grid

The (compared to the time constraints inside a power grid) relatively big inertia of the thermal capacity of buildings is a still unused potential for the grid. Especially the devices that control the temperature inside the buildings like ventilators, fan coils and other HVAC-equipment are truly the ones that show a huge (electrical) energy demand. A delayed (or earlier) switching event for these devices could lead to a significant change of a building's electrical energy load profile. If it is made possible to influence the demand of this equipment at least in an indirect way it would be possible to execute demand-response mechanisms with buildings. In this scenario buildings would fulfill the role of storages. The ability to store energy would not be for a long time but for the purpose of short time buffering would bring up new possibilities for the grid.

In the following subchapters it is pointed out how buildings can take an active part in the power infrastructure and summarize the requirements the surrounding grid infrastructure could have on the functionalities of the buildings as storages.

The chapter is started by a theoretical improvement of how to model the storage potential of demand response storages followed by an evaluation on how the capabilities of buildings could have potential use for the grid based on Austrian power data.

3.1.1 General model for demand side storages

The following subchapter is based on [Pol11] and introduces a new modeling approach for demand side storages. It is presented in a summarized way in this work because it builds the base for the potential analysis in chapter 3.1.2.

One of the main challenges in introducing demand response applications into the power infrastructure is the question on the actual amount of shiftable energy. Especially the question on the duration and amount of the shifted energy seems to be not considered in a holistic way. The characteristic of demand side storages to either shift a high amount of demand for a short period of time or shifting a lower amount for a longer time is well researched [Kup07].

Graphical estimations can be found on how much of the total energy demand is possibly shiftable in literature e.g. [Kre10] and [Bra06]. These representations are in most cases only showing an incomplete picture of the situation (see Figure 3-1 for an illustration). All these representations have in common that they give the total amount of shiftable energy for every point of time. The information on how long it is possible to shift this amount of energy is missing. The fact that it could be possible, that the shifting of energy demand could lead to an additional amount of needed energy later, because of possible necessary recharge energy [Kup07]. This rebound effect can even lead to slightly higher demands in total due to possible losses. Furthermore a combination of the existing models through adding e.g. models describing the shifting potential of different groups of consumers is not possible.

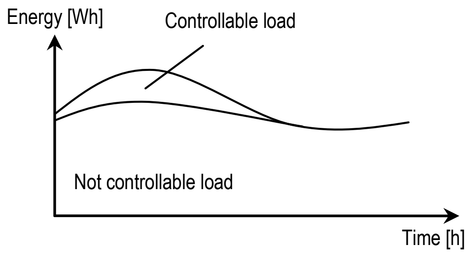


Figure 3-1: Graphical illustration of Demand-Response potential

In [Dei08], a similar but nevertheless slightly different approach is tried. In their representation the authors show the original demand, the demand after the load shifting took place and in addition to that a minimum and a maximum demand curve. The overall energy demand is supposed to be held between those two borders. Following this modeling approach it can be assured that the shifted load stays within certain limits but the temporal dependencies are included only implicitly.

In comparison to former approaches a possibility is required to not only model an energy consumer’s shifting potential as an absolute number for each point of time but also include an estimation of the flexibility a node can propose. The different nature of the various nodes in a smart power grid leads to this necessity to increase the comparability of the abilities off the different nodes. Therefore a different type of modeling that includes the total shifting potential in addition to the temporal flexibility of the process was developed.

The main idea of the model is based on the fact that processes and devices that could manage or shift their energy demand have phases of time during which it is able to maintain a greater amount of shiftable energy than in other periods of time and sometimes it is possible to shed load for a longer time than during other phases.

In a first step the measured energy consumption for each point of time is needed. This measured characteristic is split into single energy units. If, for example, the values are measured every 15 minutes there would be a total of 96 values for each day that have to be divided into single units of energy. If the energy units are measured in kWh a possibility would be to divide the values into single packets of 1 kWh each. But in fact the unit could be chosen in a way to fit best for the application it is used into. It is clear that the device has to support the discrete levels that are needed. Some devices may only support two states (on/off – 0 and N kWh) while others may have several different possible load levels.

The benefit of load shedding or shifting is that consumption peaks can be avoided and therefore either the prices for generating energy can be held low or high voltage levels on transmission lines can be avoided. The possible temporal flexibility has to be spotted out for every energy unit in the model. Each of the single energy-packets needs two more values besides its energy value to indicate their temporal flexibility. The first of these values is used for the definition on how many points of time sooner the energy unit can be used. The second value is used for the definition on how much later point of time the energy can be shifted. Both possible scenarios of shifting energy demand can be modeled either for describing a sooner consumption (shifting to a prior point of time) or describing a later consumption (shifting the energy consumption to a later point of time). Following this modeling approach it is possible to illustrate not only the absolute potential of how much consumption can be shifted on the demand side but also for how long it can be shifted.

In difference to real storages a dropping level of energy inside the demand response storages is a direct consequence of delayed operations that still have to be accomplished. The processes may be very flexible and a long time span can be between the scheduled operation time and the new operation time. In the second case the delayed process will have to start as soon as possible. Exactly this information may be very important when trying to predict a possible rebound effect. If the devices are flexible a consumption peak caused by refilling virtual storages may be avoided, if not it has to be taken into account.

In Figure 3-2 it is shown exemplary how a modeled consumption outline could look like. The illustrated case shows only the energy consumption of a node on 4 specific points of time and it is assumed that each of the energy-packets can be shifted different amounts of time in each directions. Some of the packets cannot be shifted at all and have to stay at the given position. These packets have no flexibility values at all and therefore are labeled with (0,0). Others may be shifted to an earlier point of time (-1,0) or to a later point of time (0,+1) or are flexible in both directions. With this information various types of scheduling can be obtained on the whole concept.

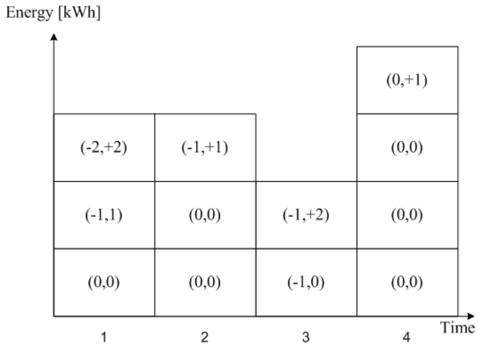


Figure 3-2: Modelling the energy demand and shifting potential

Figure 3-3 shows how shifting the demand to a later point of time alters the flexibility values of the specific energy packet. Translating this example into a real life scenario the following example is possible: it could be decided that a cooling or heating device starts its operation later than normally scheduled. In terms of interpreting the consuming device as virtual energy storage this situation could be seen as taking energy out of the storage and filling the storage up at a later point of time. The contrary case of shifting the load to a sooner point in time is shown in Figure 3-4.

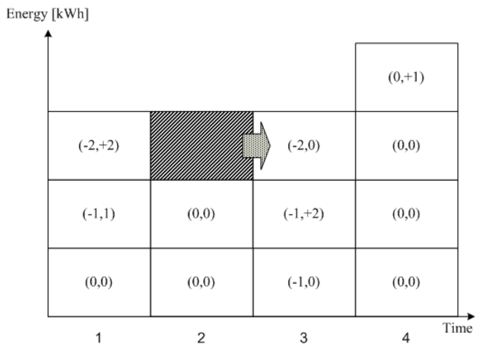


Figure 3-3: A scenario including postponing the energy demand

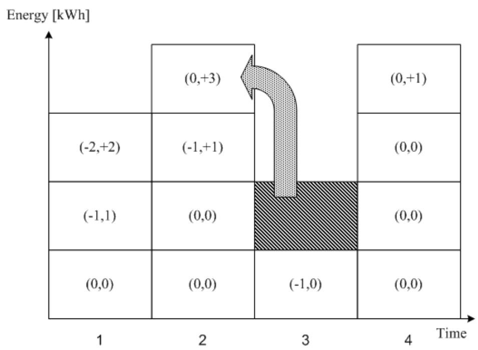


Figure 3-4: A scenario including postponing the energy demand

It cannot be neglected that load shedding techniques, like all types of energy storages, include a certain amount of energy loss. The drawback is that even for processes that can be suspended or preponed for some time a slightly higher energy demand is needed to compensate the losses during the storage period. This additional amount of energy can be referred to as unwanted rebound effect. This rebound effect has two main sources. The first is that once energy is taken out of the storage it may not be possible to hold this low storage level for a long time. The second is that the underlying processes will try to reach their normal working point or have even higher losses if the processes operate not at their optimal point of operation.

With the proposed model such storage losses can be modeled directly. For the following description each shifted energy packet will lead to a (hypothetical) energy loss of 20% of the shifted amount of energy the following time step. The specified amount of lost energy is intentionally chosen so high to make the description more illustrative because a storage loss of 20% would not be adequate in a scenario besides this description.

The first scenario, as illustrated in Figure 3-2, includes no changes of the scheduled energy demand – in this case the virtual energy storage is not used at all. It is assumed that demand response energy storage will not have additional energy losses if the storage potential is not used. Within this scenario the energy level inside the storage either can fall or rise, this follows the behavior of demand side storages that the consummation either can be preponed or postponed. The amount of energy can be seen as a relative storage level where negative values are equal to taking energy out of the storage and positive energy levels can be interpreted as stored energy. An example could be a battery-like storage that is partially filled. Following this example the storage can be filled up or emptied.

The second scenario includes the case when energy consumption is postponed to a later point of time as shown in Figure 3-3. It the example the consummation of 1 kWh is postponed for 1 period of time. Inside the virtual energy storage such a movement would lead to a drop of the energy level at the time of the initially planned consummation and recharging during the next time step. Following the previously described assumption that every shifting of energy leads to a certain amount of losses during the period of time between the events of unloading and loading the energy storage the storage level will rise from -1 kWh to -0.8 kWh (see Figure 3-5). In the illustration actively intended changes of the storage level (loading and unloading) are illustrated with an arrow, while the energy loss between two points of time is indicated through the labeling.

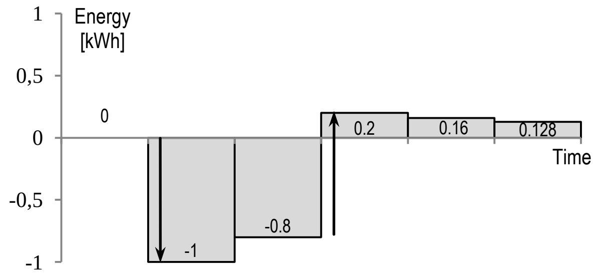


Figure 3-5: Storage level in case of postponed energy demand

The phenomenon that the storage level raises unintentionally between two timeslots directly after taking the energy out of the storage can be explained with the nature of demand side storages to be based on processes that are initially not designed for storing energy. The underlying processes, for example cooling processes, will tend to reach their specified working point. This normal working point (in the case of heating or cooling processes) may be represented in a specific temperature value that should be held. Therefore the underlying processes would try to reach this level again and the storage level rises between the two points of time. When the storage would be held on its intended neutral level this amount of energy would be needed to hold the neutral level (i.e. the energy that is needed to keep flywheels spinning).

As shown in Figure 3-5 the refilling of the storage one timestep after the unloading leads to the storage level of 0.2 kWh. This level is slightly higher than the initial neutral storage level, which is caused in the described unintentional storage refill. This leads to the case that in the following timesteps the achieved higher storage level will again be converging to the neutral storage level. In case of a higher storage level the difference from 20% again can be interpreted as an energy loss. In the described scenario the unintended storage losses will lead to a storage level of 0.16 kWh after the unloading and loading processes took place. This value will drop in the following timesteps by 20% and will ultimately reach the neutral level if no other storage action takes place.

In the third scenario an amount of energy is used prior to its scheduled time of consummation as is shown in Figure 3-4 where an energy unit is shifted from the third time slot to the second timeslot. In terms of demand side storages this last case could be seen as preloading energy into a storage per heating a building up before the heating is really needed and taking the same amount of energy later out through “not heating” during a later timeslot.

The storage levels in this third case are shown in Figure 3-6. At the second timeslot 1 kWh is added to the storage (indicated again with an arrow in the illustration). Between the second and the third timeslot the levels drops to the new level of 0.8 kWh because of internal storage losses and the described tendency of the storages to approach a preset working point. From this changed storage level of 0.8 kWh the following unloading (again illustrated with an arrow) of 1 kWh is measured from. This amount always has to have the similar quantity as was loaded into the storage. Because of that the storage level after the third timeslot will be beyond the neutral storage level by -0.2 kWh. After the shifting process is finished -0.16 kWh of difference between the intended storage level and the modeled remain. Again this error will be minimized over the following timesteps.

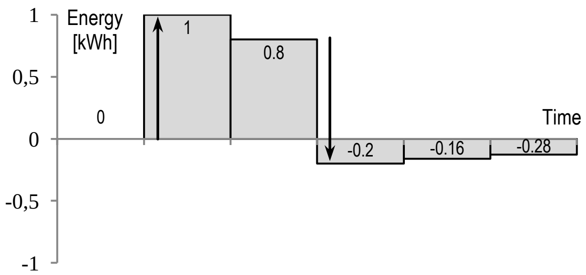


Figure 3-6: Storage level in case of preponed energy demand

In both described cases the additional amount of energy that is needed to lead the storage level back to its intended (neutral) level can be considered as a model for the expected storage losses. The amount of energy that is needed for regaining the intended neutral level (the initial working point of the demand side storage) can be interpreted as the additional energy that is needed for bringing the device back to its working point. The scenarios that are described before only deal with the shifting of energy packets over one timeslot but can be easily adapted to different scenarios as is shown in [Pol11].

With this approach different kinds and types of storages either short term or long term can be modeled in a coherent way. It is shown how the proposed approach can even be enhanced to include storage losses and with respect to that simulate possible rebound effects that are caused by reloading demand side storages. The described model will be used as a basis for the analysis in the following part of this work.

3.1.2 How to use buildings for minimizing prognosis errors of wind generation

The following chapter will focus on a consideration on the potential that different building types or more specifically different processes inside buildings can provide for the power grid in regard to their total load, their amount of shiftable energy consumption and their actual number. Before the requirements for activating the capacity inside buildings can be pinned down an evaluation on the overall potential is made. The first part deals with a statistical overview on the prognosis error of wind generation, then a simple model for a demand response storage based on official buildings is outlined before two different scenarios of leveling out the error are observed.

3.1.2.1 Statistical analysis of the wind generation error

The hierarchical sight of the power grid normally starts on top with the power generation units and ends on the low voltage level with the consuming nodes. In classical view the grid distributes its energy from top to bottom. The amount of energy that is distributed throughout the power grid is always depending on the actual demand. By controlling the demand a second possibility of influencing the power balance of the grid is established.

Therefore an objective function has to be found for providing a base to evaluate the followed approach. The objective function has to be relevant for the future smart power grid with respect of the stronger introduction of renewable energy sources into the overall energy mix and its possible solution through management of the demand side. One possible application that takes these two points in respect could be the volatile and not exactly predictable energy generation profile of wind power plants.

The difficulty of predicting the exact amount of wind generation has direct influence on needed back-up resources in terms of operational reserves. In [Fab05] (including an evaluation on the annual additional costs that can be directly derived from wind prediction errors for Spain) these costs are estimated with 10 % of the annual income of a wind farm on the electricity market. This estimation takes into account that different prediction horizons can lead to higher accuracy but shows that there is quite a potential for optimization. Another study [Ern07] states that the accuracy of wind prediction is one of the important criteria for its quality. On [Ern07, p. 83] values for the accuracy of the wind power prediction with normalized forecast errors between 2.5 % (aggregated error for three German control areas) and 8 % (error for one control area) are given. In the same work it is specifically pointed out, that smaller units of generation (e.g. wind farms) are more difficult to predict in comparison to the generation of all wind generators in Germany and typical forecast errors of 10-15 % (root mean square error) can be estimated for single wind farms.

In comparison to Germany the amount of wind generation in Austria is lower as is the area. It can be assumed that because of the difference in size, the prediction of the generated wind amount in Austria will tend to be more erroneous than in Germany. The following analysis tries to show the potential that may be gained by using demand response storages (i.e. buildings) to compensate the difference between the wind generation prognosis and the actual energy feed-in by wind generators in Austria. The analyzed data for the year for evaluating the potential can be retained from “APG – Austrian Power Grid” (also online available, see [4]).

The evaluated energy data consist of two main data series. The first includes the actual mean value of wind generated power in kW (kilo watts) for time intervals of 15 min throughout the whole year 2010. The second time series includes the predicted generation for the same time intervals also in kW. The prediction horizon for the values is 24 h (day-ahead). A graphical illustration of an exemplary week in the year 2010 is shown in Figure 3-9. It can be seen that although the tendency of the prognosis seems right the actual wind generation can never be predicted correctly.

For a statistical analysis of the two data series and their difference various definitions of the error can be taken as base. [Klo07, p.78] defines both the mean absolute error (MAE) as well as the root mean square error (RMSE) as the most common error-definitions regarding wind prognosis. The formula for the *MAE* can be seen in (1) while the RMSE is contained in (2).

$$MAE = \frac{1}{n} * \sum_{i=1}^{n} \left| P_{m,i} - P_{p,i} \right| \tag{1}$$

$$RMSE = \sqrt{\frac{1}{n} * \sum_{i=1}^{n} \left(P_{m,i} - P_{p,i} \right)^2} \tag{2}$$

In both of the formulae (1) and (2) P_m stands for the measured mean power values during discrete time intervals while P_p stands for the prognosis for the same time interval. In addition to these values other statistical values are also of interest, namely the maximum and minimum values for the absolute error.

To investigate the difference between these two calculations on the error values the following test calculation was executed. The the test data for the test included one series that stayed stable at a value of 1 while the other time series includes the values increasing from a starting value from 1 to 100. Table 3-1 shows these series in addition to the difference value $P_{m,i} - P_{p,i}$.

Table 3-1: Test data for comparison of MAE and RSME

i	1	2	3	…	98	99	100
P_m	1	2	3		98	99	100
P_p	1	1	1		1	1	1
$P_{m,i} - P_{p,i}$	0	1	2		97	98	99

To compare the two methods the next step was to calculate the total MAE (1) or RSME (2) for the first *n* elements. This was done consecutively for all numerical intervals of integer values from [1; 2] until [1; 100]. Figure 3-7 and Figure 3-8 show the different values for the errors for these intervals. The values on the x-axis show the length of the intervals while the y-axis shows the error values in linear (Figure 3-7) and logarithmic (Figure 3-8) scale.

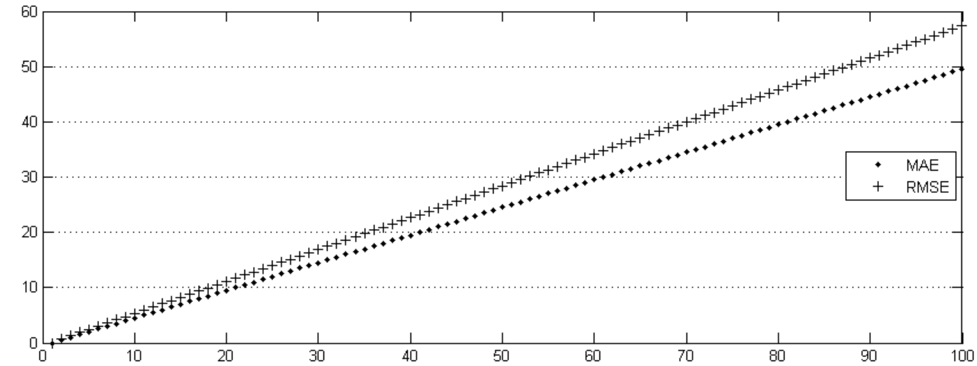


Figure 3-7: MAE and RSME for the first n values of P_m and P_p (linear scale)

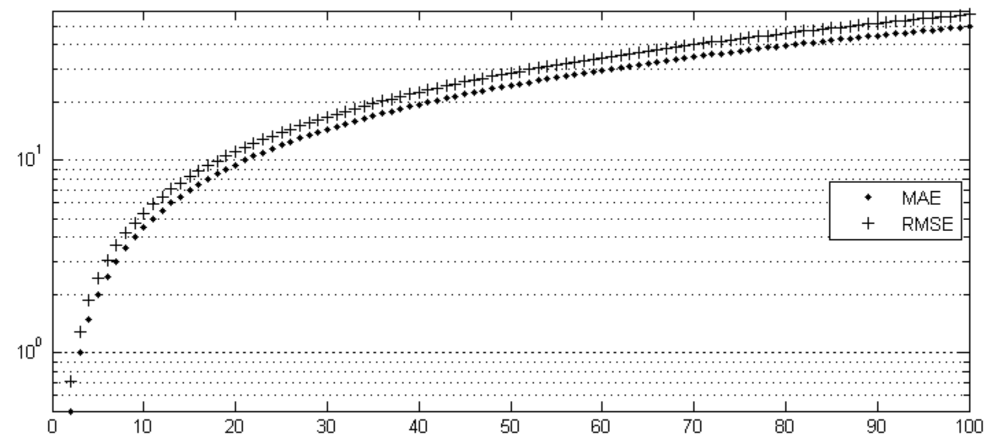


Figure 3-8: MAE and RSME for the first n values of P_m and P_p (logarithmic scale)

Both illustrations show that the errors levels increase in a nearly equal amount, but the Root Mean Square Error (RSME) values show a higher rate of increase when the difference between the two values of the time series gets higher. One cause for that is that the RSME takes the error term in an exponential way (to the power of two) and therefore higher differences between the two time series are more prominent in the overall error value than lower values.

Two other main statistical values would be the maximum (3) and the minimum (4) of the error. These two are important to define the overall interval in which all the error values can be found. The formula for the maximum would be:

$$\max_{0 \le i \le n} \left(P_{m,i} - P_{p,i} \right) \quad (3)$$

The minimum can be described with:

$$\min_{0 \le i \le n} \left(P_{m,i} - P_{p,i} \right) \quad (4)$$

In both of the two latter cases the first operand of the subtraction $P_{m,i}$ is the measured data series while the second $P_{p,i}$ includes the predicted generation values. The operands could be inserted in the opposite order but with using the upper formulae it is ensured that a too low generation (in comparison to the prognosis values) leads to a negative value. The formulae were chosen to indicate the shortage of energy if the measured values are too low and also the illustration in Figure 3-9 also is based on this assumption and shows the generation and prognosis value of wind generation during a period of about 6 days. The error values are included additionally.

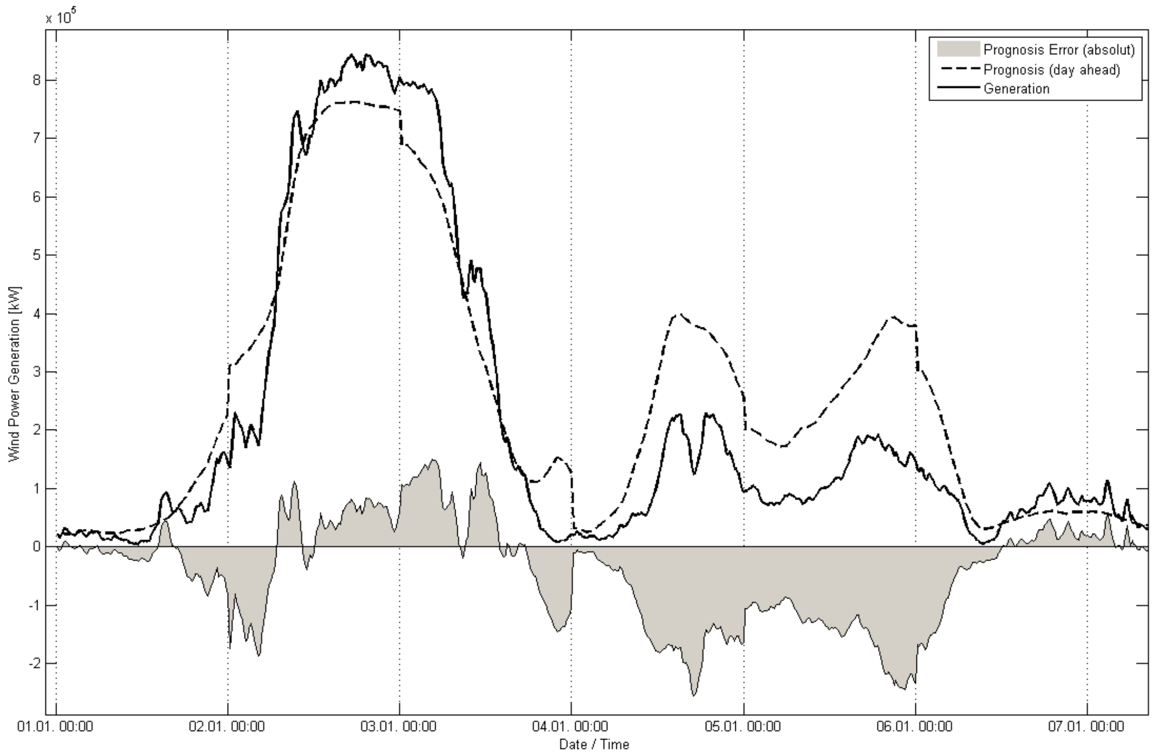


Figure 3-9: Wind generation and prognosis with prognosis error

Table 3-2 shows the statistical values that were calculated for the wind prognosis data in Austria of the year 2010. In addition to the already mentioned values also the mean value for the error was calculated and the mode. The mean error (ME) in comparison to the already described mean absolute error (MAE) includes not the absolute difference values between the two time series but the difference values including their sign. A negative difference value (indicating a lower measured generation that predicted generation) would therefore be added to the sum as would a positive one. With the mean error it can be determined if the positive and negative errors between the time series are equally distributed or not. The formula for the mean error is:

$$ME = \frac{1}{n} * \sum_{i=1}^{n} \left(P_{m,i} - P_{p,i}\right) \tag{5}$$

In a data set or time series the mode is the value that has the highest number of occurrences. The statistical analysis that is the base for the values in Table 2-1 was executed for the entire data series of 2010 for the wind generation in Austria. Two main observations could be drawn from the analysis. First it can be seen, that the positive error values (obtained if the prognosis value is higher than the actual generation) have overall higher values than the negative ones. It is assumed that the prognosis algorithms and techniques are the cause for this phenomenon. The conclusion of the author is that the different methods that are the base for the prognosis tend to predict a lower generation to be on the safe side and have a more conservative method for prediction.

Second, the two values of the mean and the mode which are both negative in the analysis seem to indicate that the situation of a too low generation is dominant throughout the whole year. The mean absolute error is with -1606 kW relatively low (compared to the absolute generation values) but together with the mode (the value with the highest number of occurrences in a time series) it shows that negative errors can be observed more often than not.

Table 3-2: Statistical values for the wind prognosis error in Austria for the year 2010

MAE	$7.097 * 10^4$ kW
RMSE	$9.651 * 10^4$ kW
Mean error	$-1.606 * 10^3$ kW
Mode absolute error	$-3.101 * 10^4$ kW
Maximum absolute error	$6.877 * 10^5$ kW
Minimum absolute error	$-4.358 * 10^5$ kW

At last the quality and performance of the prognosis was determined as in another similar analysis the authors expressed the hypothesis that the prognosis error on weekdays was significantly lower than on weekends [IEAE08, p.22]. This effect was possibly caused by the fact that the prognosis for the free days like Saturdays or Sundays was calculated on the last weekday (most times Fridays) before that specific day. This special case could be ruled out for the year 2010, as the amount of the mean absolute errors split for the different weekdays showed no significant anomalies, as can be seen in Figure 3-10.

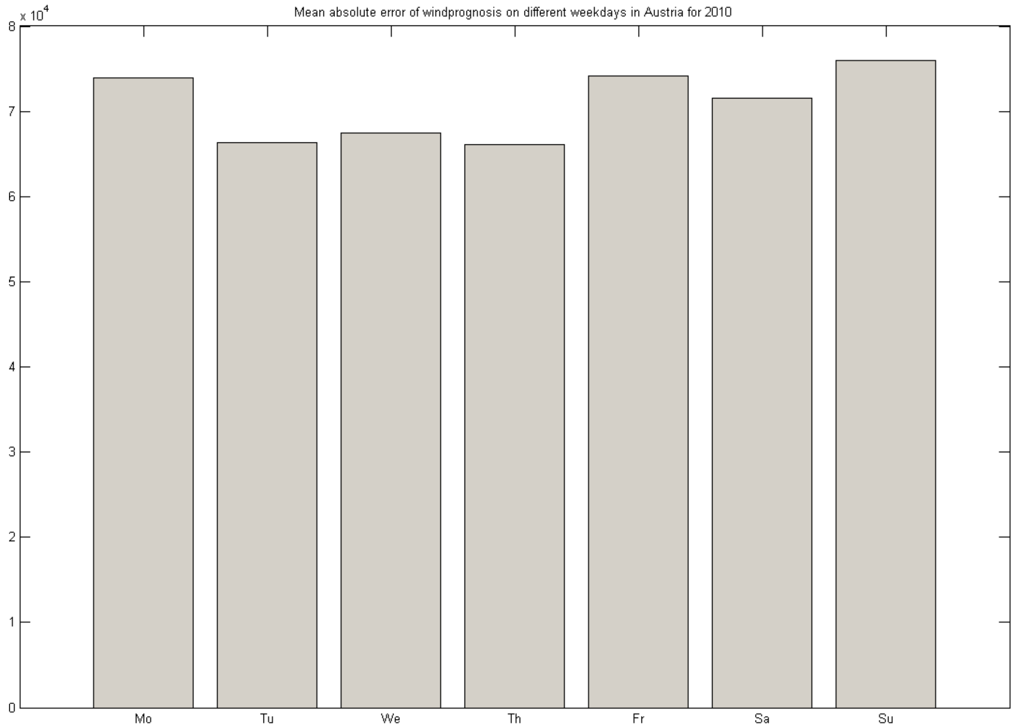


Figure 3-10: Mean absolute errors for wind prognosis on different weekdays in 2010

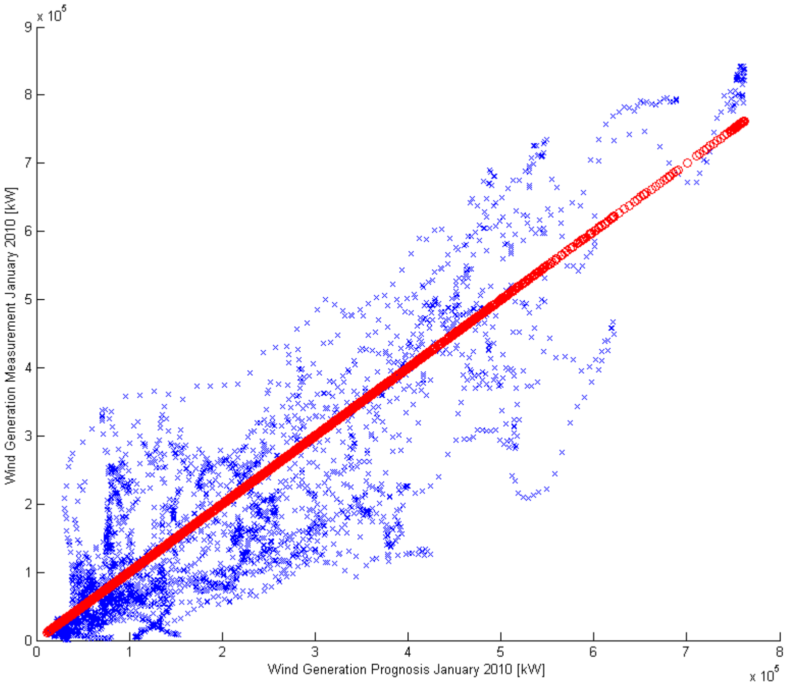


Figure 3-11: Point-graph of Prognosis versus Measurement (ideal and real data from January 2010)

Figure 3-11 includes another possibility of showing the difference between the ideal case (prognosis and measurement are perfectly equal) and the real measured data. In this illustration all predicted values for and all measured values of the 15-minute wind generation profile of Austria in January 2010 are included. For each of the points in the scatterplot a specific pair of x and y values is used that consists of the power generation prognosis for any point of time on x-axis while the y-value includes the measured data value for the respective point of time. The illustration shows how the ideal case differs from the real data. The ideal case in which the measured data equals the prognosis data for each point of time would lead to points that are located exactly on the 45° line in a scatter plot (red "o" in this illustration) while the points including the real measurement data are lying somewhere else (heavily depending on the prognosis error at that point of time). In terms of altering (especially decreasing) the prognosis error at every point of time the points would be located nearer to the 45° line of the plot.

In this case the absolute positive error is higher than the negative absolute error. It could not be analyzed to certainty if the prognosis method is causing this phenomenon or statistical variations in the time series for 2010. Nevertheless it could be shown that the prognosis methods for wind generation can never be as accurate as scheduling and prognosis for other generation technologies. This always existing unpredictability leads to the need of a constant spinning reserve that could be activated to compensate differences between real and predicted generation. In the worst situations this spinning reserve had to compensate up to $4.358 * 10^5$ kW in 2010. The error in the other direction could be compensated for example with load management or demand response techniques. In both cases some sort of storage or storage-equivalent would be needed to compensate the error between measured and predicted generation.

3.1.2.2 Buildings as storages – A simplified model

Lacking the existence of storage units in the grid it is at the moment not possible to exactly align wind generation and prognosis. Even if wind energy can never be as easy to control or to influence at least it could become predictable. It would become possible to plan the usage of each energy source without the need to take care about the erroneous fluctuations of the renewable sources. Even in financial aspects that can have effects, because the known needed spinning reserve back-up could be minimized and used for other purposes and grid operators or generation unit operators do not have to buy the option to use them.

For gaining an approximation on the dimensions and numbers that are needed to compensate the error a model has to be found, that could represent state-of-the-art commercial buildings. The focus in this work will be on this this type of buildings because following [Kup11] the service sector in Austria used up to 20% of the total electric load during the year 2007. This amount can be directly mapped onto so-called commercial buildings as educational buildings (schools, universities), hotels, hospitals, shopping malls, office buildings or others. Such buildings have quite a number of distinct characteristics in common that contrast strongly of other types of buildings such as residential buildings or buildings that are used for industrial purposes.

Table 3-3: Numbers of commercial buildings in Austria for the year 2001 [5]

Country	Commercial buildings, total	Hotels or similar	Office buildings	Buildings for: Retail or wholesale	Buildings for: Transport or communications	Workshops, industry, storage	Culture, leisurement, education	Other buildings
		Percentage %						
Austria	282 257	12.7	11.4	11.7	1.4	25.4	5.5	31.9
Burgenland	12 030	11.4	10.8	11.9	0.8	24.5	5.9	34.7
Kärnten	24 992	21.1	9.4	10.6	1.0	22.6	4.0	31.3
Niederösterreich	66 510	7.2	11.0	11.5	1.1	28.7	5.3	35.1
Oberösterreich	45 583	8.1	11.8	12.7	1.4	30.4	6.2	29.5
Salzburg	19 651	22.8	11.2	11.4	1.5	20.9	5.0	27.2
Steiermark	44 714	11.4	10.8	13.1	1.4	25.4	5.5	32.4
Tirol	28 009	28.8	8.7	9.8	2.1	20.2	4.9	25.6
Vorarlberg	12 158	16.4	10.3	10.9	1.2	25.2	5.8	30.1
Wien	28 610	3.9	18.1	11.8	1.6	21.4	6.2	37.0

In total 282 257 commercial buildings were counted in Austria for the year 2011 [Pol12]. 11.4% of this were office buildings [5]. It can be assumed that at the time this thesis is written even more commercial buildings can be found in Austria. Table 3-2 gives the (still) actual numbers, taken from the homepage of "Statistik Austria". These buildings are mainly used for commercial or business usage, but there is a variety of different types. Commercial buildings can be used for a vast variety of different facilities from schools to universities, from churches to hotels, from office rooms to storages, from hospitals to shopping mall. They all have in common that they do not count as residential buildings and the users do not live in them for their every-days live.

An office building will be used in the following as example buildings for all commercial buildings as they unify the common attributes of other commercial buildings. With a single heating and ventilation system they can provide a single point of communication as well as the possibility to influence the overall internal (in this case thermal) parameters of the buildings.

For this estimation a simplified assumption of the possible target building is made. The actual building features will be broken down to a smaller set, that includes only such values that influence the buildings ability to act as an demand response storage. Afterwards this simple model for a single building will be used to make a projection on the abilities a group of similar buildings may show.

The building that is used as blueprint for this research is a state-of-the- art office building in Vienna. The so-called ENERGYbase is an office building built after the passive-house-standard and has an area of 5000 m². 100 % of the used energy comes from renewable sources (solar or geothermic heat) and the energy costs are 80 lower than in comparable buildings. The heating, ventilation and air-conditioning system uses state-of-the-art technologies like heat-pumps, concrete core cooling and plants for humidification. [6]

In the project BED the following key points regarding the thermal behavior of the ENERGYbase could be determined (an extremely condensed summary of the results was published in [Pol12]):

- The two independent heat pumps can be activated and deactivated separately.
- During a whole year only one heat pump is needed at any time. It can be argued that the system may be designed in a not optimal way but the initial design rules indicated such a conservative design. An optimization of the HVAC-system in the ENERGYbase cannot be seen as part of this work and therefore the system will be used as-is in this consideration. The heat pumps (used for cooling and heating) have atypical load of 45 kW peak.
- The time constant for changes in the thermal domain is very high. That means that changes in the heating or cooling processes that include a total cut-off of electrical energy have little to no impact at the thermal conditions inside the building. In [Bed12] it was proven that the two components are never used simultaneously during the normal process due to operational reasons. It was also shown that a cut-off of both heat pumps for at least 2 h is possible at all times. This last point is in fact a very conservative assumption and based on the fact, that various thermal simulations have shown that during cut-off periods of 5 h the unwanted temperature drop or rise of the interior temperature satisfies the comfort limits of commercial buildings. For the following model only the minimum potential (as worse-case scenario) is taken into account. This includes the ability to switch off heating and cooling for two consecutive hours at any time of the year.

The described key attributes for obtaining a building model are also included in Table 3-4.

Table 3-4: Attributes for simplified building model

Switch off potential	-45 kW
Additional load potential	45 kW
Max. duration of load shift	2 h per activation phase

With this in mind the typical operational modes of the heating and ventilation in the ENERGYbase can be modeled in the way that is illustrated in Figure 3-12 and was also presented in [Pol12]. On the left side the mode including only one heat-pump is shown, while the second one shows the load with no device operating and the last one shows both heat-pumps active. Especially the last one (as already mentioned) is a very special case with respect to the reality that only few buildings are able to make their electrical load higher than initially intentioned.

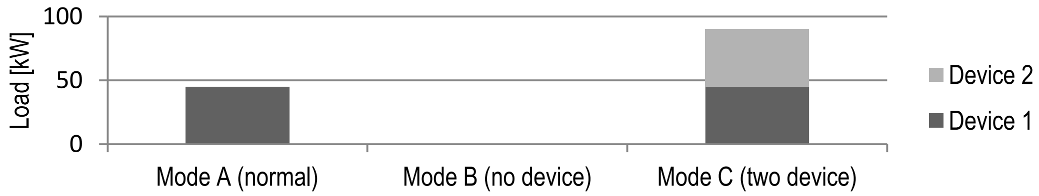


Figure 3-12: Operational modes of heat-pumps in ENERGYbase [Pol12]

Another description in terms of the already described model for a building that is similar to the ENERGYbase would include also the flexibility of the total shiftable amount of electrical load. Based on time slots of 15 min the flexibility factor at each point of time is ± 8 timeslots (2 hours) with an amount of ± 45 kW. Two hours is in this case also in the project BED determined worst case time that was measured and simulated even for rooms in which the temperatures were very close to the borders of the comfort interval (compare also chapter 4.1.3.1). Figure 3-13 illustrates the corresponding operational modes within the model that was developed on base of the described parameters. Figure 3-13 shows the model for the building for a period of 3 hours of the day, both with the maximum amount of shiftable energy and the additional information for the flexibility of each energy unit (see chapter 3.1.1). In this case one energy unit was chosen as 45 kWh as each pump is considered to be switched either on or off. The actual energy consumption for every timeslot can be therefore only be either 45 kWh (90 kWh if both pumps are operating at the same time) or 0 kWh. The described case makes one more additional requirement necessary the model has to include as the building question includes only 2 distinct heat pumps. Therefore any case in which a load situation would occur that involves higher loads than 90 kW is not possible in reality. A building agent that tries to adapt the load profile in respect to the necessities of a smart power grid would need to respect such internal limits as these also influence and limit possible use cases.

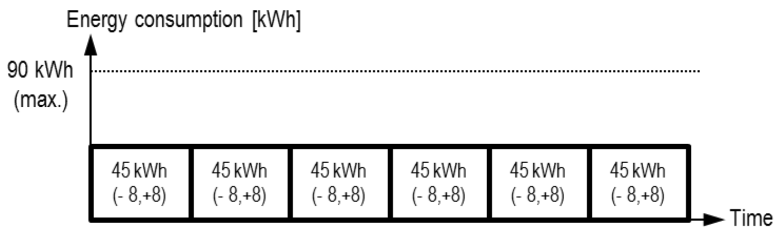


Figure 3-13: Model for load shifting potential of the ENERGYbase

3.1.2.3 Different scenarios for compensating the wind prognosis error

Two different scenarios can be defined for dealing with the prognosis error of wind generation. The first is based on the assumption that the whole error of the wind generation (phases of energy surplus and shortage) has to be compensated. The second scenario deals only with the negative error which occurs if the predicted amount of generated energy is too low. Both scenarios will be evaluated in the following two subchapters.

Scenario 1: Complete compensation

The basis for the first scenario is the assumption that not only periods of too small generation can be compensated with the help of storages but also too high energy generation can be flattened. The idea behind this scenario is to make the generation of renewables (in this scenario wind generators) predictable without the need of coping with prediction inaccuracies. The goal is that wind generation will become a perfect predictable energy source. Therefore there has to be enough potential to flatten even the highest peaks (positive and negative) of the error and therefore is important to get an appropriate estimation for the "worst case". In fact any number of storages could be used to partly compensate the error – but with taking even rarely occurring peaks into account a minimum number of storages/buildings can be determined that is able to compensate even the highest inaccuracies of the generation throughout the whole year. Figure 3-14 should illustrate this concept. The figure shows how the predicted profile should be fitted to the measured profile by either switching on or off loads. It is important to note that the illustration shows both the predicted and the measured generation.

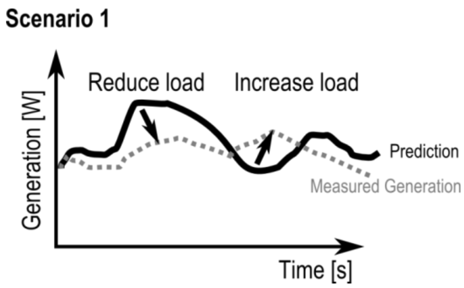


Figure 3-14: Scenario 1: Compensation of negative and positive errors with storages

The following evaluation is based on the simple model for buildings described in chapter 3.1.2.2. Although it models the abilities of buildings as storages in an abstract way it should be sufficient for this estimation. It has to be pointed out once more that the underlying building (ENERGYbase) is a testing object that ensures that the scenario also fits for future and state of the art buildings that are able to alter their load profile in a way to use "more" energy than necessary and gaining an advantage out of this.

Another step to simplify the evaluation is to scale the amount of generated and predicted energy generation down by a factor of 1:1000. This does not have any effect on the overall product, but is a mere quantitative change. The quality of the estimation is not affected. In this downscaled scenario a smaller number of units is needed than in the original one. It will be shown that a (also downscaled) error between prognosis and generation can be compensated by a calculated number of buildings. To re-calculate the number of buildings that should be able to compensate the error for the original values the number simply has to be up-scaled by the same factor.

This step can help to make a later simulation easier because only a handful of units has to be simulated in comparison with a 1000 times higher number. Another possible interpretation for the scaling could be that each of the "building" is in fact not one unit but consists of several smaller units and therefore can be seen as an amalgamation or some kind of virtual storage. Either way the result can be seen as equal in a qualitative point of view.

The number of buildings or units that should be sufficient to compensate the prediction error can be determined by taking the biggest deviations between predicted and measured values. Table 3-5 includes the scaled values of the biggest negative and positive deviations (compare with Table 3-2 for the original values). In this calculation only the absolute values for the deviations are taken into account because it has to be ensured that enough total amount of load can be shifted at all. If it is theoretical possible to compensate the generation differences for the two extreme values it is ensured that the amount of storages is sufficient for all other cases throughout the year. The period that each storage node can be switched on or off defines only how often one node has to be used for compensation. This issue will be described in detail in chapter 3.2.

Assuming that each unit can either switch off 45 kW of load or generate an additional load of equally 45 kW 9.69 units have to be switched off to compensate the highest negative deviation while the additional generation of 15.28 units is needed for leveling the highest positive deviation. The building model used in this calculation does only allow three different and discrete values of load (0, 45 or 90 kW) for the three different operational modes.

Exactly 9.69 units can never be switched off, but only 9 or 10. In the first case a small negative error would remain and the error cannot be compensated entirely. In the second case the negative error would be changed into a positive one, leading to an overcompensation of the error. The compensation in both cases is not perfect in terms of leading to a perfect match between prediction and real generation and a maximum quantization error smaller than ±45 kW has to be allowed. The cause for this quantization error lies in the fact that the smallest model unit that is used for the calculation has a peak load of 45 kW. The values for both cases of either undercompensation or overcompensation are also included in Table 3-5 for negative and positive error values.

Returning the numbers to their real scale would bring values that are 1000 times the values that are included in the table. This would lead to the values of 9690 buildings to compensate the negative error and 15280 buildings to compensate the positive prognosis error.

Table 3-5: Number of units/buildings for scenario 1

Scale 1:1000		Necessary number of units		
		Exact	Case A Undercompensation	Case B Overcompensation
Biggest negative error	$-4.358 * 10^2$ kW	9.69	9	10
Biggest positive error	$6.877*10^2$ kW	15.28	15	16

The two scenarios of under- and overcompensation would therefore lie inside the interval of [9000;15000] for undercompensation respectively inside the interval of [10000;16000] for overcompensating the error.

In the same way as the solution values have to be scaled up again the quantization error has to be scaled up. This leads to an overall quantization error with a maximum of ±45000 kW. This is due to the fact that the calculation was based on units of 1000 buildings with 45 kW load each. This inaccuracy was mainly taken into account to simplify a later attempt to schedule the buildings (chapter 3.2). Another way to interpret the error that was intentionally made is to assume that each unit consists of 1000 smaller units and handles the scheduling and managing for itself as a kind of virtual storage that groups a bigger number of smaller units to act as one several times more potent storage node. In general it can be summarized that a higher number of discrete units will lead to smaller quantization errors.

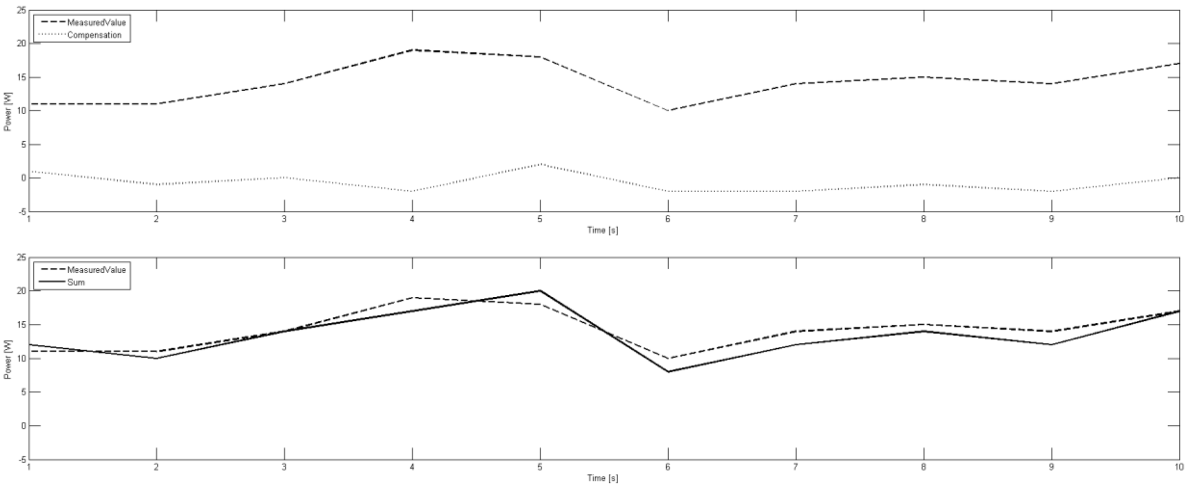


Figure 3-15: Example for adding the compensation and the measured time-series

Based on the values that are presented in Table 3-5 a calculation could be obtained on how altered time-lines that take the compensation of the prognosis error into account could look like. The calculation was based on the assumption that either the error is compensated slightly more or less its actual amount (depending on the two different cases). In the both cases the measurements for wind generation and its prognosis of the year 2010 were taken and for every value of the prognosis error it was determined how many units of demand response storages would be needed to either load or unload their storages (compare again Figure 3-14 for the appropriate action the storages have to fulfill) to counteract the error. Therefore the error value was divided by the unit-size (in this scaled case 45 kW). The resulting number was either rounded to the next lower integer number of storages (undercompensation) or the next higher value of units (overcompensation). It has to be noted that for this analysis it is assumed that always enough units are available at any point of time. Following this procedure for every error value of the year two time series are resulting, for each of the two scenarios one. These two time series including the necessary compensation amount that would be needed for the error values are afterwards added with the measured values. The combination of the measured values and one of the compensation time-series makes a new time-series that closer resembles the intended generation profile.

Figure 3-15 shows in two diagrams the described workflow. The upper diagram includes an example timeline with (possible) power values for the measured generated profile as well as another time series with values taken from an interval of [-2;2] W. This second time series is an example for the compensation time series. The second diagram shows the summation of the two time series and (for better comparison) the original time series.

In Figure 3-16 a part of the original time series and the two different compensated time series are included as well as the predicted generation profile (all scaled down in this example). It can be pointed out that the predicted profile lies always between the two compensated time series. The difference between the compensated series and target time series is based again on the quantization error that was taken into account. But it shows that the two compensated time series can be seen as the outer boundary limits for a specific accuracy that could be obtained. If the quantization error could be made smaller the time series would get closer and closer to the target.

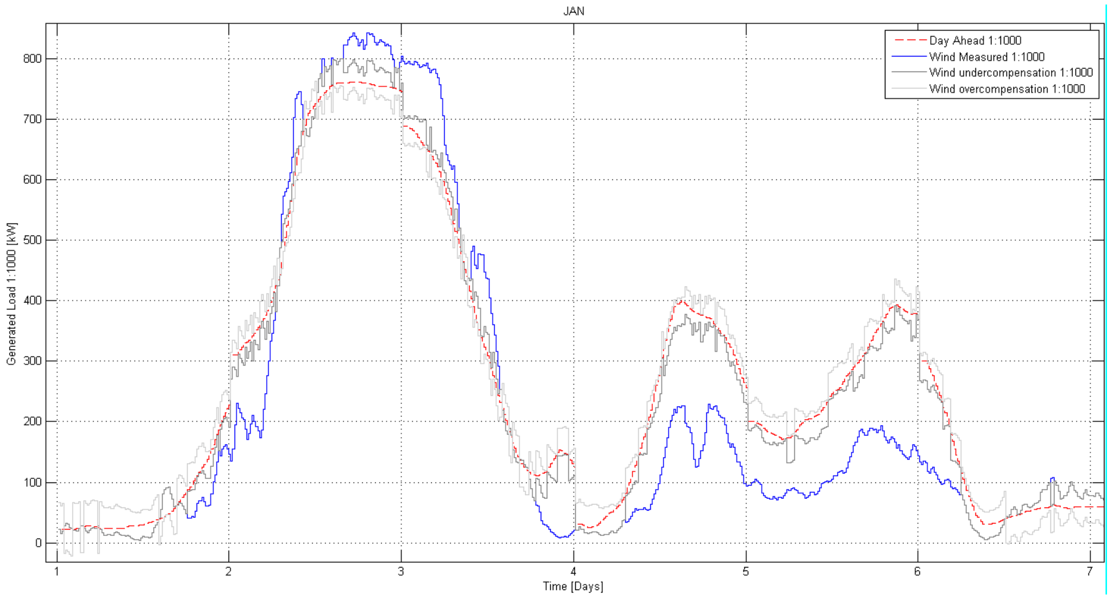


Figure 3-16: Original and predicted time series compared with compensated time series.

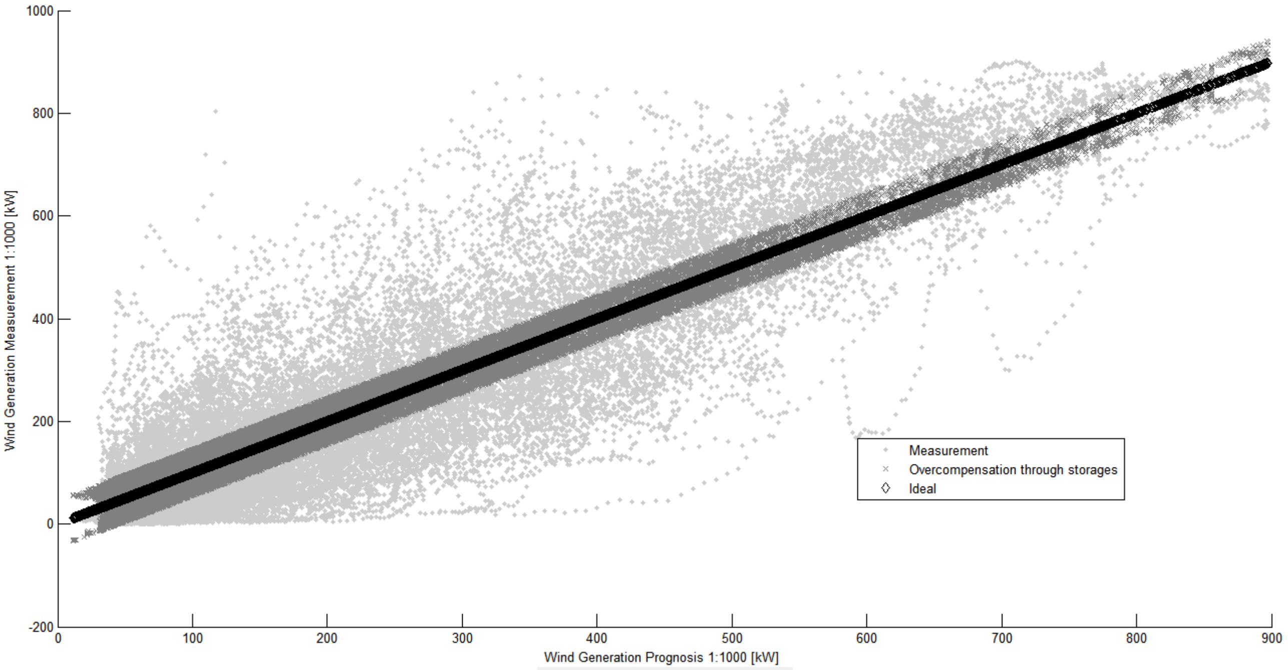


Figure 3-17: Scatterplot of ideal, real and compensated load generation profile (Overcompensation)

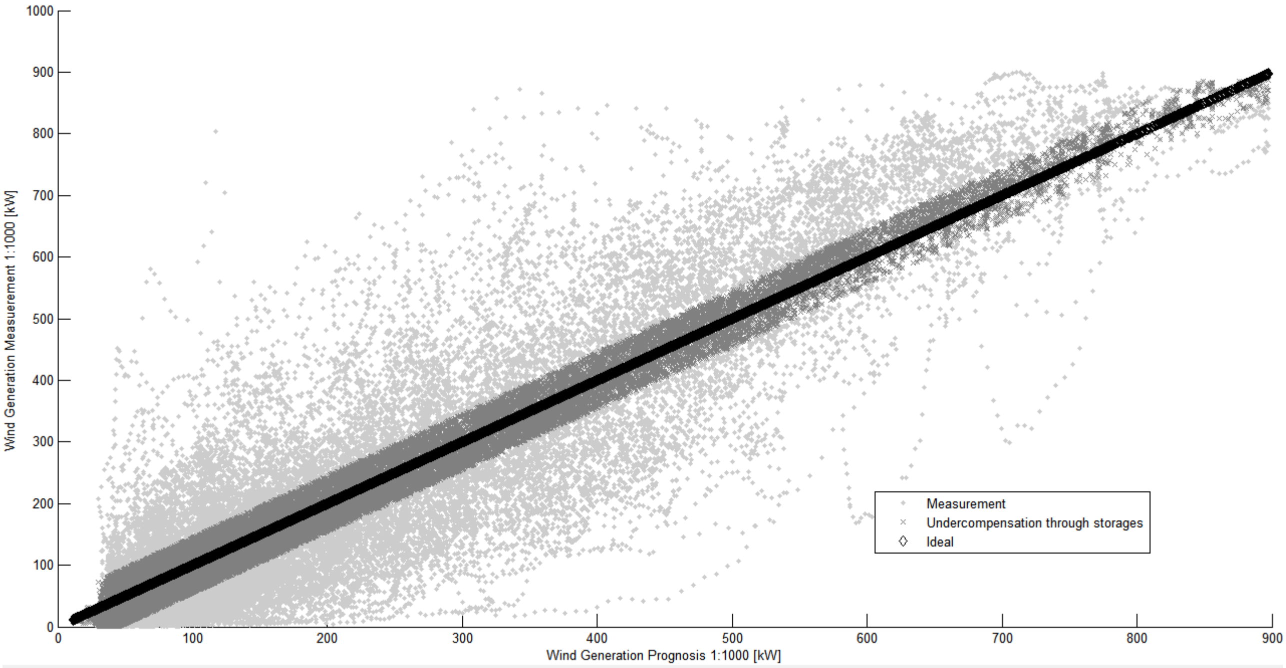


Figure 3-18: Scatterplot of ideal, real and compensated load generation profile (Undercompensation)

Another type of illustrating the possible impact the demonstrated change of the generation profile can have was already described being a special type of scatterplot. Again scatterplots can be generated for both of the scenarios and can be seen in Figure 3-17 and Figure 3-18. In both cases the points correlating to the compensated values are well within a narrow corridor around the ideal position. The size of this corridor is determined by the smallest initial storage unit – in the presented case 45 kW (comment: the values were scaled by a factor of 1:1000). So the difference between the ideal and all of the compensated points lie within an interval of ± 45 kW. It can be summarized that with a sufficient number of demand response storage nodes the measured generation points could be changed in a way to fit better to their corresponding prognosis value. The figures show that with a high enough number that is always possible.

In Figure 3-17 another special case has to be investigated and pointed out. After the compensation several points lie beneath the x-axis, indicating negative generation values. This is the case if a small positive error (more energy than expected) was compensated and turned into a negative error. This only happens if the scenario includes a total compensation up to the case that a conversion of the sign is executed. This is one indication that the scenario of overcompensating the prognosis error - generating a situation of energy surplus when in fact the generation is too low - seems not very feasible and realistic. But by executing a sample calculation for this case the upper bound can be determined, therefore providing an upper limit for the needed number of demand response storages.

Scenario 2: Compensation of negative error

The first discussed scenario shows that activated buildings in terms of their demand response abilities can be used within strategies to minimize the prediction error of wind generation. This first case was following the assumption that the involved demand response storages can perform their abilities in two directions – either generating more load than in normal operation mode or less load. Following these prerequisites positive and negative generation errors were treated in exactly the same way. This can also be looked upon in another light. If the generation is lower than initially predicted the energy provider has to keep sure that enough energy reaches the consumers although there is a shortage. This is normally done by providing more energy through other sources either in the same grid, or from the outside. In both cases a higher financial input as initially planned has to compensate for the wrong prediction. In the second case a profit can be gained with the unintentional surplus of energy that suddenly has evolved. That is because a surplus can be sold to other energy providers to support them with their shortages. So while the first case (a too low generation) generally has to be avoided, the second case could be turned into a benefit. This is one cause why the second scenario will only deal with the periods of time when the generation is lower than the predicted value and therefore a negative error occurs. In Figure 3-19 the concept behind the scenario is illustrated, it shows how phases of too high generation are tolerated while too low generation values are fitted to the predicted generation profile.

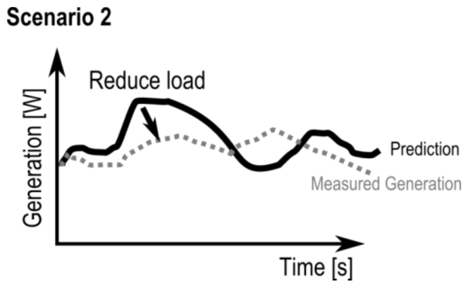


Figure 3-19: Compensation of negative errors with storages

The second cause is that at the moment it is highly unlikely that buildings are able to perform two kinds of load events. This includes switching off their normal load and generating a higher load if necessary. The examined test object, a passive house office building in Vienna, is able to do that due to its existing two heat pumps where only one would be sufficient. The used model for the storage ability of the building should be – again – derived from the mentioned office building in Vienna, the ENERGYbase. So the model will include only the “Normal operational mode” (constant energy demand of 45 kW) and the “No device operational mode” (compare again Figure 3-12). The model therefore is similar to the one used for scenario 1 with the difference that the examined object have got no possibility to add load to their normal operational mode.

The expected results of the calculation of the potential are again rough estimations of the possible potential. Again the used numbers are scaled by the factor of 1000 to have lower numbers for later usage and outlook on possible scheduling algorithms. Like before it can be assumed that the error that will be made by scaling the numbers is not changing the overall product of the estimation. The numbers can easily be returned to their initial scale and only the quantization errors that are made also have to be scaled by the same factor to ensure a correct calculation.

Like in scenario 1 the first use case is of importance - the one were an error is compensated in a way that the sign of the error switches from positive to negative and vice versa. When describing scenario 1 this compensation was called "overcompensation". In contrast to scenario 1 this will be the sole estimation for scenario 2. This is based on the initially described idea that during phases of too low generation a financial input has to ensure the compensation through various normally not active energy sources either from other energy providers or grid internal control energy.

By overcompensating the negative error it is assured that during the whole observed period of time only positive errors occur, indicating an energy surplus. Regarding the number of storage nodes that is necessary to compensate the negative error the calculation can be conducted as before. As already explained the only important information is the one regarding the maximum or biggest negative error as this is the number that is needed to calculate the needed amount of storage nodes.

Table 3-6 shows the exact numbers (again scaled by a factor of 1000). In this table both cases of under- and overcompensating the errors are included. As already stated only Case B "Overcompensation" will be discussed in this part of the work, because the case of getting rid of all negative errors and thus the chance of evading the need of providing a financial input for compensating too low generation profiles with control energy is the one that has significance for the management of an intelligent energy distribution infrastructure.

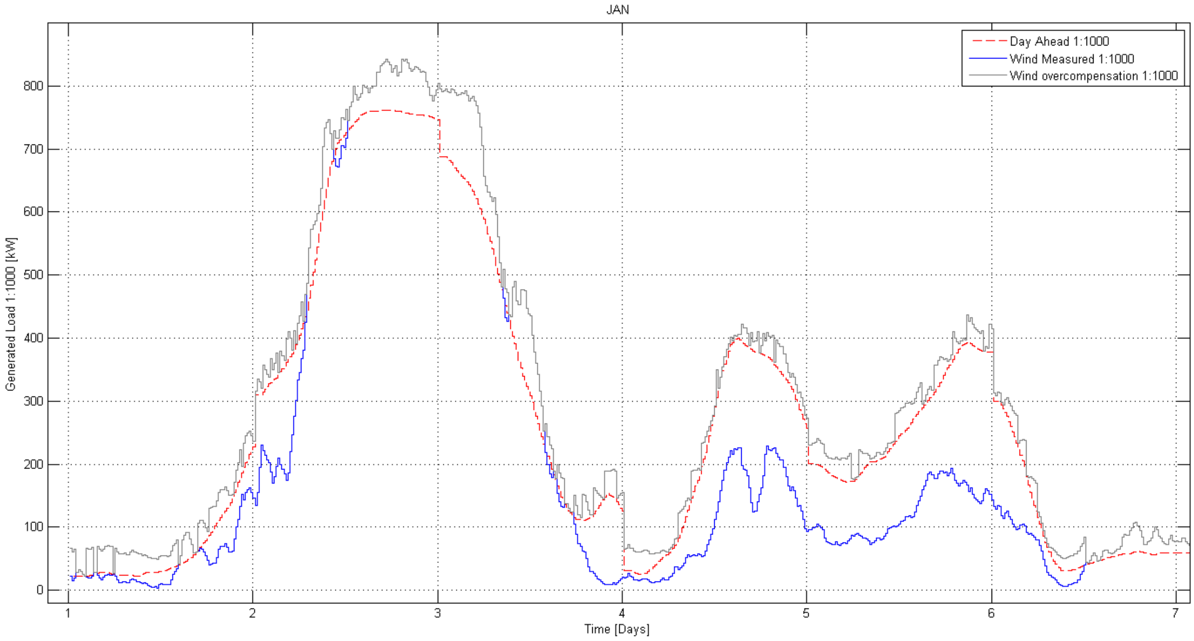
Table 3-6: Number of units/buildings for scenario 2

Scale 1:1000		Necessary number of units		
		Exact	Case A Undercompensation	Case B Overcompensation
Biggest negative error	$-4.358 * 10^2$ kW	9.69	9	10

In difference to the previously discussed cases that included the full compensation of any error the following calculation will only be based on the assumption to compensate the negative errors. Again it was calculated on previously calculated numbers (Table 3-6). It is assumed that at every point of time during the year at least 10000 buildings are available to be used as demand response storages. The actual calculation of an altered generation profile for the year was again executed in a MatLab calculation that used as many units single units of loads as necessary. Each load was assumed to be 45000 kW of switchable load – it can be assumed that with the appropriate communication and management tools single buildings and units of smaller amount can be grouped to build these larger storage units.

Figure 3-20 shows the comparison between the initially predicted generation profile (red, dashed) and the measured profile for the period between 1st and 7th of January in 2010 (blue). In addition to that a possible altered profile that includes the avoidance of any negative differences between prognosis and measurement through compensation by introducing load shifting through buildings is included (grey). It can be seen that (again) all periods in which the generation (blue) was lower than the predicted amount of energy (red) the proposed amount of switched off loads could lead to an altered generation profile that lies above the predicted generation (grey). In phases when the generation profile was higher than the predicted amount the generation profile was not changed in this scenario and therefore the grey and the blue lines are congruent.

Figure 3-20: Comparison between a measured generation profile and a possible compensated profile for



the period of 1.-7- January 2010 for the wind generation in Austria.

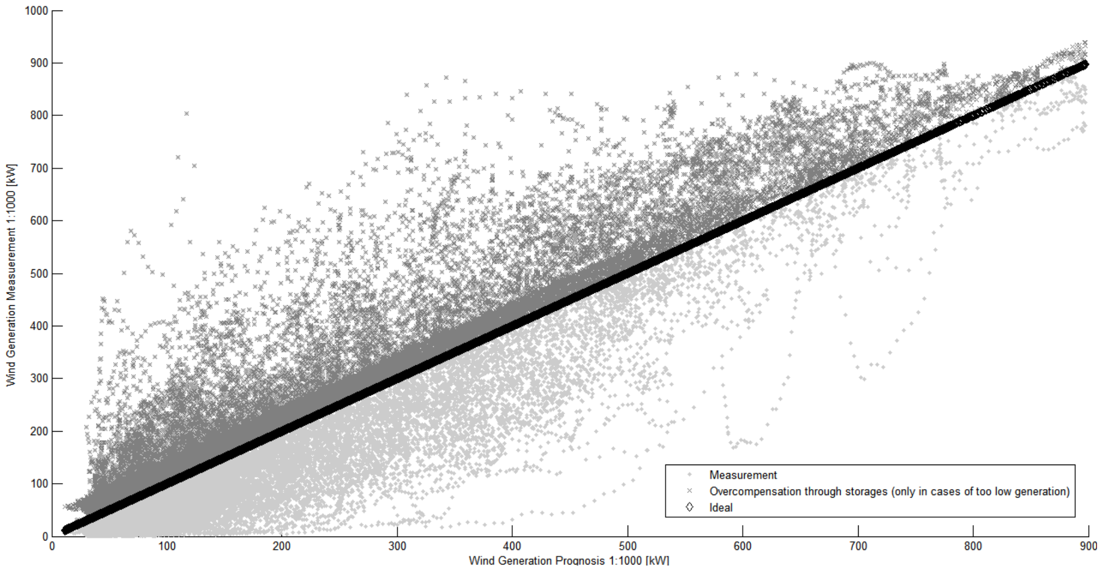


Figure 3-21: Scatterplot of ideal, real and compensated load generation profile

Another visualization that is able to show how the generation profile changes of buildings or other demand response storages are used to compensate negative prognosis errors is given in the scatter-plot in Figure 3-21. Again all the points are a pairing of the measured and the predicted generation amount for each point of time. Ideally all points would lie on the 45° diagonal because the prognosis and the generation are equal. In reality wind generation is not predictable without error and therefore the most points are close to their ideal location. By compensating only the negative errors it can be assumed that no data points will be located below its ideal location. The figure shows that exactly this scenario can be brought to pass. It can be seen that after following the compensation no data points are below the line that aligns the points with ideal positions (black).

The total amount of demand response storages that is necessary for the compensation of only the negative errors is in fact lower than in the case of compensating the entire error. The conclusion of the comparison of these numbers is that less units are needed to compensate the (financially worse) negative error than in the case that every deviation between generation and prediction should be compensated – in the first case a minimum number of 10000 buildings is sufficient for the scenario while in the second case a number of 16000 buildings can be seen as the absolute minimum.

3.1.2.4 Summary on the evaluation and financial estimation

In the prior chapter an evaluation on the potential that building could provide for the smart power grid was presented. It is shown that 10000 buildings of a specific setup could be used to flatten the negative prognosis error that occurs at any time of the year by generating electricity by using wind generation units. The underlying setup is based on a state-of-the-art building in Vienna, the ENERGYbase and it is assumed that the buildings (at least) are able to drop their energy consumption by 45 kW at any time. It was shown that with the help of loads that are able to perform demand-response switch-off actions a certain amount of balancing energy could be provided.

For an estimation in terms of financial benefits it has to be pointed out that the more critical situation for the power gird is the one in which a power shortage has to be compensated. This is also the more important case taking financial terms into account, because (at the moment) the only solution is to produce a larger amount of energy whereas in times of an energy surplus a reduction of the generation can also counteract possibly problematic situations for the power grid. In the latter case even the export of the energy to connected grids with temporal shortages is a possibility.

To gain a financial approximation it is assumed that the reduction of the load is possible for at least 2 hours and that the whole potential can be used at any time. This means that 10000 buildings/units are always needed to be ready to reduce their consumption by a factor of 45 kW. With (ideal) conditions each of the buildings would need (at least) a 2 h refill period after each full activation circle. This case can and will only be assumed here for a very rough estimation on the financial situation because due to storage losses and inefficiencies in the underlying processes it has to be assumed that the time that is needed for re-gaining the full level in the storages is longer than the initial activation period. Nevertheless it can be assumed that each of the units is able to fulfill 6 entire activation-cycles (2 h load reduction, 2 h of regeneration) on each day.

With 10000 units/buildings that are able to act as demand side storages with 45 kW of a potential load reduction a total potential of 45000 kW can be introduced into the power grid. In terms of energy this means a total potential of 112500 kWh and taking the 6 cycles of activation for each day, and 365 days every year into account a total amount of 492.75 GWh of balancing energy can be gained through the introduction of active buildings into the mechanisms and workflows of the power infrastructure.

This calculation is based on the assumption that at each time the maximum amount of buildings is needed to compensate the difference between wind generation and prognosis and the balancing is only achieved by the reduction of load of buildings. The evaluation of the time series has shown that this case is very rare and throughout the whole year 2010 would have been necessary at only three different periods of time. The given amount of necessary balancing energy to compensate the wind prognosis error can therefore be seen as "worst case" while it can be assumed that the actual amount is lower.

Finally to achieve a potential financial value to evaluate if a solution based on the potential of buildings could generate a benefit, the following approach was taken. In a first step the prices and tariffs for balancing energy for the year 2010 in Austria were made out. These prices can be received on the homepage of the "Austrian Power Grid – APG" [4] as free download. This downloaded package includes all different prices for balancing energy for every point of time (the quantization is again based on time-slots of 15 min) for the entire year. Here the so-called "Clearing Price 1" is taken as base for the calculation, because this time series includes the financial incentives for compensating direct load or generation imbalances (positive and negative).

For each of the already described scenarios a financial benchmark was calculated. The until now used values containing the average load for each 15 min-timeslot was first converted into values of the used energy in the respective time-period (in kWh) to match the price values (in €/kWh). Afterwards each of the energy values was multiplied with the corresponding clearing-price and these values then were added to gain a single monetary value for the year 2010. Formula (6) shows the formula for all the 35040 points of time during the year.

$$\sum_{i=0}^{35039} Price_i * Energy_i \qquad (6)$$

The results of this calculation are shown in Table 3-7. The prices were calculated for all the three different scenarios of compensating the wind-prognosis-error as well as the base scenario of no compensation at all. In all cases in which compensation took place the value turned from negative in the not compensated case to a positive one. This can be justified because in the first case the energy provider has to pay penalty for each time-slot in which a too low generation needed to be compensated by balancing energy from the spot market. These penalties can be minimized in the cases of undercompensation (small penalties) or entirely avoided in the cases of overcompensation. The highest possible profit was determined in the scenario that assumes that only the switch-off potential of the loads is used for compensating the negative deviations of the wind generation. This can be explained by the idea that in terms of a higher than expected generation it could be possible to sell the surplus and gain a even higher profit by that. That combined with the (in this case) avoided penalties for too low generation leads to the listed value.

Table 3-7: Clearing-prices for energy deviations

Without compensation	Overcompensation positive and negative deviations	Undercompensation positive and negative deviations	Overcompensation negative deviations
- 10862070 €	98567761 €	92374475 €	110788111 €

Summarized it can be said definitely that compensating (at least) the negative values of the wind-prognosis-error is not only possible with about 10000 active units of about 45 kW of load shifting potential but can also bring a high financial benefit for the stakeholders in the power infrastructure due to the avoidance of penalties that have to be paid if the prognosis does not match with the actual generation.

3.2 Scheduling of demand response storages

The first part of this chapter covered the estimation on how big the potential for demand response storages might be in the case of the Austrian wind generation profile. The following will give a spotlight on possible scheduling methods for the operational management of demand response storages first by presenting an easily implementable choice, and then a comparison with more advanced techniques to come finally to a possible outlook on including geographically distributed units into account.

3.2.1 Round robin scheduling of demand response storages

By introducing a group of demand response storages to the power grid the necessity comes up to make use of their capabilities in the most efficient way possible. Therefore operational management schedules for the activation of the units have to be developed. The underlying principle for a first scheduling algorithm that should lead to a rough estimation on how in a group of buildings could be activated as storages is based on the so called round robin strategy. This operational method is widely used in computer science for processes and operating systems. It will be shortly described in the first part of this chapter. The second part includes the description on how this method was adapted to create a scheduling algorithm for demand response storages.

Taking the scheduling principle of the round robin scheduling into account a fairly similar scheduling method for the proposed demand response storages was developed. In the beginning the general principle will be described, and afterwards actual examples and results will be given based on the presented scenarios. The base principle for the scheduling is that each of the units can provide a responsive load of a certain amount and can be activated for a specific span of time (corresponding with a number of subsequent timeslots). It is assumed that both the generation of additional load to buffer overgeneration as well as a load drops to buffer undergeneration can be seen as equal. For each timeslot the needed number of units to compensate the error is calculated and afterwards split and allocated to the appropriate number of units. The units are selected in a circular manner and are active only for a fixed number of timeslots at once. In cases that the error is smaller than in the timeslots before it is possible that during this period certain units are not activated, although they were before. The internal distribution counter is not reset to ensure an equal distribution of the usage of all units over the year. If all units were activated the internal counters are reset and the whole process starts new.

Table 3-8: Round robin scheduling for demand response storages

Timeslot	Error	Unit 1	Unit 2	Unit 3	Unit 4
1	2	activate	activate		
2	1	activate			
3	0				
4	2		activate	activate	
5	1			activate	
6	2	activate			activate
7	1				activate
8	1	activate			

An example for this scheduling principle is shown in Table 3-8. The example shows the activation for four different units and assumes that each of the units can only be used for 2 timeslots for each activation period. The activation periods are indicated by the bold borders around the cells. The illustration shows also two of the principles to ensure an equal distribution. First it can be seen that (for example) unit 2 is activated once in Timeslot 1 because the error of 2 could not be compensated by one unit alone. Unit 2 is afterwards not until timeslot 4 again (the empty cells indicate that the unit was not used in this period). Second in timeslot 6 two units are activated to compensate the error. In timeslot 7 the unit number 4 is activated again, to ensure that its two possible usages in each activation cycle are truly used.

The first results were achieved for the scenarios that assume that both negative and positive deviations have to be compensated. As shown before for the slightly undercompensated case about 15000 units with the ability of switching on and off 45 kW are needed and for the overcompensating 16000. Each of these units is considered to be able to switch off (or on) its load for 2 h, corresponding with 8 timeslots á 15 min. These numbers were taken to develop a possible activation schedule for an example year of wind generation in Austria. For the exemplary schedule it is assumed that always 1000 buildings are switched on and off at the same time – forming a virtual unit. Part of an example schedule for the case of undercompensation can be seen in Table 3-9. The activation indicators are assumed to be “-1” for load reduction and “1” for additional load generation (not in the shown picture). The third column shows how many of the units are needed to (in the case of undercompensation) nearly flatten the timeline.

Table 3-9: Extract of load activation plan for undercompensation of wind prognosis error, Austria 2010

From	To	Amount Buildings (x1000)	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12	B13	B14	B15	Checksum
01.01.2010 23:30	01.01.2010 23:45	-1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
01.01.2010 23:45	02.01.2010 00:00	-1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 00:00	02.01.2010 00:15	-3	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 00:15	02.01.2010 00:30	-3	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0
02.01.2010 00:30	02.01.2010 00:45	-2	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 00:45	02.01.2010 01:00	-1	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 01:00	02.01.2010 01:15	-2	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 01:15	02.01.2010 01:30	-2	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 01:30	02.01.2010 01:45	-2	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 01:45	02.01.2010 02:00	-2	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 02:00	02.01.2010 02:15	-3	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0
02.01.2010 02:15	02.01.2010 02:30	-3	0	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0
02.01.2010 02:30	02.01.2010 02:45	-3	0	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0
02.01.2010 02:45	02.01.2010 03:00	-3	0	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0
02.01.2010 03:00	02.01.2010 03:15	-2	0	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0
02.01.2010 03:15	02.01.2010 03:30	-3	0	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0
02.01.2010 03:30	02.01.2010 03:45	-3	0	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0
02.01.2010 03:45	02.01.2010 04:00	-3	0	0	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0
02.01.2010 04:00	02.01.2010 04:15	-4	0	0	0	0	0	0	0	-1	-1	-1	-1	0	0	0	0	0
02.01.2010 04:15	02.01.2010 04:30	-4	0	0	0	0	0	0	0	-1	-1	-1	-1	0	0	0	0	0
02.01.2010 04:30	02.01.2010 04:45	-3	0	0	0	0	0	0	0	0	-1	-1	-1	0	0	0	0	0
02.01.2010 04:45	02.01.2010 05:00	-2	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0

The presented scheduling principle should ensure that all the units are used equally throughout a longer period of time, regardless how often the error has to be compensated. Again it has to be pointed out that both types of load activation (negative as well as positive) are seen as equal. The point could be made that the compensation of the negative error is more valuable in financial terms, but in terms of grid stability both can be seen as equally challenging and are considered the same.

For a possible evaluation if the scheduling algorithm can meet the requirement of being “fair” in regards of equally activating each of the nodes the schedules were calculated for the whole year of 2010 in both cases. Table 3-10 and Table 3-11 include the numbers for both cases. Especially interesting is in both cases is the second row, including the total number of activation events. In both scenarios this number is more or less equal, only lower in the last columns, because the scheduler started to schedule on January 1st with unit number 1 and the total number of timeslots in which compensation needed could not be divided by the number of units without remainder.

Table 3-10: Total number of activations of loads for undercompensation of wind error in 2010

Unit	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12	B13	B14	B15
Events	2600	2600	2600	2600	2600	2600	2598	2592	2592	2592	2592	2592	2592	2592	2592
Load Drop	1338	1283	1291	1316	1337	1314	1324	1368	1361	1401	1425	1410	1389	1384	1353
Load Rise	1262	1317	1309	1284	1263	1286	1274	1224	1231	1191	1167	1182	1203	1208	1239

One main difference between the two scenarios is the higher number of activations in the second scenario. This deviation by the factor of about 1.7 (~2600 events in comparison with ~4626 events for each unit) can be explained with the fact that in the second case even deviations smaller than 45000 kW are compensated by the scheduling algorithm and a shortage is always turned into a surplus by changing the sign of the error and vice versa. This was made to provide the ability to fully compensate any error an additional unit is needed at every time of the year. These differences can also be seen in an excerpt of the scheduling table for the overcompensation-scenario (Table 3-12).

Table 3-11: Total number of activations of loads for overcompensation of wind error in 2010

Unit	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12	B13	B14	B15	B16
Events	4624	4624	4624	4624	4624	4624	4624	4624	4624	4624	4624	4624	4624	4624	4622	4616
Load Drop	2136	2135	2169	2172	2209	2232	2224	2220	2282	2302	2244	2184	2118	2131	2130	2125
Load Rise	2488	2489	2455	2452	2415	2392	2400	2404	2342	2322	2380	2440	2506	2493	2492	2491

Table 3-12: Extract of the load activation plan for overcompensation of wind prognosis error, Austria 2010

From	To	Amount Buildings (x1000)	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	B11	B12	B13	B14	B15	B16	Checksum
01.01.2010 23:45	02.01.2010 00:00	-2	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0
02.01.2010 00:00	02.01.2010 00:15	-4	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0
02.01.2010 00:15	02.01.2010 00:30	-4	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
02.01.2010 00:30	02.01.2010 00:45	-3	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
02.01.2010 00:45	02.01.2010 01:00	-2	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
02.01.2010 01:00	02.01.2010 01:15	-3	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
02.01.2010 01:15	02.01.2010 01:30	-3	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
02.01.2010 01:30	02.01.2010 01:45	-3	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
02.01.2010 01:45	02.01.2010 02:00	-3	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
02.01.2010 02:00	02.01.2010 02:15	-4	0	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 02:15	02.01.2010 02:30	-4	0	0	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 02:30	02.01.2010 02:45	-4	0	0	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 02:45	02.01.2010 03:00	-4	0	0	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 03:00	02.01.2010 03:15	-3	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 03:15	02.01.2010 03:30	-4	0	0	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 03:30	02.01.2010 03:45	-4	0	0	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0
02.01.2010 03:45	02.01.2010 04:00	-4	0	0	0	-1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0

The presented method of scheduling demand response storages showed a principal solution for the problem of managing the time triggering of such storages. The method was presented for the smallest amount of units that is able to fulfill a total flattening of the prediction error, and it can be shown that according to the results over the span of a year always a timespan of at least 24 hours between the activation of one unit could be guaranteed. Only in singular cases of high wind activity this duty cycles were reduced to only 3 hours. This happened in both scenarios less than 10 times over the whole year. If a bigger number of buildings would be involved in the process that minimal time period would increase instantly providing enough time for the storages to recover.

For ensuring the completeness of the presented approach also the schedule in the case of the last scenario including the compensation of the negative error values was created. Again it was assumed that each of the included units can be activated for a maximum of 2 h. In this case it is specified that each occurring error value will be compensated at it whole, even if that leads to an overcompensation of the error. It was already calculated that 10000 storages units (10 units á 1000 units) are sufficient to fulfill this task. A smaller part of the calculated schedule in this case can be seen in Table 3-13.

Table 3-13: Part of the load activation schedule for overcompensation of negative wind prognosis error, Austria 2010

From	To	Amount Buildings (x1000)	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10	Checksum
31.01.2010 23:45	01.02.2010 00:00	-3	0	0	0	0	0	0	0	-1	-1	-1	0
01.02.2010 00:00	01.02.2010 00:15	-3	0	0	0	0	0	0	0	-1	-1	-1	0
01.02.2010 00:15	01.02.2010 00:30	-3	0	0	0	0	0	0	0	-1	-1	-1	0
01.02.2010 00:30	01.02.2010 00:45	-3	-1	-1	0	0	0	0	0	0	0	-1	0
01.02.2010 00:45	01.02.2010 01:00	-3	-1	-1	0	0	0	0	0	0	0	-1	0
01.02.2010 01:00	01.02.2010 01:15	-3	-1	-1	0	0	0	0	0	0	0	-1	0
01.02.2010 01:15	01.02.2010 01:30	-4	-1	-1	-1	-1	0	0	0	0	0	0	0
01.02.2010 01:30	01.02.2010 01:45	-4	-1	-1	-1	-1	0	0	0	0	0	0	0
01.02.2010 01:45	01.02.2010 02:00	-3	-1	-1	-1	0	0	0	0	0	0	0	0
01.02.2010 02:00	01.02.2010 02:15	-3	-1	-1	-1	0	0	0	0	0	0	0	0
01.02.2010 02:15	01.02.2010 02:30	-3	-1	-1	-1	0	0	0	0	0	0	0	0
01.02.2010 02:30	01.02.2010 02:45	-3	0	0	-1	-1	-1	0	0	0	0	0	0
01.02.2010 02:45	01.02.2010 03:00	-3	0	0	-1	-1	-1	0	0	0	0	0	0
01.02.2010 03:00	01.02.2010 03:15	-3	0	0	-1	-1	-1	0	0	0	0	0	0
01.02.2010 03:15	01.02.2010 03:30	-3	0	0	0	-1	-1	-1	0	0	0	0	0

This time in all the cases in which a positive error occurred no balancing action is scheduled while in all other cases the necessary number of storage units is activated as in the other presented schedules. Again, the idea behind these actions is that not actually an electrical storage is activated but the consummation of different loads (in the example heat pumps) is not taking place at that time but some time later. The processes that are exploited can be different, but in the case of the heating pumps it would be the internal thermal capacity of buildings that is helping to delay the electrical consumption. It can be assumed that due to storage losses a slightly higher load can be expected after the loads are shifted. Because of the presumption that the activations take only place in phases of too low generation the later necessary compensation can mostly be covered in times with positive prediction errors thus lessening also a small amount of the positive error. The presented calculation does not take this into account but gives only a general view on the problem itself.

Table 3-14 shows a collection of statistical values on how often each of the storage units would have been activated in the scenario at hand. It can be seen that because of the fact that a much lower overall number of units is used in this scenario the actual activation events are more often for all of the units. In comparison to ~2600 activations for the first scenario (undercompensation of all errors) and ~4620 activations in the second case this case is lying somewhere in the middle.

Table 3-14: Total number of activations of loads for overcompensation of negative wind error in 2010

Unit	B01	B02	B03	B04	B05	B06	B07	B08	B09	B10
Events	3897	3896	3896	3896	3896	3896	3896	3896	3896	3896
Load Drop	3897	3896	3896	3896	3896	3896	3896	3896	3896	3896
Load Rise	0	0	0	0	0	0	0	0	0	0

As this scenario was mainly based upon the overcompensation paradigm it has to be primarily compared to the second scenario including ~4620 activation events for each of the units. Compared to this scenario the presented 3896 activation events are an even lower number than the value indicates, especially if the smaller number of storage units that are involved is outlined again. Also a factor could be, the already mentioned, fact that negative errors occurred more often during the monitored time-span (year 2010) as could be seen by the negative mean and median values (compare Table 3-2). The number would decrease again quite an amount if the maximum activation period could be increased (in this example it is assumed that it is 2 h) because it was outlined to be a worst-case scenario that could be increased surely with further research activities in this area.

Some lessons can be learned from the presented analysis. If a higher number of units could be included into the power grid in a similar way all time spans would increase and the number of events for every single unit would decrease. This is mainly because of the higher flexibility of the method through the inclusion of more units the load could be spread onto. A difference also would bring the increase of the maximum time-span for load-shifting for every event (here it was set to 2 h). With a higher value the duty cycle between the activation of one specific unit would also increase.

In summary it can be stated that the presented results show the “worst case scenario” due to the fact that a minimal number of units with a minimal amount of shifting time is the basis of the calculation. It therefore can be assumed that with longer activation intervals even less numbers of units would be needed to fulfill the goal of compensating the wind prognosis errors, or the same number of units could be used to compensate even higher instabilities inside the power infrastructure.

3.2.2 Comparison of round robin scheduling to advanced algorithms

The main working hypothesis this work is based upon is that a building can be used as demand response storage. As this should be valid not only for one building but also a group of buildings the following chapter will focus on how different internal states of the buildings (based on their different locations and usage profiles) influence this intended behavior. This was taken into account for a more detailed look on different activation patterns or schedules and their ability to help with the compensation of certain under- or overloads inside the power grid. The existing data on the wind prognosis error from the year 2010 was taken again as target function.

It can be assumed that some kind of optimization potential can be found within the scheduling mechanism of the group of units and the presented round-robin approach can be optimized. The presented workflow in the last chapter was based on the assumption that the different units are equal in terms of storage ability and general availability. It therefore was considered to be a good starting point to activate the units in a subsequent manner in a timeslotted activation pattern.

Different mechanisms for scheduling are thinkable and a more in detail research on this topic should be part of this chapter. It has to be evaluated if different sizes of buildings and their different abilities could be represented and taken into account for activating the units. Another question would be if it could be an advantage from an energetic point of view to drown and refill storages in periods directly after each other. The usage of round robin scheduling could sometimes lead to similar situation, but not because it is an internal constraint to do so, but more or less unintentional. A potential usage of such a scenario would be to keep the storage loss that happens low to counteract the tendency of building automation systems to bring certain parameters back to a target working point.

The following subchapter will therefore give a brief comparison of three distinct scheduling algorithms that could be used for the described application. Two of the algorithms are well known from other domains - the already mentioned round robin pattern as well as an adaption of the earliest deadline first algorithm. The last one was developed under the supervision of the author and will be described in brief fashion. A detailed description of the algorithm and the used method of development and evaluation can be found in the original work [Her12] and only a summary of the results will be included here.

The earliest deadline first pattern (EDF) that will be used as the second reference has one main difference compared to the round robin: It is not dependent on the assumption that the used storage units have to be all equal in terms of their parameters. They all could have different internal levels as wells as total storage values symbolized by their different time constants (the main parameters that describes a building's ability to act as demand response storage. For the EDF the units that should take part are ordered in a decreasing priority list mainly by the fact which of the units would reach its deadline before all others. For this survey this deadline was defined by the time a buildings internal temperature would need to reach a certain predefined limit and the underlying specifications for modeling the temperature will be described in more detail in the chapters 4.1 and 5.1. Here it should be only said that it depends on one hand on the starting point (the present temperature) and the physical details of the building (insulation, layout, size). Figure 3-22 shows how different buildings could have different time-spans until a certain temperature is reached. In this example building 1 would have the highest priority because the internal parameter used for "storing" energy will reach the lower limit in the shortest amount of time. Afterwards the buildings 3 and 2 would follow.

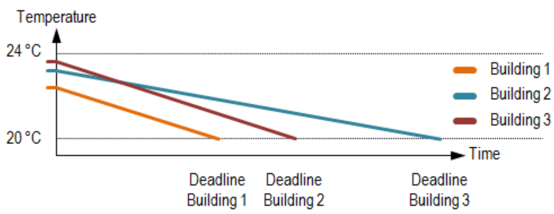


Figure 3-22: Illustration of deadlines for earliest deadline first scheduling

One main difference between round robin and EDF are their different requirements on the communication infrastructure and the underlying protocols. To give an example: Round robin can be realized by sending mainly status and acknowledgement-messages of the type "Load/Unload Storage" and the following confirmation (if an acknowledged service is intended). Such messages do not need any special requirements on the communication protocol as they could be implemented in nearly every kind of protocol on almost all state of the art physical layers. In a very bare bone application it would even be possible to go without the channel for the acknowledgements and make the communication truly one-directional. In [Kup08] a comparable approach is described were no acknowledgement is sent from the nodes when the load is shifted. If round-robin could be implemented in a similar way it would need the least amount of communication and on side of the controller itself. If the number of connected nodes is big enough (and not only single nodes are activated at one specific point of time) even lost connections could be compensated in a (statistical) way by always assuming a certain ratio of communication errors. The controller itself would only have to keep track of all possible communication connections (although there is no possibility to detect any dead links) and activate the nodes in a periodical manner as described (with all advantages and disadvantages one-directional communication includes).

EDF on the other hand does have more complex requirements not only on behalf of the communication infrastructure but also on the smart grid controller itself. The whole mechanism has to take track about already activated nodes as well as it takes the internal status of the different storages into account. So it a) needs a way to keep track of the known storages and their main internal parameters and b) needs a way to exchange more complex data on a regular timely basis to be able to evaluate the best strategy. Therefore the underlying protocol has to be able to submit larger amounts of data into two directions. The smart grid controller is dependent on the information and the status the nodes are submitting. Therefore no dead links can be allowed and the information status on the valid and active communication connections has to be updated as well as the actual status of every single node. In addition to these points the data is also necessary in a timely fashion and therefore not every protocol (and physical layer) is possible.

The algorithm that was developed for this analysis has a even more complex set of requirements on the communication infrastructure as well as the smart grid controller. A number of reasons can be named as cause: the most prominent reasons is that the algorithm should not only take the actual status of the storages into account. In difference to the other two scheduling mechanisms it also should be able to model its output optimal to a given target function. In the given case be the prognosis-error of the wind generation was defined as the target function.

The developed scheduling mechanism has two different approaches to fit its output optimal to this target function: on one hand it takes the day-ahead prognosis and fulfills a fixed scheduling step prior to the actual events. This step is done because with prior adaption to the prognosis, it can be covered that in expected phases of high generation the storages are kept on a lower level to compensate the surplus and vice versa. As was shown before the overall wind prognosis covers the correct tendency of the profile most times correctly. With this as starting point such a step can be justified for keeping a balance between the well suited storage nodes with high capacity and long storage times and the other nodes and their respective usage for the intended application. The prior adaption to the prognosis is less strict and more a convenience and fairness feature. When the respective point of time comes up the mechanisms will (also) fulfill a short term balancing. Alone for those two steps quite an amount of information exchange is needed and therefore a sophisticated infrastructure is needed. The following comparison between the algorithms will solely focus on the possible performance an algorithm could bring and not on the difficulties and/or challenges an algorithm may introduce on its infrastructure.

[Her12] includes also the results of a number of simulations based on different smart grid scenarios. In each scenario the internal parameters of the storage units was monitored as well as the performance of the algorithms mainly measured in remaining prognosis error after the load shifting approach as well as the number of activations of each storage unit. While the first target parameter is the main output – minimizing the prognosis error, the second will show how “fair” in terms of balancing the number of activations for each storage unit.

The comparison between the new algorithm that was developed in [Her12] and a round robin approach on one hand and an earliest deadline first approach on the other hand can be summarized as follows. While round robin has the advantage over the other strategies that it does not need any deeper knowledge about its subordinate units it can be ranked as least optimal strategy – leading in all different scenarios to a higher average difference between load and generation. In scenarios including a bigger number of diverse storage nodes round robin even does not show a fair balancing between the different storage nodes any more. The cause can be pinpointed by the not existing information exchange between the controller and the nodes. This leads again to the conclusion that the approach that was presented in 3.2.1 can be rated as "worst case" algorithm and that every other algorithm that could be introduced in the smart power grid would lead to even lower requirements on balancing energy. The main results of the different simulations (S1-S4) for each of the algorithms are collected in Table 3-15.

One main result that has to be especially pointed out is the strong dependency of quality and amount of exchanged information to the performance of the used algorithm. In short: The higher the quota of information the smart grid controller has about its storage nodes and the more communication is sent back and forth the better the performance is. Earliest deadline first shows better results than round robin simply because the algorithm has more information on how much energy each storage node is able to store and when it is full/empty. It therefore can switch to a different node that is more able to fulfill the expected task in a more suitable way. The main target of [Her12] was to develop another algorithm that is even better performing than Round Robin and Earliest Deadline First.

Table 3-15: Main simulation results of scheduling comparison [Her12]

		S1	S2	S3	S4
Round Robin	Total Error [%]	2951	6352	10157	13.45
	Average Error [kW]	1927	4724	7554	10000
	Max. Energy Surplus [kW]	103841	108809	110748	348039
	Max. Energy Deficit [kW]	121638	144590	148179	200132
Earliest Deadline First	Total Error [%]	2178	41824	6843	24381
	Average Error [kW]	1620	3498	5089	7929
	Max. Energy Surplus	91547	95949	95297	364816
	Max. Energy Deficit	117395	126025	131891	200471
[Her12]	Total Error [%]	$6.778*10^{-6}$	$9.2*10^{-6}$	0.122	0.66
	Average Error [kW]	0.5	0.684	90986	494.78
	Max. Energy Surplus	41760	41761	10199	108779
	Max. Energy Deficit	1499	2499	108417	82393

One other result that can be taken out of [Her12] is an observation on the fairness of the different algorithms. This determines the idea that the necessary load shift is "equally" distributed to each node. In [Her12] the fairness is defined as "not giving preference to a node and every load event should be distributed to all nodes". Using Round Robin scheduling the participation of the nodes at every event differs from about 7% to 27%. EDF activates every node in 11% to 20% cases while the algorithm developed by [Her12] activates a node in 99% of all load shifting events. This may seem a perfect argument why in any case the "new" algorithm should be the way to go, but on the other hand to gain these numbers a sophisticated communication infrastructure has to perform multiple information exchanges. If this communication is (due to whatever reason) not available, the numbers cannot be reached and the performance suffers. And it even may not be the goal to appoint every load event to all subnodes. That may be a good decision if the controller controls a subnet with different buildings that act as one virtual storage node for the upper layers of the power grid. On higher layers of the infrastructure a controller may need the possibility to appoint a certain amount of compensation to only one node and that would not be possible by using this algorithm.

To break another lance for the round robin approach some advantages have to be worked out as well. Without any information it is still possible to schedule the different units with round robin, even prior to the events that should be compensated. This is especially interesting if the communication link can be erroneous and therefore smaller packets of data (activate/deactivate) and based on them more robust error-detecting/avoiding mechanisms have to be used. And if bigger (for example virtual) units – subnets or virtual storage power plants) – could be built inside the smart grid, a round robin approach could be used to spread the load of balancing to all sub-grids that implement their own "optimal" scheduling strategy on lower levels. It even is thinkable to take a step back from the "pure" round robin and rate the storage nodes (or subnets) depending on their storage capacity and introduced some kind of "weighted" round robin.

Due to the fact that it is highly unlikely that someday in the future really all (theoretically) possible storage nodes could be somehow influenced from the grid size, and that especially in the beginning the influenceable nodes that could be used as demand response storages have enough capacity to flatten the prediction error of wind generation each of the presented algorithms would be able to be rated as "optimal".

Every finally introduced solution has to be based on "best effort". This best effort always has to include a realistic approach in terms of an easy as possible implementable in terms of complexity and costs. It can therefore be assumed that not the most optimal algorithm will be chosen in first place but an algorithm that can be used for a multitude of different nodes. In addition it can be said that in the beginning it is likely that a system that is based on the presented approach will not have the capacity to control enough storages to compensate the whole error.

The installation of a smart grid controller and the associated sub-units (in this example always a building with demand controller unit) itself would be major deal for the power grid, regardless of the scheduling algorithm. As it was outlined in this chapter even in the worst case a round robin scheduling approach could minimize the deviation from prognosis and generation to at least about 10% of its initial value (always assuming there are enough units to compensate the whole error). That is still a reduction of nearly 90% and therefore a major advantage to the initial situation. In combination to the idea of keeping every unit despite the demand response controller for the building as simple as possible the round robin approach can be seen as first way to go for a smart grid controller.

So in summary it can be stated that introducing the demand response storages at all could be a huge game changer for the grid operators and even the worst approach in terms of remaining error value could minimize the total error to about 10%. The question regarding the optimal algorithm can therefore be - at the moment - postponed to a later date.

3.2.3 Application proposal for geographical distributed demand response storages

The last chapters were focused on a description how temporal scheduling with distributed demand response storages could be fulfilled. The main focus of the proposed mechanisms was to decrease the difference between predicted load profile and actual electrical generation. With appropriate techniques this is doable but the discrepancy between actual demand and actual generation of renewables is not including any further stress the grid has to burden because of renewables.

One big other challenge is that the power lines inside the grid (at the moment) are dimensioned in a way to (mainly) route the power from the higher parts of the hierarchy (power plant) to the lower parts (consumers). Therefore the power lines tend to be not as potent in terms of maximal transmittable voltage. Renewable power sources generate the power at the location were the circumstances are best for exploiting the power of wind or water or the sun and afterwards need to transmit the power to other parts. Often these places are not at the same locations the architects of the power grid thought to be the “generation spots”. So the infrastructure is simply not built to support some of the peaks that could occur when the wind is really blowing. That these situations are not simply theoretical show some situations that occurred during the last years in southern Germany. Although the wind farms in northern Germany were generating with full power it simply was not possible to bring the energy to southern Germany because of the weak grid [10], even although the energy could have been needed there. But such situations are not only possible in Germany, also in Austria the first challenges do occur because of too much wind energy and too weak power lines [9].

In these situations when in one part of the grid power is injected (or should be injected) that simply cannot be supported – a grid bottleneck occurs. These situations mainly occur when two subnets of the same grid are not connected in a way to support the transfer of all the energy that could possibly be generated in one of the subnets to all connected networks and nodes (for example one or more low-voltage grids that are connected with not sufficient transmission lines between the two parts).

Control strategies that could avoid such scenarios have to be developed. In comparison to the already covered scenarios that mainly helped to avoid or at least decrease deviations between generation and consumption of electrical energy in the temporal domain these scenarios would have additional geographical constraints. To cover also deviations in the spatial domain the control or management unit must have additional information about the overall structure of the grid and possible weak links between subnets. The basic assumption that the deviation between consumption and generation has to be avoided should not change at all – but the control strategy would have to include one more constraint and therefore has to add one more “layer” of strategic decision-making.

The following basic strategy is intended to give a starting point on how these scenarios could be included with the already described mechanisms but can only be a starting point for a more detailed research question. The basic idea is to include knowledge about the different subnets on the control unit or smart grid controller and their available storage and generation nodes. In addition to that the knowledge about the highest possible transmission between different subnets has to be taken into account. With this information and the appropriate decision making and control mechanisms the following scenario could be solved in an exemplary way (all values are examples to demonstrate the described strategy):

It is assumed that two connected parts of the power grid (Subnet A and B) include both storage nodes. Similar nodes in both parts are paired logically by the supervising grid controller. In a situation when the generation in Subnet A is sufficient for the load in Subnet B but the transmission line cannot deal with the load the necessary energy for the load in Subnet B could be taken out of the storages in the same section of the power grid, while the “logical partner storages” in Subnet A buffer the energy. When the critical situation is over the energy that was stored in Subnet A is used to refill the storages in Subnet B. This and similar strategies can help to provide a “Grid-Bottleneck-Problem” and help to increase the usage percentage of renewable energy. Similar strategies are already followed by grid operators but instead of taking the energy out of storages to meet the demand in different grid regions, additional generation is needed to avoid the transmission over the weaker grid sections as occurred in [9,10].

The following (exemplary) values should demonstrate the described procedure again. The following values are included in the model scenario:

- Grid: 2 Subnets A and B
  - Subnet A: Generation max. 2 Units / Storage 4 Units/Timeslot / Load: 0 Units
  - Subnet B: Generation max. 0 Units / Storage 4 Units/Timeslot / Load: 2 Units
- Transmission Line: max. 1 Units / Timeslot
- Assumption at the beginning of the example (indicted by Timslot 0 in Table 3-16):
  - Storages in Subnet A: Empty
  - Storages in Subnet B: Full

Table 3-16 includes an overview on the activation sequence of the storages to avoid an overload on the transmission line between the two subnets A and B. In the beginning the generation in Subnet B meets all the demands in the said subnet (generation is on par with load). When the generation suddenly drops (for example no sun/wind power) the generation in Subnet A is activated to meet the demands (Timeslot 1). Because of the fact that the power line cannot transmit the needed amount of energy, the additional needed energy is taken from the storages in Subnet B while the generated surplus is stored in the storages of Subnet A. It can be seen that the load at the transmission line is always at the maximum while first the storages in Subnet A are loaded (to take in the additional energy) and the storages in Subnet B are emptied. This situation remains as long as the energy production in Subnet A is too high for the transmission line. The ideal case would be that the stored energy in Subnet A is transferred into the storages in Subnet B to restore the initial setup (Timeslots 5-8) when the critical situation is over. But if it is not possible to restore the generation in Subnet B a shutdown (in this example) could not be avoided any more after Timeslot 4. So this strategy can be used as long as the generation in Subnet B fails to support the loads to prolong the operation in Subnet B for a while. This example shows that with geographical load shifting a shutdown could be avoided in the ideal case and in most cases postponed. Even if this “best effort” strategy may not be ideal it could bring important time to shutdown critical infrastructure or power up emergency power supplies in facilities that need special protection (e.g. hospitals).

To summarize the outlined proposal it can be said an additional – at the moment theoretical - application can be found for demand response storages. The proposed mechanism of using the internal capacity of buildings for load shifting mechanisms can not only help to compensate prediction errors but also avoiding the grid-bottle-neck problems that occur when renewable energy sources inject energy in low- or medium-voltage grids. In both cases evidence in form of test installation and larger scale simulations have to follow to show the exact potential and work out the main requirements on the included nodes.

Table 3-16: Storage activation for geographical load management

Timeslot	Subnet A			Power line	Subnet B		
	Generation	Storage	Load		Generation	Storage	Load
0	0	0	0	0	2	4	-2
1	2 (+2)	1 (+1)	0	1 (+1)	0 (-2)	3 (-1)	-2
2	2	2 (+1)	0	1	0	2 (-1)	-2
3	2	3 (+1)	0	1	0	1 (-1)	-2
4	2	4 (+1)	0	1	0	0 (-1)	-2
Storages in Subnet B are empty!							
5	0	3 (-1)	0	1	2	1 (+1)	-2
6	0	2 (-1)	0	1	2	2 (+1)	-2
7	0	1 (-1)	0	1	2	3 (+1)	-2
8	0	0 (-1)	0	1	2	4 (+1)	-2

4 Demand side management with buildings

A significant number of buildings, especially office and other commercial buildings, have installed systems for controlling the HVAC (Heating, Ventilation and Air Conditioning) devices and other subsystems. These systems are able to communicate with the outside world as well as with the inside devices of the buildings. This ability to communicate and receive stimuli from the outside world, as well as the installation of power generating units in or on the buildings could very well give the systems a head start for being considered as possible connection points to the smart power grid.

The following subchapters give a specific introduction how the connection between a building and the power networks can be enforced by establishing communication and information exchange as well as an estimation how different processes inside a building can be exploited to store energy for the power grid. In the first part general requirements are pointed out that internal processes of buildings have to fulfill to be able to act in the outlined way. It also includes a more detailed model on how to use the thermal capacity of a building as well as an additional mechanism on how to make specific commonly usable models adaptable and therefore easier to apply to various buildings.

The second subchapter lines out a theoretical model of demand response controllers for buildings that is supposed to connect a building's automation system with the smart power grid and is able not only to connect the communication but also to symbolize a building's storage capacity and deals with demand response requests. For this it has to include simulation models for predicting the possible future of certain parameters of the internal processes. The presented approach will be used as model for an implementation attempt that is described in subsequent chapters.

4.1 Using internal processes in a building for storing energy

In the following subchapter a general catalogue of requirements is lined out on how a building's internal processes might fit for the task of load shifting. After this overview the chapter includes a closer examination of the heating, cooling and ventilation processes and a short overview of other possible processes. Detailed examples show possible ways to model two main processes inside a building, namely the thermal sub process as well as a ventilation process. The section is closed with the description of how prediction models for the process parameters can be improved by introducing self-learning strategies for adapting internal processing parameters.

4.1.1 General requirements for load shifting with internal processes

Buildings that are able to perform demand response actions for a smart power grid have to fulfill a number of requirements. Beside the necessary communication link with a central entity that manages the subordinate nodes and coordinates (or delivers) the demand response requests such a building needs at least one device that is directly or indirectly controlled by an automation system of sorts and influences an internal parameter that is exploitable as internal capacity.

Before pointing out different possible loads for load shifting it is necessary to determine the requirements an internal process/load has to meet to possibly be able to fulfill the intended role. The base of it all is that some kind of energetically transformation takes place and is controlled/influenced by an electrical device. This device is in fact the load that is used for load shifting. In the ideal case the device is constantly using a (small) amount of energy to hold a physical constant at some pre-set value, but as long as the time-constraints of the process are not too severe and can be altered in some way every device that meets the requirement could be used. With this as basic requirement some other important features have to be met as are:

- Electrical device that directly or indirectly influences a physical process
- The electrical device has to be a able to be connected to some sort of communication/management device (controller), in the best case a fully installed distributed control solution
- The devices controls a physical process that has
    - different energy levels on which it can operate and that lead to different electrical loads
    - long time periods (in comparison to the energy grid)
    - the possibility to alter the energy level for a short amount of time without harming any persons, goods or the internal security and safety
- An underlying physical process that is not directly connected to the comfort of the users

While most of the points might be inherently clear, especially the last point might need more clarification. It includes the idea that if a process meets the other requirements, but is directly and immediately connected to the user's comfort it might not be possible to delay the intended (user's initiated) action. For example: If a user switches on a device and wants the action being performed more or less immediately (like lights or small ventilators) it is not possible to shift the load in any case because the user is will not be satisfied if he/she has to wait in any way.

4.1.2 Identification of usable processes for load shifting in buildings

In chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** general thoughts outlined the onstraints that subprocesses of buildings have to meet to possibly be used as influenceable loads for a smart energy grid. In this chapter a more extensive list is given including different processes that could be used for demand side management in buildings in addition to a short description on how this could be achieved as well as the addition of some more processes that are out of the question for being influenceable processes.

Although thermal as well as ventilation processes dominate the buildings energy consumption also other processes are imaginable to store energy. For example could the behavior of different subsystems like some pumping processes or even some generation devices be interpreted as storages or at least as shiftable loads in the temporal domain. The following list contains most of the different subsystem that generally are or could be existent in general purpose buildings. If considered possible it is shortly described how shifting the electrical load could lead to energy storage effects – or why it is not imaginable or possible.

- **Heating/Cooling:** Heating and cooling can be defined as active influencing the air temperature inside a building. Depending on the mechanism it is either a direct coupling between electricity and the alteration of the air temperature inside a building (electric heaters or small room air-conditioning machines) or through the usage of a bigger subsystem that depends on a – in most cases liquid – carrier medium for the temperature difference (like water) that is dependent on pumping (for example through heat pumps). In either way there exists a direct dependency between the alteration of the temperature and the electric load of the corresponding heating or cooling unit. In combination with the thermal insulation of a building this subsystem serves all the necessary requirements for acting as demand response storage.
- **Ventilation:** Big buildings depend on a steady and constant change of air to reduce the amount of CO_2 in the air as well as the humidity. This is mainly done by ventilation systems that can guarantee to hold both parameters inside defined limits. The ventilators that are responsible for this are exclusively powered by electricity and therefore the required direct link between changeable parameter(s) and the load of the supporting unit is inherently given.
- **Filtering/Heating of swimming pools:** It can be assumed that most general purpose buildings would not have installed swimming pools, but if there are swimming pools they also could be used as demand response storages. Especially the internal parameters of water temperature (again altered through heaters) and the filtering of dirt/suspended matter out of the water (mostly depending on pumps) could be used as internal storage parameters. It has to be pointed out, that during phases of usage (mainly during the days) the according industrial standards [DIN15288] are strict and certain limits have to be met without compromise. But during the night (and phases of non-usage) it would be possible to use swimming pools (or better the heaters/pumps of swimming pools) for demand response storage.
- **Pumping of water from A to B (with tanks or reservoirs)**: For some applications and usages it is necessary to pump liquid substances from one tank to another. These pumping processes might have defined deadlines, but the actual time of operation might be not defined. One example for such an application would be pumping processes in a purification plant. Although even less common than swimming pools the possibility is listed here to give a complete picture. There are already initiatives that try to activate these processes for the smart grid (compare [Leb11]).

The already listed possibilities are (in different degrees feasible and even thinkable). There are some more that are possible in terms of technical feasibility, but out of comfort reasons (the internal temperature has to be kept between specific limits to ensure the comfort of the users/inhabitants) or usability not realistic.

- **Escalators:** In comparison to classic elevators escalators have the advantage that if they are turned off the users still can manage to leave the device without facing major challenges; this can be interpreted as “fail-safe” mechanism. But mainly out of reasons that are based on user comfort the operators avoid times and phases in which the escalator is not functional. Therefore this device may not be the best choice as demand response storage.
- **Ovens and fridges, Washing/drying machines:** So-called “white goods” appear in quite a number of publications for being able to follow demand response commends (a work based on this premise can be found in [Kup08]). As this can be seen as direct and deep access into the living space of the human consumers, it is safe to assume that most private users are not positively mined on this approach due to reasons of protection of their private sphere. This has to be accepted and therefore this approach does not seem feasible any more as a large scale rollout is likely to provoke a strong opposition. In addition to this problem the mentioned approach would need at least one communication link of any sort to each and every household if a common “smart grid gateway” could be introduced. If not, a communication link to each device would be necessary what even decreases the chances of realization.

While the first and second list contain possibilities that are (generally spoken) feasible in a technical point of view but may be challenged by other reasons, the following two possibilities have to be explicitly taken off this list, because the personal safety of the users might be not guaranteed any more.

- **Lighting:** A defined amount of light (especially if switched on by a user or inhabitant of a building) always has to be guaranteed. In addition to that the user comfort would be altered in a not acceptable amount even with switching off the light for the shortest periods of time.
- **Elevators:** In comparison to escalators elevators are never a possibility for the usage as demand response storages simply because of the possibility of users being trapped.

The following chapter will focus on some of the here merely outlined possibilities and give a closer look on the underlying processes as well as possible simulation models for the parameters.

4.1.3 Taking a closer look on heating, cooling and ventilation

For the whole situation inside a building, the temperature and the relative humidity of the air are especially important. Those parameters define if an inhabitant or visitor of the building feels comfortable or not. In office and other commercial buildings these parameters are heavily influenced by the devices of the heating-, ventilation and air conditioning (HVAC) units. The different devices like humidifiers, vents, fan coils or pumps happen to be heavily energy consuming (in comparison with the other devices inside buildings) and therefore good candidates for demand response usage.

In addition to that these devices are mostly controlled through a centralized or decentralized management and control system. Taking into account that a building automation system should make decisions based on the thermal situation of a building certain possibilities and requirements have to be found to support a valid decision making process. Constraints have to be found to provide the possibilities to make decisions based on the thermal parameters like temperature (inside and outside) and humidity (absolute and relative).

One main requirement always has to be that there never should be any loss in comfort for the buildings users. The characteristics of the time constants inside the power grid and the thermal processes support this concept. Without active cooling or heating the inside temperatures of buildings will tend to converge against the outside temperature levels. This process can take from hours to days depending on the building's insulation and the difference between outside and inside temperature level. In comparison the processes in power grids are much faster. The differences between the time constants give an amount of flexibility that is intended to be used by demand response mechanisms inside the power infrastructure.

The following two sub-chapters will each focus on one of the two main questions that have to be answered for deciding if the followed approach can be realized. These questions are:

- What constraints or limits could be used to ensure the comfort of the inhabitants/users of a building?
- How can the future behavior of the internal processes of a building be predicted in a feasible way?

Answers to both questions are necessary to build a rule-set for later decision making processes.

4.1.3.1 What constraints or limits could be used to ensure the users comfort?

For finding suitable constraints the presented approach will be word inside the given limits by established normative corpses. Following the German industrial standards (Deutsche Industrie Norm - DIN), especially the DIN13779 and DIN15251 ([DIN13779] and [DIN15251]) the values of temperature and relative humidity of the air inside a commercial building have to stay inside fixed limits. These limits define a so-called area or range of comfort.

In the subsequent work it will be assumed that the buildings in question are all out of Category II, according to [DIN15251]. That means that a "normal amount of expectations" is taken into account for the building, respectively "new or renovated buildings" [DIN15251, p. 12]. In addition it has to be pointed out that the following values only are to be used for the following working areas as they are defined for buildings of Category II: single person offices, multi person offices, conference rooms, auditoria, restaurants and classrooms [DIN15251, Annex 3].

Regarding the heating, two different periods of time are specified. When cooling is required (therefore this will happen mostly during the "warm period" in spring/summer) the temperature should stay between 23 and 26 C while during heating periods (autumn/winter) the temperature has to be kept between 20 and 24 °C.

There is no difference between the ranges for the relative humidity for heating and cooling period. The humidity value has to stay between 25 and 60 % throughout the whole year. In Figure 4-1 the cases for the heating and the cooling case are illustrated on an hx-chart (or isochromatic) that includes the temperature values displayed over the humidity values. The striped areas are showing in both cases the zones that would include "appropriate" value-pairings (temperature/humidity) in reference to the two standards.

The two areas are the same in terms of the humidity values but quite different in terms of temperature. One cause is that it is harder to cool down in summer, respectively heat up in winter and therefore it is (on terms of used energy) better not to heat up/cool down that much – therefore a mere question of technical abilities.

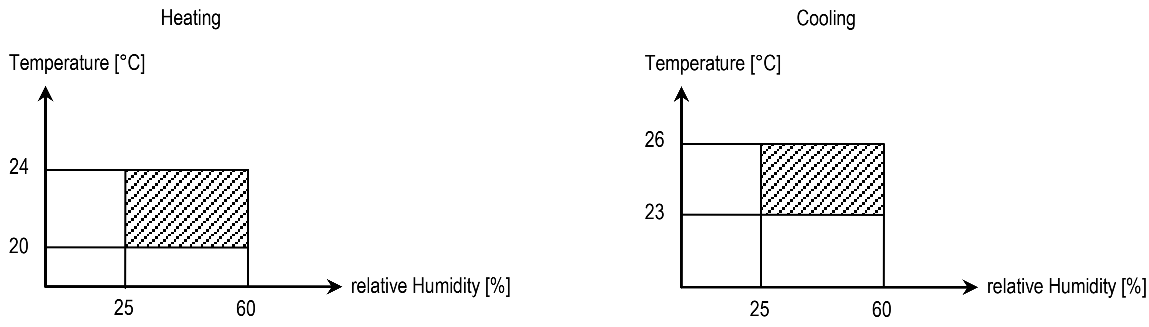


Figure 4-1: Comfort areas in HX-chart for commercial buildings (Category II) in case of heating and cooling, after [DIN15251]

The other side of these cases is the expected amount of clothing of a building's users. In summer it is expected that the inhabitants and users of the building wear much less and therefore the air temperature has to be higher to fit most people's comfort level. For dynamical simulations a target value right in the center of the intervals should be used [DIN15251, chapter 7.2.3]. This means a target value of 22 °C should be used for the heating case and a target value of 24.5 °C should be used for the cooling case. The standards do not include any such prescription for the humidity but it can be assumed that a target value right in the middle of the interval, therefore 40-45 % is also appropriate in either case.

It can be summarized and expected, that if the air temperature and humidity of a building's inside can be kept between the limits the German industrial standard demands, the highest possible comfort for the users can be assured.

4.1.3.2 How to predict the future behavior of the thermal processes inside a building?

The second challenge for using the air temperature for delaying energy consumption of the HVAC systems is the question on how to decide if switching off or delaying energy consumption is possible or not. In this case it is necessary to predict the future of the specified parameter (in this case the temperature) to get more knowledge on how the parameter will change in the next period of time.

This is necessary for deciding if shifting the energy is possible at a given point of time. It was already stated that the comfort of the users must never be altered. Therefore a simulation is necessary if (for example) by switching off the HVAC-system (or parts of it like the heating pump) for a given period of time is possible without leaving the comfort zone defined by the German industrial standard (compare chapter 4.1.3.1). The system should be efficient, as exact as possible and/or necessary and lightweight in terms of computational requirements. That last point is especially necessary because a detailed thermal simulation with established tools like TRNSYS or EnergyPlus [7, 8] needs the know-how and knowledge of specialized personnel to be set up and also some computational effort to gain the exact results for which those tools were intended.

One requirement for the system to be designed is that as few different parameters as possible should be necessary to setup the model and to execute the simulation for predicting future parameter values. Again this has mainly practical causes. A simpler simulation model can be implemented on less powerful and therefore cheaper microprocessors and the existing systems often do not even provide more detailed measurement data. The list therefore should include: The external temperature to provide the influences of the weather, the internal temperature and humidity, knowledge about the building (insulation, physical layout).

Important information that has to be included inside the decision making process are the type of model that should be used, the parameters that are needed, the timeframe for which the simulation should be calculated, besides the boundaries and limits, a specific form of rule-set, that is used to find a decision (as was pointed out by using the comfort-area inside the isochromatic hx-chart). In addition to these values a rough estimation of how much energy could be used additionally or less by altering the processes system parameters can also be important to make decisions. How a model for the thermal subprocess could look like will be covered in the next subchapter.

Based on these parameters as initial information a simple but effective decision making algorithm should be established for each subsystem. For the thermal subprocess inside a building it mainly consists of the following steps.

1. Get the actual temperature and humidity and locate the current situation inside the isochrometic chart.
2. In addition to that get more information about the current situation like time of day and outside temperature.
3. Depending on the gathered sensor data and information: Predict the future behavior of the thermal processes and predict the future situation.
4. Depending if the predicted situation lays inside the comfort area of the isochrometic hx-chart the decision of a possible load shedding is made.

4.1.4 Examples for modeling thermal processes

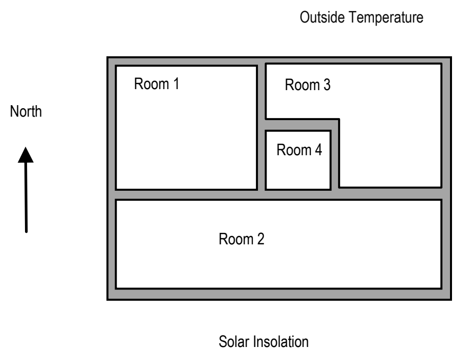
One challenge for using buildings as storages is that a mechanism has to be established to provide the ability of the system to decide if demand response in any way is possible. A simulation model for predicting the internal status of the storage is therefore necessary. The open question that heavily influences the proposed algorithm is the possibility of finding an efficient and fast way for predicting the thermal behavior. In the following section two possible ways of modeling a building are described and compared taking the attempted usage into account. The the first introduces the so-called lumped model approach; the second includes differential equations of first degree to model the thermal behavior

In comparison to established very detailed thermal simulations of buildings (with EnergyPlus, TRNSYS) both proposed solutions are surely not as accurate. One main advantage is that both methods should be much faster to compute and therefore highly implementable and highly optimizable. It is assumed that the disadvantage of being not as accurate can be avoided as both models are meant to be used for short-term predictions in comparison of long-term simulations that should show a building's behavior over the observation periods of whole years.

4.1.4.1 Lumped model

In the following part a simplified physical model of the whole building is presented. The different physical factors and dimensions are translated from the thermodynamic point of view into an electrical substitution model. Similar approaches, often also referred as thermal lumped models, are also described in [Hub04] and [Su09]. In this kind of models the following representations are used to model thermal factors with electrical representations:

- Thermal resistances (like walls) are modeled as electrical resistances
- Thermal capacities of different substances as electrical capacities
- Temperatures are modeled as voltages
- Sources of temperature (positive and negative) are modeled as voltage sources



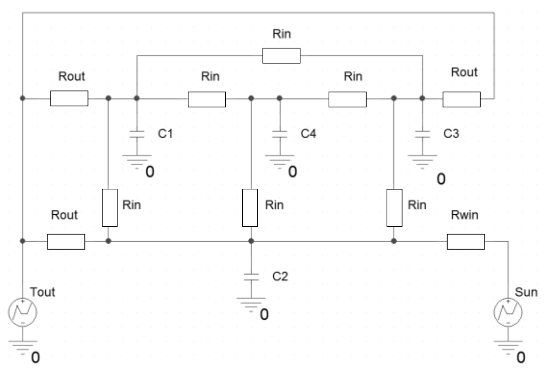


Figure 4-2: Example for lumped model approach of modelling the thermal behaviour of buildings

An example for this approach to model a building with its electrical equivalents is shown in Figure 4-2. It shows how the air temperature (and the thermal capacity) of the different rooms are translated into an equivalent capacity element. The voltage over the capacity would be the temperature while the capacity itself is the very same. Walls are nothing else than resistances for the thermal current between rooms and therefore in this model also resistances between the nodes that represent the rooms (or the outside). For simplification in this example it was assumed that all walls of the same type (for example between rooms) have the same resistance value. This last point is due to the fact that an outside wall would have a higher value of insulation than an inside wall. Thermal sources like the outside temperature or additional influences like solar insulation are modeled as additional voltage sources.

The shown example is the implementation of a building without any additional temperature sources. This mere representation of the buildings physics without any additional active elements was chosen to give an impression of the overall method. In the upper model each of the rooms represents its own thermal zone or domain. In any similar modeling multiple rooms could be collected inside one thermal domain. The temperature that represents such a zone could either be the measurement of one single room or a derived value out of multiple measurements (for example the average temperature). Additional (presumably controllable or switchable) sources for taking influence on inside temperatures can be also modeled by separate voltage sources that either are added by switches or not. In a same manner also additional capacities (if available) could be added to represent additional storage capacities that could be added if necessary. Possible capacities of the walls are neglected as an evaluation of the different types of walls would mean an even higher effort and complexity. It is assumed that the capacity of the walls is partly represented by the resistances of the walls and partly merged into the capacity of the zones/rooms.

The transition into the electrical substitution model opens up the possibility to translate the circuit into a system of differential equations. This system consists of as many equations as rooms (or better capacities) that should be represented by the model. The influential parameters on the different values depend directly on the physical structure of the building itself. So in this way a room's temperature will have only direct influence on the adjacent rooms but not on a room on the other side of the building. In general it can be said that the maximal number of equations is equal to all internal capacities that should be represented (in the example this number would be four). The maximum number of influencing parameters on each of the internal values in question (in this model the voltages of the internal capacities) is the sum of the maximum internal number of values in question and additional external temperature sources (here in total six).

$$
\begin{aligned}
C_1 * \dot{T}_1 &= -\left(\frac{1}{R_{out}} + \frac{3}{R_{in}}\right) * T_1 + \frac{1}{R_{in}} * T_2 + \frac{1}{R_{in}} * T_3 + \frac{1}{R_{in}} * T_4 + \frac{1}{R_{out}} * T_{out} \\
C_2 * \dot{T}_2 &= \frac{1}{R_{in}} * T_1 - \left(\frac{1}{R_{out}} + \frac{3}{R_{in}} + \frac{1}{R_{win}}\right) * T_2 + \frac{1}{R_{in}} * T_3 + \frac{1}{R_{in}} * T_4 + \frac{1}{R_{out}} * T_{out} + \frac{1}{R_{win}} * T_{sun} \\
C_3 * \dot{T}_3 &= \frac{1}{R_{in}} * T_1 + \frac{1}{R_{in}} * T_2 - \left(\frac{1}{R_{out}} + \frac{3}{R_{in}}\right) * T_3 + \frac{1}{R_{in}} * T_4 + \frac{1}{R_{out}} * T_{out} \\
C_4 * \dot{T}_4 &= \frac{1}{R_{in}} * T_1 + \frac{1}{R_{in}} * T_2 + \frac{1}{R_{in}} * T_3 - \left(\frac{3}{R_{in}}\right) * T_4
\end{aligned}
\tag{6}
$$

The system of differential equations given in (6) is the representation of the model in Figure 4-2. Experiments with this type of model indicate that its behavior is similar to low-pass filters. That includes that any change of the influential parameters (here outside temperatures) will lead to a delay in the adaption of the internal values. This behavior can also be investigated in buildings itself.

Important for making predictions with such a model is to determine the constant parameters that could provide the highest accuracy. After setting up the system of linear differential equations, a way of finding the right parameters is needed. This tuning of the model has to fulfill the main purpose of making the model as accurate as possible. For this process it is needed to have measurement data for each of the specified thermal zones or rooms. For each zone/room a value for the internal temperature is needed. In addition the outside temperature on the north and the south side are necessary. The two temperature values for the outside are needed to get the influence of the sun on south side by subtracting the north form the south side.

To summarize this approach it can be pointed out that any model like the one in (6) the determination of the constant would need at least the following input information:

1. All inside temperature values T_{1-n} for a specific point of time *x* have to be available.
2. All outside influential temperatures (T_{out}, T_{sun}) for the point of time have to be available.
3. All inside temperature values $\dot{T}_{1-n}$ for a specific point of time *x+1* have to be available.

With these values a backwards-solution of the system of equations can be calculated. The differential equation is therefore transformed to difference-quotients (we only have discrete values and therefore a procedure for projecting the discrete values onto the continuous values). To lastly solve the system an additional assumption has to be made – otherwise the system of equations would not be possible to solve without any further information.

Up until this point the following parameters are unknown: $C_{1-4}, R_{in}, R_{out}, R_{win}$. These seven unknown values cannot be determined in unambiguous manner as there are too few equations for that. This leads to the necessity to find more information in terms of more detailed measurement data or specific parameter-values that provide a more accurate knowledge about the building's characteristics. In either case a much higher effort would be necessary to set up the whole system. A priori it was defined that this situation should be avoided and therefore a different solution has to be found.

One possible way to do that would be to find out more information about the sizes of the rooms and having a possibility to estimate the temperature capacity of each room. As it is a simplified model of the building another possibility is to assume that the capacity of each room is the same. Adding this assumption to the setup leads in the end to the four unknown values $C, R_{in}, R_{out}, R_{win}$ within a linear system of four equations which makes it in fact solvable with the help of the presented data.

To summarize the attempted modeling process it has to be pointed out that the presented model based on the lumped model approach is in fact solvable and also the backwards calculation to obtain the parameters from measurement values is possible. But the attempted approach to find a simple to setup and easily obtainable model has to be re-evaluated. To initially setup the model, measurement values for all different temperatures are needed as well as an very detailed knowledge about the architectural details of the building (for example which room is adjacent to which). In addition to this detailed knowledge for getting started each temperature of each room has to be monitored to provide the ability to determine a new set of building parameters for a more accurate prognosis. This leads to problems because even in state of the art buildings like the ENERGYbase [6] the monitoring of the temperature does not cover every room.

In case of [6] and other buildings often only the rooms that are most exposed and on the shady sides of the buildings (north / north-west) are controlled and as long as the internal values of these rooms are inside the margins the automated control system does not change anything. In addition to these drawbacks the multiple assumptions that have to be made (all capacities are the same, all internal walls are the same, all external walls are the same) do not make the model in any case more accurate. It can be therefore stated that using the model itself is not feasible due to the already presented reasons. Another possibility to predict the temperature inside a building has therefore to be found. One other, more feasible, approach will be presented in the following chapter 4.1.4.2.

4.1.4.2 Exponential equation

In comparison to the already presented approach the following modeling approach can be summarized as being even more reduced. It was already mentioned that most buildings that depend on an automated heating/cooling system do not monitor every location inside the building but rely on few measurement points that represent the building well, e.g. the “worst-case” locations (for example an exposed office at the north side of the building). The system normally influences the temperatures at these locations in a way that the internal parameters are kept inside the comfort area of the users. It is assumed implicitly that all other rooms will stay as well inside the margins.

Keeping this in mind would bring up the following line of thought: The demand response controller that is proposed and researched within this work should provide predictions of the upcoming temperatures inside a building. If there is only one (or at least few) possible points of measurement inside the building only this can be taken into account for the prediction. The control of the building depends only on this or these value(s) and therefore the prediction model also only has to take care of the few values that are monitored at all. In the following it is assumed that only one value is present for the inside temperature. If more values exist every other value would need its own set of equations accordingly.

Formula (7) shows an equation that models the temperature adaption of a body to its surrounding temperature. In this case the air temperature itself is represented by the internal temperature T_{in} while T_{out} is the outside temperature. The constant value τ characterizes how fast the temperatures converge. In fact this approach is not that much different to the first approach, as the formula could also be derived from a simple One-Capacity-One-Resistor low-pass. But in contrast to a low pass filter were the single values for resistance and capacity make up the characteristic of the filter function, here only the product of the two values is of importance. This can be stated due to the fact that for a decision making unit it is not necessary to know if either the thermal resistance of the insulation is the determining factor or the internal capacity.

$$T_{in+1} = (T_{in} - T_{out}) * e^{-\frac{t}{\tau}} + T_{out} \tag{7}$$

The proposed formula is nothing else than an even more simplified lumped model approach as it was described in chapter 4.1.4.1. But instead of having one capacitive element per room/thermal zone in this case one single capacitor stands for the capacity of the whole building, while one resistor takes over the role of simulating the losses of this system (compare Figure 4-3). In this illustration the resistance R and the capacity C are considered as their thermal counterparts. The thermal constant τ in equation (7) is formed as in similar electro technical approaches by multiplying the resistance and the capacity $\tau = R * C$. As in electricity it is not important for the result if either the capacity or the resistance is the main reason why the system is following an input slowly or quickly as the same effect can be achieved by either a high resistance (insulation of the building) or a high capacity. In fact in the building domain mostly it will be the insulation that is the characterizing value as the capacity of the air is more or less always the same (and only dependent on the size of the rooms).

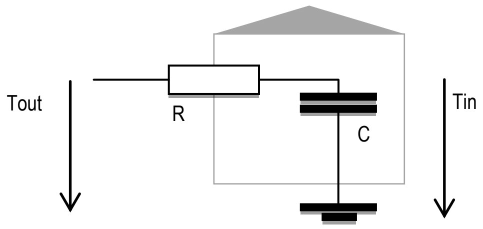


Figure 4-3: Illustration of exponential approach

The biggest advantage of using the approach based on one equation per building is that just a minimum of measurement values is required to setup and obtain the model. In fact, as the next part will show it is even possible to setup the system with a mere estimation of the actual values. Another advantage can be named by pointing out the necessary computational power (and complexity) that would be included to solve either set of equations. With the more detailed and complex model a demand response controller would have to solve a set of differential equations every time a prognosis is needed. Depending on the complexity this requires a sophisticated solving strategy within the system as not every microcontroller (and in the end the proposed solution should even work on low-profile systems and not on high-end devices) is able to solve this type of mathematical problems. A single equation of this type is easier to handle. Calculations of this type are (in the worst case) even solvable through polynomial approximation through even the most low-budget or outdated processor (compare also chapter 5.2 for a more detailed revision of this topic).

Besides these main advantages also some drawbacks have to be pointed out, first and foremost, the accuracy of the so much simplified model can never be as good as with a more detailed model. So if a detailed and accurate prognosis or a prediction long time into the future is needed the approach with only a single equation may not be sufficient.

Another thing has to be considered beforehand. Formula (8) could either be used in a "one-step" calculation to directly calculate the result for a given point of time in the future or via "multi-step" calculation by dividing the interval into smaller interval and use the resulting value as new input for the formula. Due to its exponential nature and one constant set of input values - as long as all parameters stay the same - both ways lead to the same result. While the values of the starting temperature as well as the thermal constant always stay the same in the proposed formula this cannot be guaranteed for the outside temperature T_{out}. In the following the influence of this parameter will be determined for the presented scenario.

The example uses the following starting parameters:

- $T_{in,0} = 20°C$
- $T_{out,0} = -2°C$
- τ = 500 h (1800000 s)

- t = 10 h (36000 s)

Using these parameters directly with formula (9) leads to a result of $T_{in,36000} = 19{,}5644°C.$ As the value of the outside temperature cannot be taken as constant over the whole time interval of 10 h the calculation could also be executed in steps of fixed, discrete time-intervals and the actual outside temperature could be used.

Table 4-1: Example for multi-step calculation of inside temperature

Time	Temperature inside	Temperature outside
t_n	$T_{in,n}$	$T_{out,n}$
0	20	-2
3600	19,95604397	-1,826661914
7200	19,9125221	-2,287125398
10800	19,86816717	-2,757673803
14400	19,82296071	-4,546849917
18000	19,7742698	-6,638388291
21600	19,72149727	-10,39645981
25200	19,66132155	-6,712492864
28800	19,60862663	-11,04735729
32400	19,54737594	-13,19625603
36000	19,48195412	-20,32199502

Table 4-1 includes an exemplary calculation that starts with the same initial parameter values and assumes that the calculation is executed after every hour. The outside temperature in this example highly volatile as it can randomly change up to a value of 90 % of the prior value. From the start of the example until 10 h later the temperature changed from -2 °C up to -20 °C. The result for the inside temperature on the other hand – although totally different outside temperatures were chosen – did not change that much at all. The result of $T_{in,36000} = 19{,}4820°C$ only shows a difference of 0.1 °C from the single-step example. The main cause for this is surely the high thermal capacity and that leads to the conclusion that for short term predictions (at least up to 10 h) the single-step calculation can always be taken without any error compensation.

4.1.5 Example for modelling a ventilation process

Another process that was determined to be used for demand response storages was the ventilation. One of the parameters heavily influenced by ventilation is the CO_2 ratio of the air. This is besides temperature and humidity the third main system parameter that is directly influenced and monitored by most automated ventilation systems. In the funded scientific project BED (Final report [Bed12]) the CO_2 ratio inside a specially optimized building [6] was covered not only in office rooms but also inside the auditoriums of a university of applied sciences that is partly located inside the building. It showed that the parameter in question was more likely to be outside the limitation boundaries inside the university auditoria. Modelling the CO_2-process the measurements of the university rooms were therefore more interesting for getting worst case models.

The first step was to graphically analyse the different time-series that covered a measurement period of 12 subsequent days. This period included weekends, holidays and also a “bridge day” and seemed therefore representative. Moreover a much longer period does not seem necessary, as the CO_2- ratio is mainly dependent on the overall usage of the rooms and not by seasonal effects.

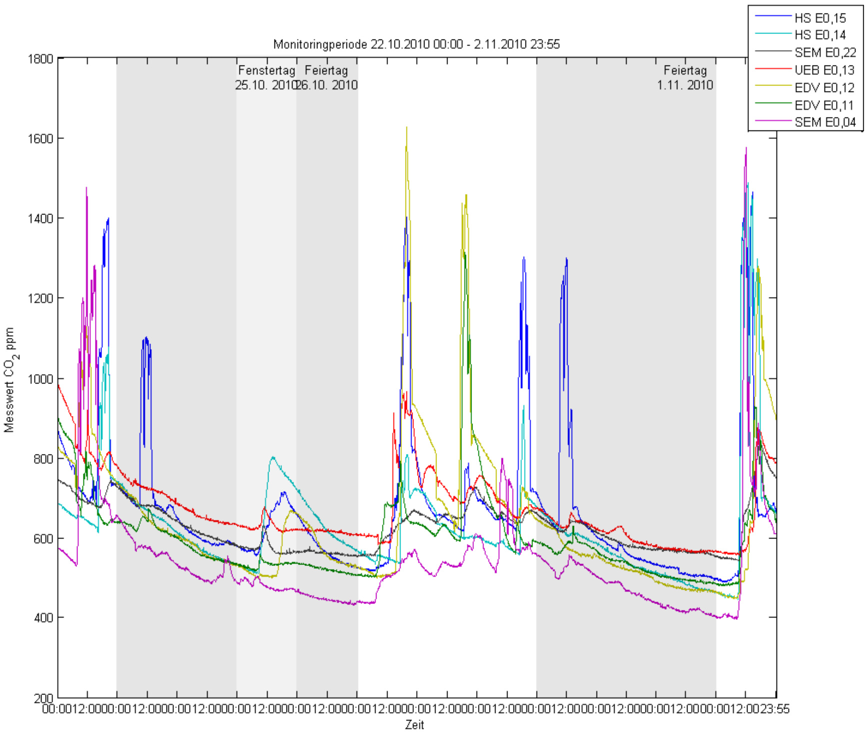


Figure 4-4: Graphical analysis of CO2-ratio inside rooms of an university of applied sciences

Figure 4-4 shows a graphical view on the time-series. It can be seen that the main peak values always appear during daytime and stay well inside the limits for providing a rating of “Good” for the overall air quality [DIN13779, DIN15251]. The energy consumption of the ventilation (see Figure 4-5) does indicate a correlation to the peak values as an increased energy consumption could be detected.

Overall a correlation between workday/higher amount of building users and higher energy consumption seems plausible, but this does not indicate that the ventilation always follows the amount of usage. Some examples for this last statement can be directly seen when comparing Figure 4-4 and Figure 4-5. On Saturdays between 10:00 and 14:00 the measurement values of the CO_2-senors indicate a usage of room HSE0.15 – a fact that seems to be ignored by the ventilation because the low energy consumption shows that the ventilation was operating in some kind of “weekend” mode. The counterexample can be seen in both figures for the 26^{th} of October (free day for work and universities): the energy consumption of the ventilation indicates no difference to “normal” workdays, while the CO_2-measurements show that no lectures were given.

The main challenges by using the ventilation of a building as demand response storage will always be the requirement to guarantee a certain quality of air at any point of time. Especially buildings and rooms with a large fluctuation and high numbers of attendees will always have harder requirements on the ventilation than others. This all indicates a small margin for the operation as demand response storage.

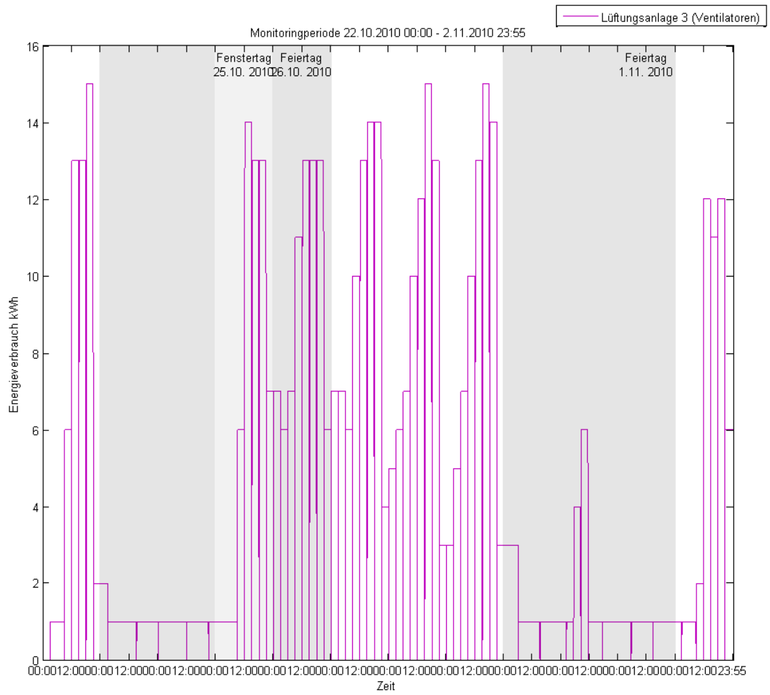


Figure 4-5: Energy consumption of ventilation

To come to a (partly) functional simplified model for the ventilation the following assumptions can be made without compromising the quality of air:

- Switching-off the ventilation can only be executed outside the normal work-hours.
- Switching-off events can always last for a maximum of 15 min (900 seconds).

These assumptions constraint the model quite a bit, but can be a basis for further optimizations. More detailed models may bring a much higher flexibility but will never be more constraining than the presented approach. It can be therefore seen as "worst-case" model that may be applicable for a wide variety of different installations. The presented model will therefore be also part of the prove-of-concept implementation that is presented in chapter 5.

4.1.6 Introducing adaptive behavior to the simulation models

One disadvantage of the usage of simplified models for simulation and prediction of different internal processes like the temperature level of the air or different others is that a simplified model tends to be slightly more incorrect than a more complex one.

Therefore it has to be ensured that the predicting unit of a demand response controller (independent on the complexity of the used simulation model) has to provide a possibility to self-test the used model.

Another interpretation of the described problem is the challenge of finding the appropriate parameters for a specific subsystem. If a demand response controller should for example use the heating pumps as the switchable load for influencing the temperature of the air the model would always be the same – even for different buildings. The same model could be used – in principle – for any building in which a similar demand response controller should be used but an adaption of the internal calculation parameters has to take place. This has to be done because of the different physical, geographical, climatically and other parameters that make every building unique.

So a possibility has to be found that includes a self-learning or –adapting mechanism to help the first setup period as well as periodical checks of accuracy. Each used model would have to include a possibility to improve the model by itself besides its main calculation for predicting the building behavior.

An example for such a pair of calculations could be the following simplified model for a room's inside air temperature as already covered and introduced in chapter 4.1.4. Formula (10) takes into account the actual measured inside temperature as well as the actual outside temperature (T_{in} and T_{out}) and a thermal parameter τ and the time-span in which a new temperature value is expected. The formula does not take into account any active influence on the temperature like heating or air conditioning but includes only the passive envelope of a room. The thermal parameter τ in this formula includes all the different physical parameters like the thermal resistance of the wall and the internal capacity of the air. This leads to the conclusion this parameter can be seen as a physical representation of the whole building.

$$T_{in+1} = (T_{in} - T_{out}) * e^{-\frac{t}{\tau}} + T_{out} \tag{10}$$

To gain an appropriate value for τ for the provided formula the following rearranged formula (11) can be used. All the values that could be measured were used to calculate the appropriate thermal parameter.

$$\tau = -\frac{t}{\ln\left(\frac{T_{in+1} - T_{out}}{T_{in} - T_{out}}\right)} \tag{11}$$

Exemplary values for the thermal constant τ for a passive house building were derived in a research project [Bed12] and can be given (for an office building in passive house standard) as values between 8.4 to 8.7 days (~ 750 000 s) [Bed12, p. 32].

To include an appropriate and automatable workflow into the simulation (and later overall operational process), the principal simulate/decision workflow only has to be slightly altered. This alteration has to include a check if the simulated value for a specific point of time is too different from the measured value or not. If the answer is yes the parameter set should be learned again, if not the already calculated parameter(s) could be used for the next simulation as well.

Figure 4-6 shows a graphical illustration of the described workflow. The operation starts with the comparison of the measured data and the simulated data for the same point of time. If the difference between simulation and the real world is within specified boundaries the process waits for the next event within the simulation which could either be the next point of time, or any other event (for example a new incoming request). If the difference of error between measurement and simulation is outside the boundaries the parameter (or a whole parameter set – depending on the used calculation principles) has to be calculated before the process is (again) set to wait for the next event.

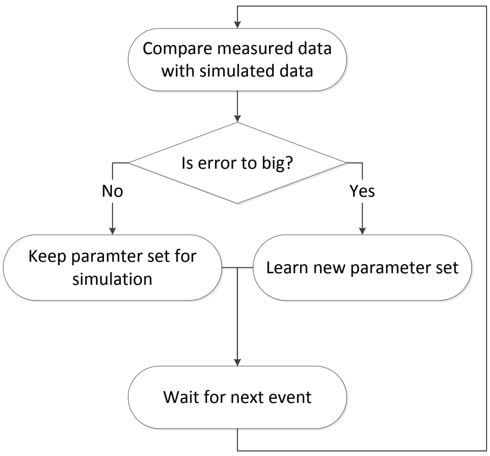


Figure 4-6: Principal workflow for including self-learning mechanism to the prediction mechanism

To test if the proposed algorithm and workflow provide the functionality it was aimed for, more thorough tests are needed. Especially interesting are the questions of the actual accuracy of the proposed calculation as well as if the calculations can provide a model with stable parameters (are the parameters always calculated in a way that will provide more correct answers). For these tests two different (exemplary) series of temperature values were generated.

Both time series model the cooling curves for a room, calculated with the prior described formula (10). In both cases it is assumed that the given time constant τ of the room changes over the observed period of time. For real world scenarios this can be the case if the initial setup of the system is based on an incorrect measurement or calculation or if the building is renovated and the thermal insulation was improved, or a window was left open for a long time. In either way the value for the thermal constant does not fit with the initial value and has to be recalculated.

With these principles the algorithm was tested in the following way:

1. The calculation is based on absolute knowledge of all future values and therefore one time series could be calculated that includes the "real" values based on the knowledge of all included parameters. How this was calculated will be described in detail for both scenarios separately.
2. At each point of time the actual internal and external (based on a time series taken from a weather file for January) temperatures were taken as base to calculate the expected temperature inside the room/building. For this calculation it is assumed that no external influence (heating) alters the experiment.

3. The calculations were performed for different values of prediction horizons (from 15 min to 2 h). This was done to provide a possibility to understand the influence of this value on the calculation.
4. At every point of time all existing predicted values are compared with the “real” time series. The difference is calculated and if this difference is not within an interval of +/- 0.1% a new time constant τ is calculated. This new time constant will then be used for all future predictions.

The first test case is based on a cooling curve that starts with an internal temperature of 22 C and an initial time constant of 9000000 (2500 h). The value of the time constant changes transition-free multiple times inside the interval [900000; 9000000].

The first scenario is presented in the diagrams in Figure 4-7. In the upper part of the figure the predicted temperature values are displayed in comparison to the time series that represents the real values (black). Depending on the prediction horizon the deviation between real and predicted values can last for some time, but never longer than the actual prediction horizon indicates. The differences at the start of the graph are due to the fact that no prediction took place before t=0 and therefore some of the time-series do not contain any prediction values for this period. But for all other points of time it can be observed that at the first instance in which a deviation could possibly be detected it is in fact detected and a new value is calculated. The later calculated values fit again into the allowed error interval.

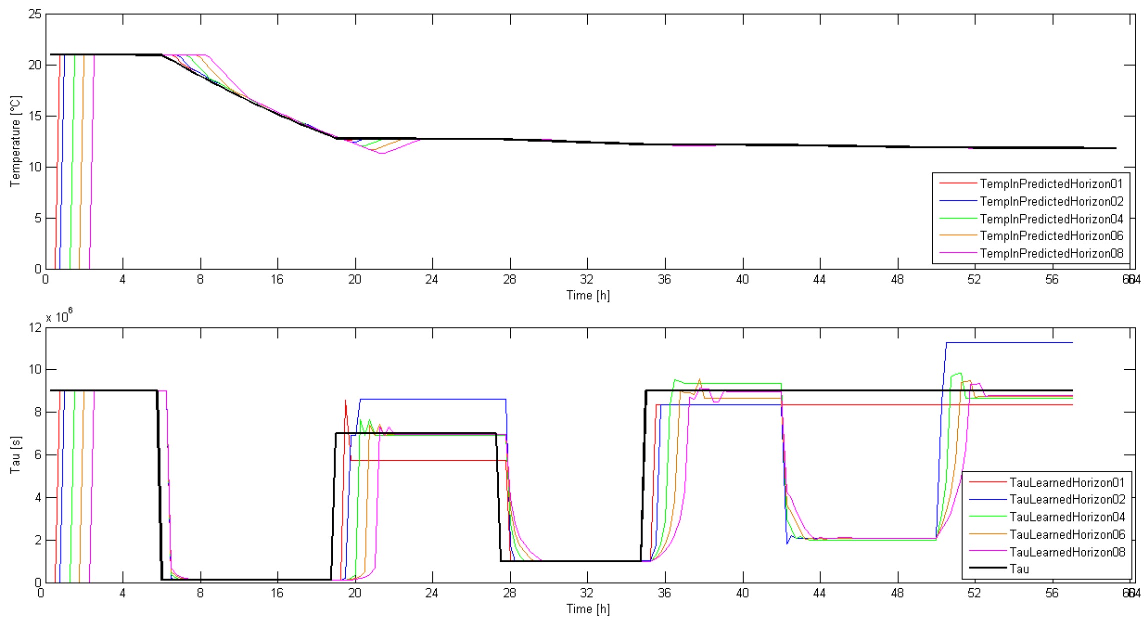


Figure 4-7: Test results for self-adapting prediction model - Case 1

In the bottom part of Figure 4-7 in which the different (calculated) values for the thermal parameter are displayed. The graph shows that the values are calculated new as soon as a deviation is detected and that the proposed calculation of the thermal parameter tends to overshoot a bit and sometimes even to generate wrong values. But especially these problems are generated because of the drastic and abrupt changes of the thermal parameter as well as the type of the mathematical equation (logarithmic) in comparison to the graph itself (linear, stable). The promising result of the approach is that although the parameter is not really determined exactly and sometimes quite erroneous – the predicted values only seldom leave the allowed interval. These can be lead back to the initial setup of the whole system – the prediction horizons are with maximal 2 h very small compared to the values of the thermal calculation parameters of up to 9000000 s (~2500 h). As soon as the prediction horizons start to become longer the presented approach has to be re-evaluated.

In the second test case also a pre-generated, but different, time series was used. In comparison to the first test case not only temperature drops but also sudden temperature leaps should occur. This is to model every eventuality and include not only temperature drops/cooling behavior but also heating characteristics and check if the adapting model can adapt also to this kind of changes. The changes of the temperature constants are exactly in the same manner like in the first example.

The results of this test scenario are again illustrated and shown in Figure 4-8. Again the results indicate that a recalculation is initiated if the error is considered too big latest after the first expiration of the prediction horizon after an unexpected change. Especially the newly introduced positive temperature leaps combined with the positive leaps in the thermal constant (at the exactly same moment) challenge the whole mechanic because in these situations a totally wrong prediction has to be taken into account. The graph in the bottom part of Figure 4-8 shows again a strong overshooting at these instances and only after some time – the longest after 2 durations of the prediction horizon – more correct prediction values can be achieved again. The latter is caused by the nature of the test data having hard jumps - a situation normal temperature series would only have if some of the measurement points are missing.

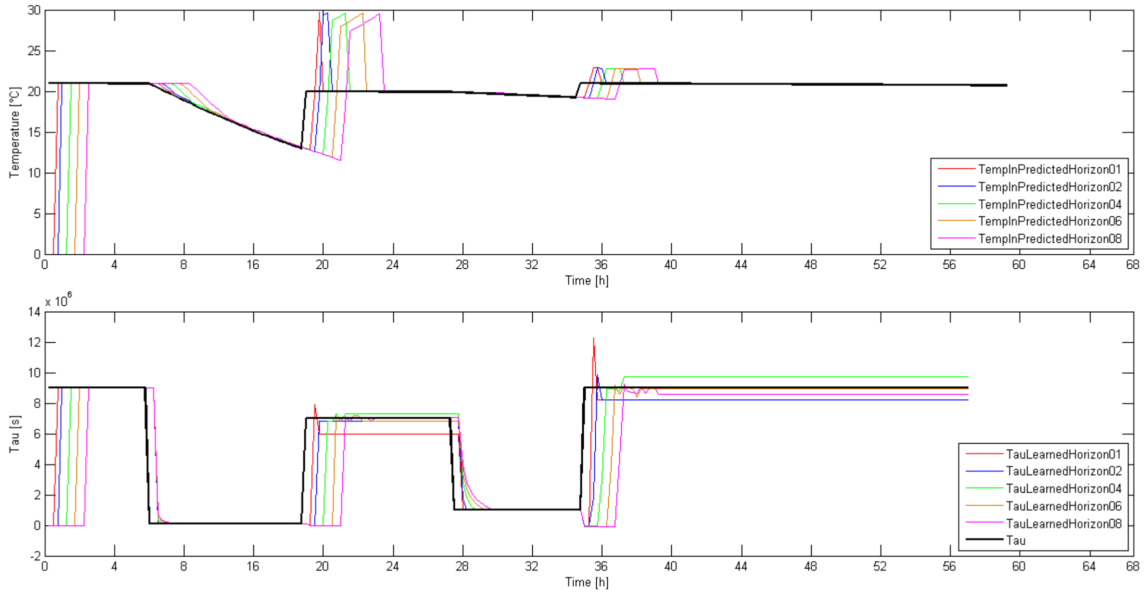


Figure 4-8: Test results for self-adapting prediction model - Case 2

The jumps into the positive direction lead in addition to a wrong parameter because normally a cooling-down characteristic can be assumed while a positive jump can lead to a slightly negative "cooling down" (in this case a heating up) parameter. This situation can be observed for all the calculated time series around the time of 20 and 36 h after the start of the record (bottom of Figure 4-8). This happens only for the first detection of the "positive" jumps in the temperature measurement and is corrected directly after the next expiration of the prediction horizon.

To conclude the current evaluation it is proved that the proposed strategy of periodical executed self-validation of the prediction model and autonomous adaption of the simulation parameters works even if the underlying physical characteristics change drastically. In all of the test cases a parameter could be calculated that improved an erroneous calculation and brought it back into the allowed error interval. It has to be pointed out that although after a while correct predictions are available again there is the possibility of (temporarily) erroneous results.

In defense of the algorithm it has to be pointed out that the scenario was designed to show the problems and challenges it has to face. For example is an error-interval of +/- 0.1 % incredible narrow and maybe not expedient given the fact that especially for temperature measurements this could be very well much higher than the expected measurement accuracy and noise. Nevertheless a nearly correct prediction is performed with time constants that seem not correct at all. This leads to the assumption that predictions within a short prediction horizon could be performed even with nearly wrong parameters.

In addition it can be assumed that with the proposed solution short-term predictions are always within a certain range because such drastic changes in the thermal abilities of a whole building (or comparable objects in terms of their thermal characteristics) are highly unlikely, especially in such small timespans as the experiment indicates. For both cases real world pedants can be found: A change of the thermal constant by a factor of 10 (as indicated multiple times in the test) could be achieved by the upgrade of the thermal insulation of the building. A pedant for a negative jump – indicating a long term decrease of the thermal abilities - could be for example a leak of the building hull or a broken window. Both cases do not occur randomly and often over time and a newly initiated setup and recalculation phase (with temporarily overshooting values) can safely taken into account in these cases.

Some points could be considered to improve the performance and/or adapt the strategy for other slightly different scenarios:

- It has to be considered how big the error is allowed to be. The error interval was chosen +/- 0.1 % for the experiment but it seems clear that due to measurement uncertainties and other defining factors this is a level of detail and accuracy that may not be needed at all.
- In the presented approach every time an error that is too big is detected a brand new parameter (or for more complex models a set of parameters) would be calculated. The two main points in this regards are that the parameters inside of buildings do not change in such a drastically way as presented and new physical abilities can never be independent from their predecessors. With this approach already determined knowledge about the model is neglected as soon as it seems to have left the allowed interval. This is a good approach if sudden

and big differences in the parameters are to be expected. In long term experiments it may be an improvement to introduce a mechanism that includes a kind of internal system memory to improve the results and introduce a stronger stability and hysteresis. This could be, for example, be achieved by introducing a weighted average of the last few values. With this the newest values could be improved by taken also the old values into account. In the presented experiment this would have made longer times for adapting to new situations necessary.

To conclude it can be summarized that the principal mechanism works well for predicting the temperature in short term scenarios and adapt the internal parameters if necessary. Certain details can and should be discussed and adapted if slightly different scenarios are chosen, but the overall technique will work for other physical simulation scenarios that are based on certain inertia or effects like hysteresis of system parameters.

4.2 Proposing a demand response controller for buildings

The following chapter will outline the structure and functional units a demand response controller for buildings should include that is able to perform the actions and tasks that were defined throughout the thesis. Regardless of the technological constraints there are some main components that can be identified which have to be existent inside a demand response controller for buildings. It does not matter if the units are mere functional units or build as physical entities as long as the intended functionality is taken over.

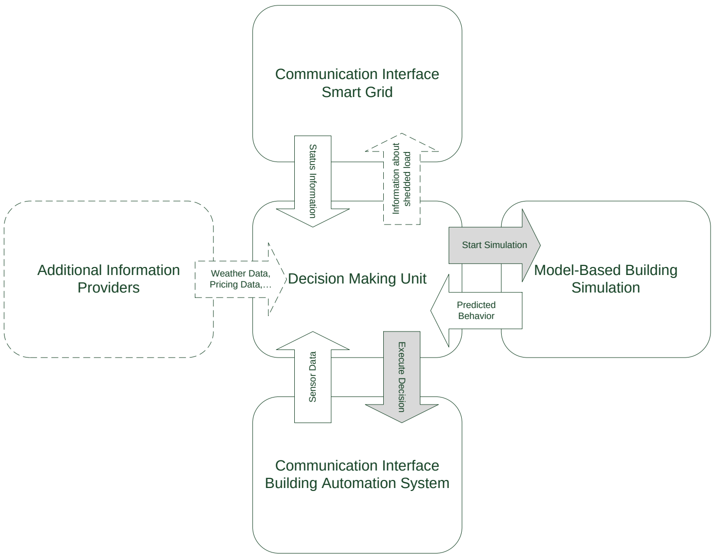


Figure 4-9: Principal entities inside a demand response controller for buildings and intended information exchange

Figure 4-9 shows a structural overview of the different entities and what kind of information they are intended to exchange. Beside the required information and units (indicated by a solid border) also additional information providers (and information flows) can be included (indicated by dashed borders). As required units the different communication interfaces to smart grid and building automation as well as the decision making unit and the simulation unit are included. Additional information that is not required but could lead to better performance would be data from weather predictions or pricing information.

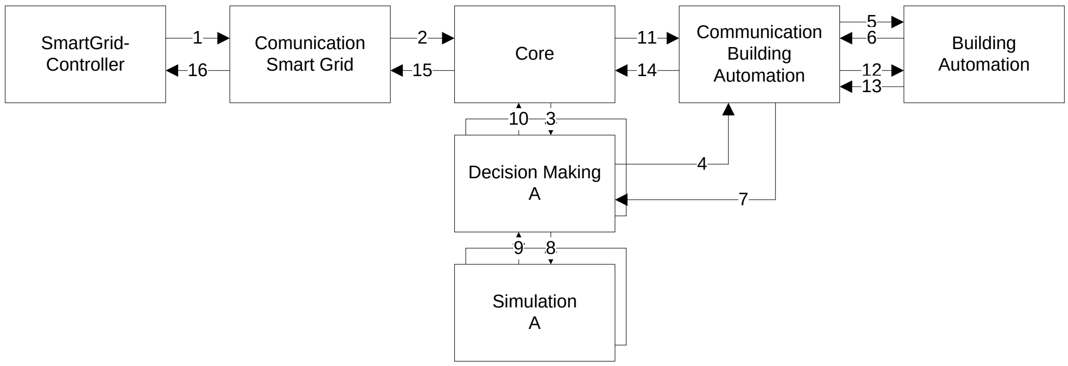


Figure 4-10: Communication workflow inside the demand response controller

In Figure 4-10 a possible internal communication workflow between the different parts of the smart grid controller is illustrated in detail. The following list includes a detailed description for every step in the process. The numbers of the list correspond to the enumeration in the illustration.

1) Demand response request by the smart grid controller (centralized management unit)
2) Communication interface interprets the request and forwards it to the main part of the controller
3) The main part of the controller starts decision making process
4) Decision making unit requests newest measurement data from building automation unit through appropriate communication interface
5) Communication interface to building automation demands newest measurement data
6) + 7) Measurement data is sent back to decision making unit
8) Obtained measurement data is used to start simulation of internal building parameters for using as base of decision making process
9) The simulated values are sent back to decision making unit. On the base of a predefined rule-set (minimum/maximum, within boundaries) the actual decision is made if load can be shifted or not, or if additional load can be generated somehow
10) Final decision is returned to main program
11) The main program forwards the appropriate actions to the building automation system through the communication interface
12) The communication interface to the building automation system „translates“ the decision to the correct actions (i.e. deactivate heating pumps, changing time-schedules or set points)
13) + 14) Acknowledgement of the building automation system that the demanded actions were undertaken

15) + 16) Acknowledgement in direction of the smart grid controller of the decision and action that was obtained for the last demand response request.

Another way to illustrate the intended behavior is included in Figure 4-11. It shows the communication flow between different entities. Every entity in the illustration symbolizes its (multiple) communication interfaces to the outside. The demand response controller for example has to provide a communication interface to the smart power grid (Smart Grid Controller) and the building automation system. The timeline includes only the events that take place in the case of a request for load change (in this case "load event"). It does not include the request of new measurement data from the building automation system, or the possible refinement/change/adaption of the simulations. It shows that after each received load event all simulations are started (Simulation 1-n) and after these are terminated for each of the result sets a decision is made if the load can be changed or not. Then the demand response controller initiates on one hand the appropriate action by communicating the switch on or off events to the building automation and on the other hand it communicates the load event result back to the smart grid controller. Another possibility would be to simply schedule the action (if the load events indicate a later point of time) – in chapter 3 the issue regarding the communication with the smart power grid is discussed besides others.

The given structure and workflow of a (still theoretical) Demand Response Controller Unit will be evaluated in the following chapter that includes several (different) simulation scenarios as well as experiments to prove the feasibility of the approach.

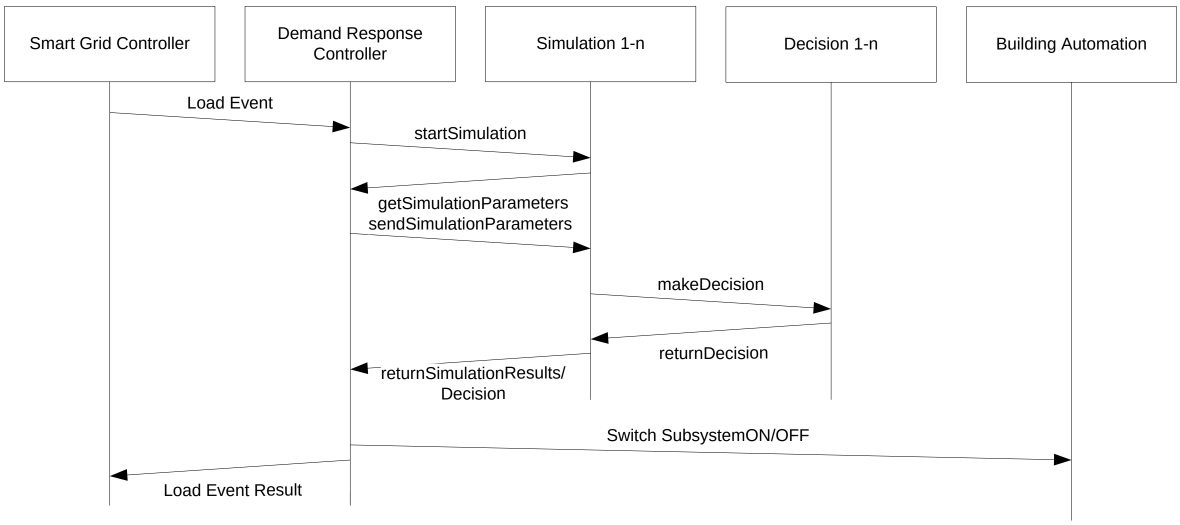


Figure 4-11: Communication timeline of the different parts of the demand response controller

5 Simulation and implementation

While the previous chapters outlined theoretical structures and workflows the next chapter will include the description of a possible implementation of the demand response controller in a simulating environment. It includes an overview on the different parts of the simulation model, the simulation results as well as a discussion of the results.

In another part an experimental implementation of the adapting simulation model inside the field component of a building automation system is described. The experiment included the actual implementation of an integral part of the demand response controller on a low-profile field device. This should prove that the described demand response controller could even be implemented inside a building automation system of sorts, proving that the whole setup is also deployable without the introduction of additional entities. The sub-chapter is ends with a discussion of the obtained results.

5.1 Simulating adaptive energy control of future buildings

The next part focuses on a test implementation for simulating a possible software implementation of the demand response controller for buildings that is presented in this work. The focus will be laid on the demand response controller for the buildings and especially on a proof of feasibility of the mechanisms for adaptive simulation models that were introduced in chapter 4.1.6. The part starts with a description of the different parts the simulation has to include, an introduction on the overall concept and notes on the implementation itself. This first part is followed by a presentation of the main simulation results. The part is closed by a discussion of the results and concluding comments.

5.1.1 Description of the simulation model

The following part of the work focuses on a possible software implementation of the demand response controller for buildings. A simulation is necessary because the functional description of the demand responses controller has to be proven to be actually functional within actual application scenarios. The whole functionality is focused on the different application scenarios of the demand response controller, and therefore the additional functional units (e.g. Smart Grid Controller Unit) cannot be seen as “final” implementations of the necessary functionality. The units provide only the necessary functionality to interact with the demand response controller. For providing a full functional simulation model of the process all parts and entities that are/were described in the previous work have to be included in the model. Before the different units and their usage within the simulation are described it has to be stated once more: the described simulation does not simulate all units of a smart power grid, but only the demand response controller with additional “helper” units as said controller was the main focus of the work.

First the two main application scenarios that were defined will be introduced. These two main questions were the base for the simulation model and the obtained results regarding those scenarios will be part of chapter 5.2.3). The main questions for the simulation were:

1. Is it possible to use a self-adaptive building model for predicting the system parameter for a given point of time in the future and use this calculated value later for evaluating the prediction accuracy of the model?
2. How long does it take until a given system parameter will leave a boundary interval if it is not influenced anymore? How does a combination of parameters affect the capability for acting as demand response storage?

The first question defines the intended main workflow of the demand response controller for buildings while the second question was intended to give an estimated timespan for future optimizations of the model. And to give (again) validation to the already mentioned assumption regarding thermal storages every unit could be switched off for at least 2 hours (as was mentioned in chapter 3.1.2.2).

After describing the simulation scenarios a short overview of the different units that were defined as necessary for the simulation is given:

- Smart Grid Controller Unit
  The implemented Smart Grid Controller Unit executes demand response commands at predefined points of time. These points of time are not dynamically scheduled. This functionality was not implemented mainly for being in the position to execute demand response request at any given point of time, without the need of “overruling” a scheduling mechanism before. In addition the smart grid controller unit was implemented as simple as possible due to various other reasons. First it was assumed that a first generation smart grid controller would follow the approach of “least knowledge” and “least communication” about and with its subordinate nodes. This assumption was made under the point of view that communication errors are quite common and therefore a minimum of communication should be sufficient without compromising the result. In addition it has to be assumed that the controller situated at the building side of the system could and should be kept as simple as possible to introduce as much new units to the newly built system.
- Demand response controller unit for each building
  A more detailed description of different aspects of the implementation of these units would make this overview too bloated and was therefore put into its own subchapter (see chapter 5.1.2).
- Building Automation Unit for each building
  The building automation system is substituted in the simulation with a database of measurement values from a real building automation system. At any given point of time inside the simulation a “real” measurement value is provided from the unit. The database includes also every load value of the specific electrical loads inside the building at the points of time that are in question. These values can also be obtained by the demand response controller

unit. The unit itself was therefore designed only as stand in or pipe to introduce real world temperature values from real building measurement. If triggered for a new value it simply gives the next value in a list. This means not less than that every value is predefined and the (maybe given) control commands effectuated. As the simulation should focus on the evaluation of the adaptive model behavior introduced in 4.3 this was not an option because one of the simulation scenarios was to test the maximum length of load reduction before the predefined intervals would have been left. The buildings real behavior in comparison to the model could not be made part of the simulation model because it would have either needed the data for all possible switching events – or a slightly modified model that simulated the building with slightly different building parameters. It was decided not to follow this approach to concentrate on the predicted values. Nevertheless the second approach will be also be evaluated and is outlined in chapter 5.2 to show how the adaptive model could be used on one hand for prediction and on the other hand as stand in for the building itself.

- Communication paths between the nodes
  Although possible inside omnet++ (the chosen simulation framework) the communication channels do not implement communication errors as this was not the focus of the investigation.

Due to the reason that the omnet++ framework was considered as basic framework for the simulation two other supporting units were needed mainly out of supportive reasons:

- Clock unit
  The clock unit was mainly necessary because omnet++ is intended as event-based communication simulation framework. To provide synchronized events of all units one main timebase was necessary. To avoid synchronization issues one clock unit sending “tick” messages for triggering the units was implemented. This part of the implementation shows again the advantage of using an event-based framework. It seems counterintuitive to use such an framework and synchronize the units again, but not the units but the functional sub-units (mainly of the demand response controller) were the focus. With every unit being triggerd by the “clock” unit it is assured that every action that has to be finished before the next clock tick really is really finished. So the main overall simulation itself is not time-synchronized to ensure that every process of every subunit is finished and afterwards the clock tick starts the next simulation circle.
- Logging Unit
  This general purpose unit is necessary for providing one central accessible point for logging. Every unit (of every type) is internally (not over the “real” communication channels) connected to the logger. This unit logs without any delays every message that is sent to it. The logs are used for later analysis.

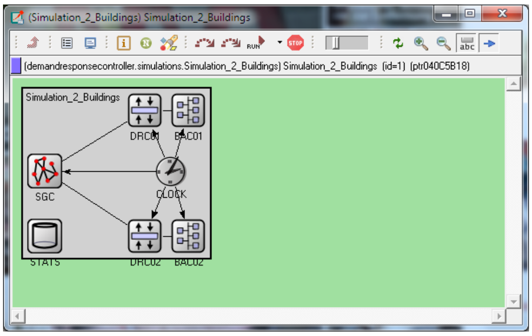


Figure 5-1: Sample simulation in omnet++ framework

Figure 5-1 shows an exemplary screenshot of the finished simulation including all previous mentioned units. The illustration shows an example simulation of two demand response controller (DRC) units and the corresponding building automation (BAC) units as well as one smart grid controller unit (SGC) and the additional CLOCK and STATS unit. It can be seen that all units have to be connected with each other via communication channels – the only exception is the statistics tool which is not connected via visible channels due to the reason that the visual overview would get much too crowded because any unit would have been connected too this unit. The whole overview shows also the modular approach that would be easily expandable to simulate multiple demand response controller units. The following subchapter will include a more in depth overview of the actual implementation of the demand response controller unit.

5.1.2 Further requirements for implementing a demand response controller unit

Some additional things had to be especially considered for the simulation implementation of the demand response controller unit. Because of this and the fact that the demand response controller unit was the main focus of the presented approach the following short chapter will outline the implementation of this unit in a more detail.

One of the main mechanisms the demand response controller has to provide is the ability to manage multiple simulation models of different nature and type as well as all underlying mechanisms for using them to simulate future values and additionally check the accuracy simulation models. It also has to take care of the self-adapting simulation models to determine new model parameters if the previously executed simulation turned out to be too far from the actual results.

Besides the self-adapting models the main mechanisms of the demand response controller still has to be to calculate future values of specific system parameters. In the implementation mainly two models were implemented: an exponential simulation model for the internal temperature of a building (compare chapters 4.1.4 and 4.1.4.2) and a simplified model for the ventilation inside a building (compare chapter 4.1.5). The “normal” workflow was already described in chapter 4.2 and illustrated in Figure 4-11 and could be implemented after these guidelines. The overall functionality could therefore be implemented as intended.

One small adaptation had to be made to the concept. Per definition the smart grid controller is able to send “SmartGridRequirementMessages” at any possible time – even in between the points of time that are determined as starting points of the calculation. As every simulation – if event based like the chosen or time based – needs a certain quantization of time it was defined that if a "SmartGridRequirementMessage" is received before a point of time it will be delayed and processed at the next possible point of time. In this way no special buffering strategy was necessary to cope with the described scenario. There were no other additional changes necessary for adapting the initially planned functionality for the simulation.

The main mechanism behind the implementation of the self-adaptive approach of the simulation model can be depicted as follows (the described communication flow is depicted in Figure 5-2). It has to be said clearly that this figure only shows the "self-learning" subtask. As the "predicting task" will only be triggered if a "SmartGridRequirementMessage" was received prior to the clock tick the example here assumes that there was not such a message. The workflow can be interpreted as follows:

1. Every time the controller is triggered by the clock tick it looks into the former results of previous simulations for the actual point of time. If there is a result available it sends a parameter request to the building automation for obtaining the actual value for the predicted parameter (for example the internal temperature).
2. If the building automation is receiving a parameter request (for example for the actual temperature) it sends the actual parameter value back.
3. The demand response controller takes the parameter and checks how big the difference between the previously simulated value for this clock-tick and the actual measured value is. If it is bigger than a given limit, the internal simulation parameters are re-calculated. For this task the "reverse" calculation is used as was described in chapter 4.1.6.

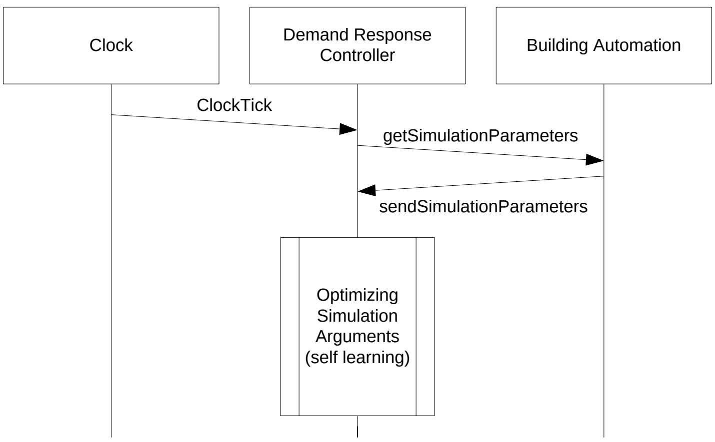


Figure 5-2: Communication flow including demand response controller after clock tick

5.1.3 Simulation and discussion of the results

Two main questions were defined in 5.1.1 that should be investigated by simulating a network with buildings that are equipped with a so-called Demand-Response-Controller unit. The following part will try to give answer to both of these questions. Those questions were:

1. Is it possible to use a self-adaptive building model for predicting the system parameter for a given point of time in the future and use this calculated value later for evaluating the prediction accuracy of the model?
2. How long does it take until a given system parameter will leave a boundary interval if it is not influenced anymore? How does a combination of parameters affect the capability for acting as demand response storage?

Regarding the first question this section will held short as the main results of these simulation runs have already been shown and described in detail in chapter 4.1.6. The simulations included a demand response controller that was given different prediction horizons and the calculated results were compared to the real values. It was shown that even with highly unlikely profiles and a “not precise” parameter set for the simulations quite exact results could be obtained. The tests were only processed for the “temperature” model as the “ventilation” model was so much simplified, that in the actual parameters could not be précised any more. The main reason for this was that a detailed usage model (how many inhabitants will be at which time in which room) would have been needed that would have been far outside the scope of this work. Nevertheless – the feasibility of the approach, and therefore the first main question, can be positively answered by showing that the temperature model could be used in the intended way, adapting of its internal parameters is possible also during the execution of the process without compromising the results. In fact the mechanism is able to precise the results as soon as “faulty” parameters are detected and a parameter set that produces more accurate results is calculated. This is a mayor advantage over the often used approach to “setting up a model and execute it” as the refinement has not to be made after the execution but is automatically made during the process.

The second simulation made a slightly different simulation necessary. Whereas the former use-case took a fixed time-span as prediction horizon and calculated the system parameter for this future point of time, this use-case needed another type of calculation. The exponential equation for calculating the temperature (compare also chapter 4.1.4.2) was therefore transformed into the formula included in (12). The parameter in question no longer was the inside temperature but the time it needs to reach a certain target temperature if the building was left without any interaction like heating.

$$t = -\tau * \ln\left(\frac{T_{in,target} - T_{out,start}}{T_{in,start} - T_{out,start}}\right) \tag{13}$$

As in chapter 4.1.4.2 shown for its transformation this calculation can either be calculated in one single step, or in multiple steps with taking into account that the outside temperature could be changing. Three main reasons can be made out why in this case (also) the single-step calculation is the better choice. First and foremost: In this special case the single-step calculation will be the more adequate one – via multistep the calculation would produce a time-interval (two distinct points of time) in which the violation of the target temperature occurred. Single-step on the other hand would produce an exact value for the time at which the calculation would reach the limit. The second cause is (again) the small influence the outside temperature has that could be pointed out previously. The third argument is the much simpler and quicker way of calculating. While the demand response controller would need to keep track of all possible calculations if it calculates the time-limit in a multi-step calculation, the single-step calculation can be implemented in “one-shot” that is executed at every point of time.

To answer question 2 two different simulation models for different devices were implemented for the demand response controller. These two models are a model for the heat pump of a building – an essential device for both heating and cooling – that influences the temperature and the ventilation that is used for influencing the CO_2-ratio inside the building. Both models are already described in more detail; compare the chapters 4.1.4 and 4.1.5. As both were examples and should prove the feasibility of the approach not actual limit interval were chosen, but relative ones. This is due to the fact that the standards [DIN13779, DIN15251] allow a certain violation of the comfort levels. The lowest allowed temperature (in case of heating) for the following example will therefore be 17,5 °C, while in summer (cooling) the highest allowed value will be 28 °C. For both cases measurement periods were chosen that would provide the actual temperature inside the building, as well as the outside temperature. As thermal constant a value of 727010 s was chosen, as this was determined as valid thermal parameter for a state-of-the art office building in [Bed12]. The simplified model for the ventilation was implemented in a way that would allow a maximum time for switching of 900 s. In chapter 4.1.5 this was already pointed out as absolutely worst case model and every “better” model would even increase the overall performance. The simulation scenarios were chosen to include the hottest and coldest periods of the year, because if the whole approach proves possible and valid during these intervals all other points of time with temperatures in between would also be covered.

For a period of 11 days between 22^{nd} and 31^{st} of January in 2010 (the interval that included the coldest measured value for this year in Vienna) the maximum, minimum and values for switching off the different devices is shown in Table 5-1.

Table 5-1: Statistical results for simulation period 1

	Heat pump	Ventilation
Minimum switching off time	10127 s	0 s
Maximum switching off time	88156 s	900 s
Mean value switching off time	30679 s	431 s

Another illustration of the gained results is shown in Figure 5-3. It shows in a three dimensional graph three different time-series (green = ventilation, blue = heat pump, red = sum). The influence of the ventilation can be seen as very low, as it has low time flexibility and a low overall potential (in kW). The blue timeline shows the times of the heat-pump – these values are much higher in temporal flexibility and overall switch-off potential. The red time-line shows the combined (sum) value at every point of time.

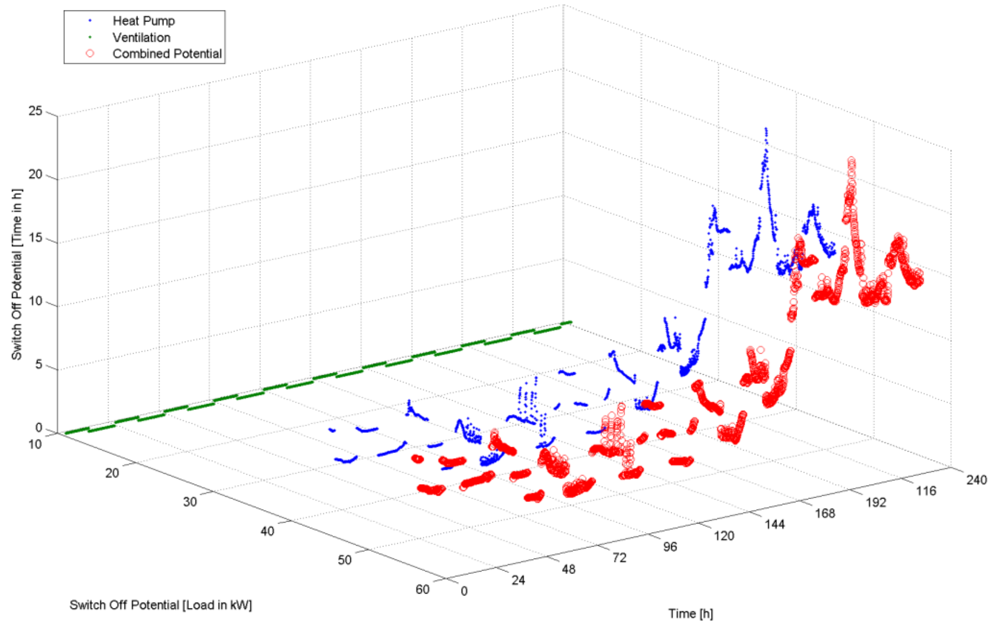


Figure 5-3: Maximum switching off potential during a period of 11 days in January 2010

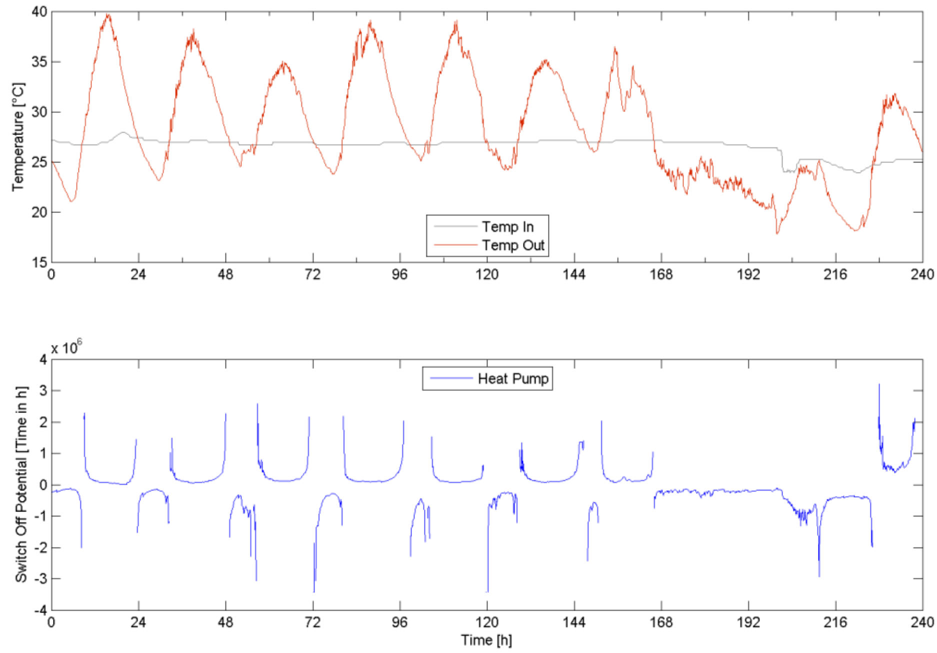


Figure 5-4: First graphical analysis for simulation scenario 2 (heat period)

The second simulation period on the other hand was defined as inside the "warm" period from 11th until 20th of June in 2010 – therefore the heat-pump in the presented case was used as cooling device. This period was chosen because in the respective year the warmest temperatures (nearly 40 °C) were measured during this period. A first graphical analysis of the potential of the heat pump can be seen in Figure 5-4. It is noticeable that the temporal switch off potential includes more or less periodical jump discontinuities with additional changes of the signum. A look at the additional graph that includes the outside temperatures (red) and the inside temperatures (grey) shows that these discontinuities occur when the outside temperature is lower than the inside temperature (mainly during the nights).

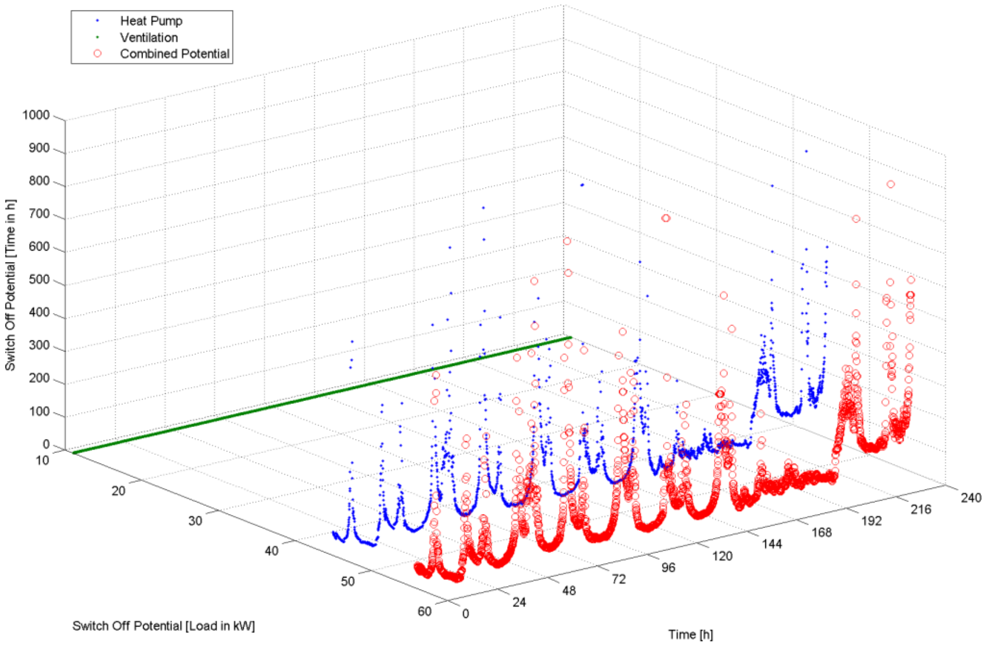


Figure 5-5: Maximum switching off potential during a period of 9 days in June 2010

The simulation shows here one weakness as the simulated internal parameter for the temperature drifts always against its target value – and that is always the outside temperature. In any case – the Figure 5-5 shows again the different timelines (green = ventilation, blue = heat pump, red = sum) with only the total values included as the temporal switch off potential can only be a positive time value.

For the statistical value this scenario surely can be named problematic as no maximum value for the switch off potential could be calculated. Table 5-2 includes therefore only the minimum value as maximum and mean value are not meaningful in the presented scenario.

Table 5-2: Statistical results for simulation period 2

	Heat pump	Ventilation
Minimum switching off time	57776 s	0 s

Although not every value for every scenario could be calculated in the intended way the presented results are still a valid ones as the main constraint for using a building as demand response storage is surely the minimum time that the building could be taken off the power grid.

The simulation showed therefore results for both questions – that self-learning mechanisms can be implemented in a way that introduces adapting simulation models into a demand response controller for buildings and that a state-of-the art office building as the ENERGYbase [6] in Vienna could be taken off the power grid at any time of the year for at least 10127 s (about 2.8 h) with a maximum switch-off load of 45 kW (which is the minimum time that could be reached in the heating case in January). In hot periods like in summer this value is even higher. The assumptions that were made in chapter 3.1.1 are therefore valid ones.

5.2 Adapting building automation as energy control system

The simulation results presented and discussed in chapter 5.1.3 show that the proposed system could and would work if the appropriate mechanisms would be introduced into building automation systems. The following chapter will give a spotlight on a possible implementation of the presented approach with a real automation system. The first part includes the description of an experiment that was based on the LON-works system. The second part lays out the detailed approach and some details on the implementation. The third part summarizes the results and findings.

5.2.1 Overview

One main objective of the presented approach is to find a possible way of including building automation into the smart grid demand side management process. It therefore has to be proven, that building automation is able to fulfill the expected tasks. There is no need to prove that building automation is able to provide the ability to switch on or off specific resources like pumps or ventilation devices as this is can be seen as one of the main objectives of building automation and is therefore inherently given.

Of high interest in these regards is the question if and with what restrictions a common building automation node could provide the ability of predicting a certain behavior of the room (or part of the building) that it is controlling or monitoring. It may not be a necessity for newly designed building automation systems as these could provide the abilities of including demand response controllers in the system itself. Based on the simplified models presented in chapter 4.1.6 the following chapter presents a experiment that was based on development and evaluation boards for the LON automation system to work out the answers to the outlined questions.

The main goal of the experiment was to show if a commonly used building automation node has the ability to serve as prediction unit for the controlled parameter by processing a simulation model. In addition it should determine if the deviation between the last predicted value and a new measured value is outside given boundaries and if this is true it should be able to compute new parameters for its prediction.. It was considered that a communication connection between the building (represented by its automation system) and the smart grid is existent as well as the ability to control different loads or devices inside a building. These two abilities can be seen as necessary requirements and on the other hand well-established.

The main point in focus of this experiment was the ability to predict a certain (temperature)-behavior of the controlled build as well as adapting the prediction model in a way to gain a more accurate prediction in cases of too big deviations between prediction and measurement. This ability is crucial for introducing a lightweight, but fairly feasible, solution to introduce a demand response controller for a building. This is the case because if a (maybe already existing) node in a building automation system could provide the intended abilities it would be possible to adapt an existing building automation system easily. It would be possible to provide the shifting potential of a building's loads to the smart grid with just an update of the building automation.

5.2.2 Approach and implementation

For the experiment a testing environment of three LON-nodes was set up that would provide a broken down model for the building and its automation system. The three nodes and their tasks used in the experiment in detail:

- A temperature sensor node – it takes over the role of providing the outside temperature for its subscribing nodes
- The room itself – This node should model the behavior of a room based on very fundamental rules and determine a modeled (inside) temperature. As the experiment should show the prediction ability it was decided to use a model for the room instead of real measurements to provide a better control of the experiment. In future tests this could be easily replaced by a temperature sensor node like the first one.
- The room control – This node should provide the main objective of the experiment. In it the outside and inside temperature are used for predicting the possible future temperature based on a simplified simulation model. In addition the node should be able to compute new parameters for its internal simulation if the deviations between predicted and measured values are getting too big.

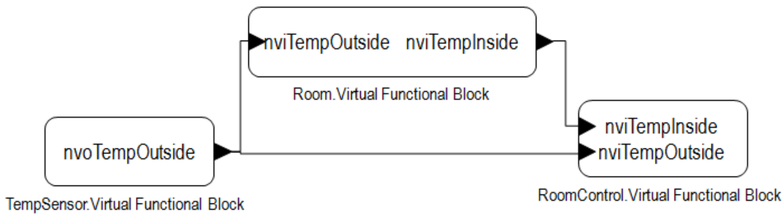


Figure 5-6: Internal information flow of experimental setup

The internal information flow and dependencies as well as the binding between the functional LON-Objects are shown in Figure 5-6. It can be seen that the temperature sensor provides its value for the "Room" node and the "RoomControl" node. The first needs that value to "calculate" the internal temperature. As already described this was considered the best solution within the experiment to gain full control of the values and to be able to manage the experiment which should mainly focus on the third node's tasks. This third node, called "RoomControl" was supposed to fulfill its tasks with only two inputs – the outside temperature and the temperature inside the room. The following chapter will include a more detailed description on the approach that was followed as well some challenges that occurred.

As target system the LON building automation system was chosen and as experimental test bed a rudimentary system of three development nodes was chosen. Those three development nodes were of the type “FT 5000 EVB LON” and are normally are used as development nodes for small control loops inside a building (picture in Figure 5-7). An exemplary use case for these nodes would be what formerly was known as “Direct Digital Control” – a node for taking care of a number of sensors and actors at once. All in all it can be said that especially the used processor (“Neuron Core” by Echelon) on these boards are not the most powerful devices for computation and lack the ability to do floating point arithmetic’s in an efficient way.

Figure 5-7: Target platform FT 5000 EVB LON

Nevertheless the experiment should determine if the intended abilities were also implementable on these “worst case” systems to show that the whole approach was doable at all. The main challenge was to find a way to do the necessary calculations for predicting the process parameter. To calculate for example temperature values a certain amount of precision is needed, especially if the data range in question should cover only a defined interval.

For the intended experiment one main drawback was encountered: The intended systems (FT 5000 EVB LON) have – at best – a very rudimentary implementation of floating point arithmetic included. The existing functionality includes only the basic operations for floating point data types (compare also the NEURON C Programmers Guide [NeC92]). Special mathematical operations like the exponential function and logarithmic functions are not available at all. This all leads, together with a suboptimal and slow implementation of the basic functions for floating point data types, to a situation in which it is not possible in any way to implement even a rudimentary numerical solution or workaround for the intended functions. As those functionalities are essential for even the most basic modeling of internal behavior and automatic adaption of the model (compare chapter 4.1.4 and 4.1.6) an even more simplified solution had to be found to ensure that the intended proof of concept is possible on the lowest possible level.

The two main challenges that arise out of the nonexistence of any floating point calculation are the following:

- The temperature model and the parallel calculation for adapting the model parameter have to be computed without the use of any exponential or logarithmic functions. Either a numerical approximation for those functions or an even more simplified model has to be found to solve this question.
- The data values have to be interpreted or adapted in a way to provide a higher precision than simple integer data types could. The cause for this is mainly that at the calculation should include at least 2 digits behind the decimal point.

The found solutions for these challenges and the results, as well as the conclusions will be covered in the last part of this chapter.

5.2.3 Results and conclusion

In the last chapter two main challenges for the intended implementation of the prediction algorithm on a NEURON-C based LON-controller where pointed out. The basic challenge was to find a temperature model that was executable on the target system and includes the necessary accuracy.

The controller that provided the outside-temperature was the smaller problem, because it "simply" modeled a temperature sensor. Two possible solutions for this task were found, besides using a "real" sensor. The first solution was to simply feed the intended data by providing pre-measured or compiled data values. As this solution is not very flexible for experimental evaluations another method was finally implemented. This second method included symmetrical saw-tooth-waves that were smoothed with the help of a first-order low pass-filter. This approach should model a changing outside- temperature between given limits (to model the time-dependent temperature function). The basic saw-tooth-wave can be formulated with the help of a mathematical function in the following way:

$$Temp = Day * k_d + Hour * k_h + d \tag{14}$$

In formula (14) *Temp* is the resulting outside temperature, *Day* is a value of the interval [1 .. 182 .. 1] which should model the day of the year beginning with the cold-season, to the summer and back to the cold-season, while k_d is a weighting factor for the days. *Hour* out of the interval [1 .. 12 .. 1] to symbolize the hours of the day while k_h is again a weighting factor, this time for the hours. At last *d* is a value that leads to an offset at the y-axis of the wave, to gain an intended mean value.

$$T_{f+1} = T_u * k + T_f * (1 - k) \tag{15}$$

The discrete lowpass-filtering is outlined in formula (11) and included the parameters T_u (unfiltered value), T_f (filtered value step n), *k* (filtering factor) as well as the filtered value for *step n+1* T_{f+1}.

An exemplary graph for the two functions (filtered and not filtered) showing the temperature function for four days in the cold period is included in Figure 5-8. The underlying data was collected by the serial port of the development board. It can be seen that an (intended) rising of the temperatures takes place as a result of the inclusion of the different days of the year. A similar result could be obtained by the usage of a sine-function, but was not possible in the presented approach because of the lacking mathematical function set on the device.

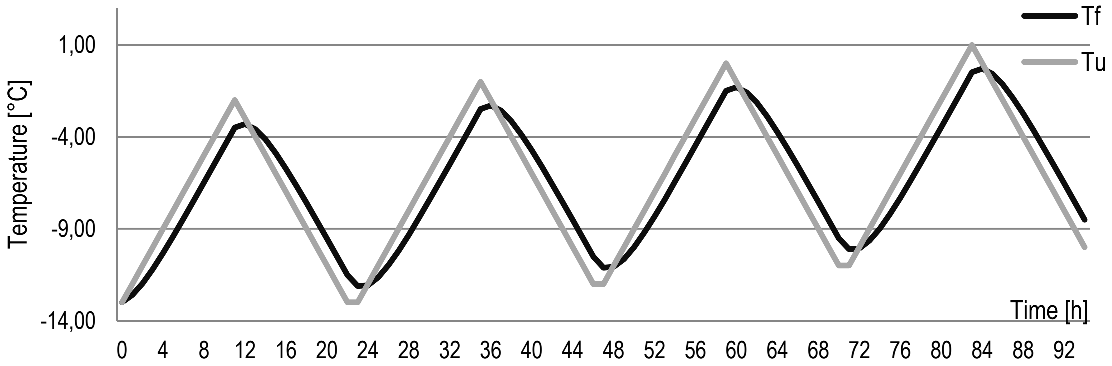


Figure 5-8: Exemplary sawtooth-wave with low-pass smoothing (Temperature outside)

The next challenge was to find an appropriate implementation of the exponential function similar as outlined in chapter 4.1.6. The solution here was to make use (again) of first-degree low-pass filters. In a time-discrete implementation such filters can be used in the same way as time discrete exponential functions. The appropriate formulas in this case are, for the exponential function:

$$T_i(t + \Delta t) = (T_i(t) - T_o(t)) * e^{\frac{-\Delta t}{\tau}} + T_o(t) \tag{16}$$

In formula (16) the factor τ is the time-constant of the adaption of the internal temperature to the outside temperature. The discrete implementation of this would be a filtering function as shown in formula (17).

$$T_{i+1} = (T_o(t) - T_i(t)) * k + T_i(t) \tag{17}$$

In this formula the factor *k* (more or less) includes all the physical and other dependencies and is the singular parameter that decides of the whole profile of the function. In this aspect it is similar to τ, but without the need of any exponential function (the cause is that fixed time-intervals are used in this case and the factor is calculated only once with a *Δt* of 1.

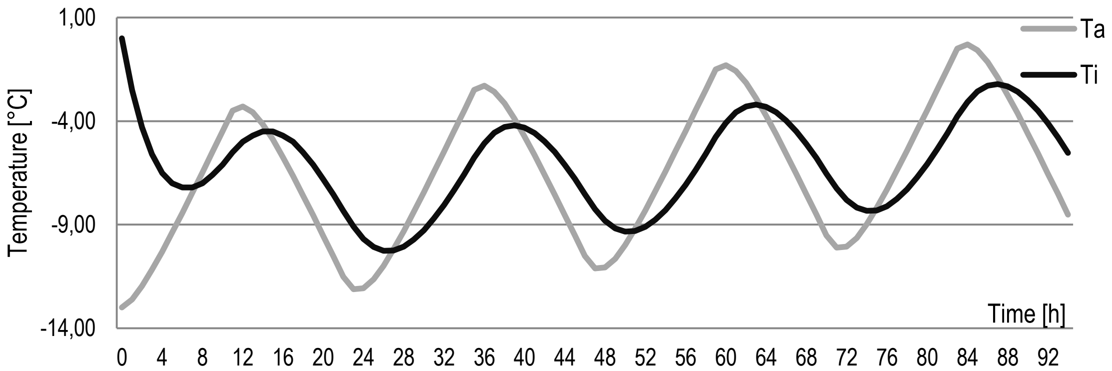


Figure 5-9: Outside and inside temperature

The calculation of the factor out of the measured temperature values for adapting the model if the errors were too high was managed by a simple transformation of formula (17). Figure 5-9 shows an exemplary calculated outside temperature and the corresponding inside temperature. The displayed data was again collected by the serial port of the development board. It has to be said that the factor k in this case was intentionally low to show the typical low pass behavior of the model. For a more appropriate model of the thermal behavior of a room or house a much higher value of *k* would be needed to show a typical value for the insulation.

One more specialty of the implementation has to be pointed out. All of the used filters can be seen as IIR (Infinitive Impulse Response) filters of first order – in mathematical point of view a function for calculating moving averages, to be more specific “Exponentially Weighted Moving Averages”. Those have the special case that a filtering constant $k > 0.5$ would lead to overshooting characteristics which have to be avoided in the presented case, mainly because thermal parameters do not show such characteristics. This also has to be taken into consideration.

The second main challenge was the problem of the non-existing floating-point calculation unit on the used development boards. Also for the intended implementations based on low-pass filters and more simplified calculations a solution was necessary for this problem. This solution could be found in implementing the temperature data values with the help of fixed-point data-types. It was possible to store one value of the interval [-30; 40] inside two values of 16-bit integer values by keeping a precision of 2 digits behind the decimal point. For more details on the specific implementation see [Bra13].

Figure 5-10 shows the exemplary results of a test run. During the test run the parameter that models the physical behavior was changing and the outside temperature was modeled according to the already outlined methods. It can be seen that after a short period in which the simulated internal temperature and the predicted data series were not congruent the expected value follows the actual internal temperature. This is due to the fact that at the beginning of the simulation the model includes a very high default value of the main calculation parameter. After about 2.5 h of simulated time the self-adapting mechanism has finally found a parameter value that fits the requirements. This also can be seen in the illustration.

So it can be summarized that an experimental implementation of the adaptive behavior for a demand response controller was implemented on a typical LON-field-controller. While several changes to the intended functionalities have to be made to find a working solution, it still fulfills all the outlined requirements of predicting and adapting the simulation model for an observed parameter (in this case the temperature).

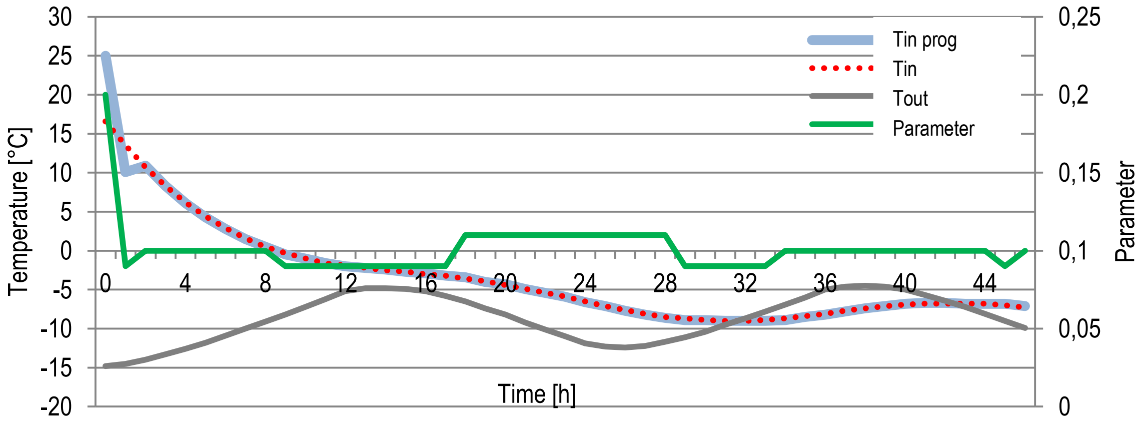


Figure 5-10: Exemplary results of a test run

In summary it has to be pointed out that it is a valid argument that normally not a FT 5000 EVB LON would be used as demand response controller for a whole building. On one hand because of its limitations in the computational domain and on the other hand because of the normally intended use as low level control-loop controller. The node is therefore stronger associated with the field-area of a building automation system. LON would even include possible ways to face the challenges in the computational area by providing so-called host-based nodes in which the LON-node only provides the communication and another microcontroller that fits the requirements in a better way is responsible for the actual calculations [Die97, p. 66-68].

And it is surely true that in a theoretical way the communication with the outside of a building, automatic analysis of data and the alteration of set-points and/or schedules is strongly connected with the management domain of a building automation system which makes a dedicated management node the more suitable choice for the intended functionalities.

But the fact that even a low-level control node with minimal specifications in terms of computational power of a LON-network could meet the most-crucial requirement in a sufficient way shows that a demand response controller that works within a building automation system may be an easy to reach and very realistic goal for future building automation systems (or future adaptions of already existing systems).

6 Conclusion and outlook

The last chapter of the thesis is divided in two parts. The first subchapter includes a summary of the presented work and the main results. An outline of the main contribution is given. The last part gives an outlook how the automation of buildings and especially the connection between building automation and smart energy grids can lead to a new sight on buildings as active nodes for the power grid.

6.1 Using building automation systems for the energy system

The presented work followed a top-down approach for determining the possibility on how buildings, with the main focus on commercial buildings, can be used as demand response storages for the smart power grid. Starting with a literature comparison on the actual state of the art that included both fields of technology that are the focus of the work namely the area of energy storages, especially demand response technologies and their usage as virtual storages, and the field of building automation for influencing the devices inside buildings.

The analysis shows that various different storage technologies exist, mostly either for long term storage of energy or extremely short term storages (seasonal storages like hydro-power vs. short-term storages like super-capacities). The first manages its functionality by mainly transforming the electrical energy into another manifestation, for example kinetic energy (flywheel) or potential energy (hydro storages) via electrical devices like pumps or motors. This leads to transformation losses but is the key ability for storing energy over longer time periods. The second on the other hand does not have the need of transformation as superconducting devices are able to store the electricity as it is. The area “in between” those technologies – namely storage capacities for smaller amounts of energy for periods of hours or days is not really existent. If energy is needed in periods of shortage additional generation power is necessary – a surplus of energy can often not be used and either has to be given away for free or avoided by switching off generation units. Especially the second scenario can be problematic as the operators of generation units need a guaranteed quantity of sales for being profitable.

Beside the stronger integration of renewables also other applications become more and more interesting inside smart power grids, for example flattening of wind profiles or compensating the prediction error of wind or solar power or avoiding short-period grid-bottleneck situations. All of them do neither need very long nor very short periods of storage potential. The main applications regarding the flattening of wind and other renewable profiles deal with the requirement of storing energy for minutes or hours.

Demand response algorithms and methods propose the altering of the electrical load to gain a virtual storage effect. By switching the load off in times when the generated amount of energy does not suffice the need can be interpreted as "taking energy out" of a virtual storage. The same parallel can be drawn in the opposite situation where switching on of additional loads can be seen as "putting energy" into a virtual storage. Different works have investigated the possibility to use significantly slower processes than the processes inside the power grid to exploit the slower time constants to get such virtual storage effects. This processes can be located for example in thermal processes like heating or cooling which are often controlled or even executed (pumps, ventilation) by electrical powered devices and feature very slow changing internal parameters (for example temperature).

As this work was mainly focused on the building domain and how buildings could enrich different applications inside a smart power grid a detailed and exhausting analysis was included to prove that today's communication solutions would fit for the proposed use case. This analysis included an in-depth analysis and comparison of so-called "smart grid communication protocols" and came to the conclusion that the most promising candidate(s) for the communication inside a smart power grid would are either OpenADR (in combination) with SIP (Session Initiation Protocol) or ZigBee. It also became clear that not "one" protocol can be found that would support every use case inside a smart power grid, but the choice has to be heavily depending on the targeted application. Nevertheless it could be shown that the communication side of a smart power grid is very well developed and therefore the sole focus of this work on the application side can be justified.

The third section dealing with state of the art technologies gives a spotlight on the potentials building automation could have by controlling specifically the domain of load and energy management. Several approaches are described and the conclusion has to be that the different systems are very well able to control the various aspects of energy consumption.

Based on the analysis of the state of the art the conclusion was drawn that buildings might be potential candidates to provide a virtual storage effect for smart power grids that fit to the needs of prediction error compensation for wind generation profiles. The starting point of the work that is presented here is on investigating a way how automated commercial buildings could be turned into active nodes for the smart power grid. In that regard the main hypothesis is that buildings that are equipped with building automation and control systems for controlling their internal devices can be seen from the outside as one single load that can be influenced by the smart power grid. In this process a new possibility to describe and model demand response storages was developed. It is based on the idea to describe the ability to increase or decrease the demand of used energy during specific timeslots. Each of these smaller entities of energy is given an additional (temporal) flexibility.

Based on this model a realistic use case in today's power grid was formulated to show the possible impact the proposed solution could have not only in the future but already today. To evaluate the potential of buildings the work presented a detailed analysis of exactly how buildings could become an active part of the power infrastructure was necessary. This scenario is based on the assumption that the internal capacity of different units (in this case buildings) so-called demand-response storages could be made possible. These devices are able to alter their energy consumption based on incentives of the smart power grid. The analysis is based on a simplified building model that is used to show the general abilities and functions a building could provide for the power grid and how buildings could become demand response storage for the power grid. The analysis shows that taking the different requirements of the power grid and building nodes into account it is theoretically possible to compensate the prediction error of wind prognosis with the help of a number of storage units.

On that behalf the exact nature of the error of the wind prognosis is first analyzed before three different sub-scenarios are shown. Following an evaluation it is shown that compared to the actual number of existing commercial buildings in Austria only a small number of active buildings would be necessary to compensate the prognosis error of wind and therefore make wind generation a perfectly predictable energy generation form. The analysis on larger groups of buildings showed that about 10% of the existing commercial building would suffice to make wind generation a perfectly predictable source of energy. In a sub section the challenge of scheduling the activation of a number of distributed demand response storages and the load shedding of buildings is tackled. The comparison of different scheduling strategies shows that while all of them are feasible a direct correlation between performance and necessary amount of communication and information exchange between the units can be derived. The chapter concluded that buildings as demand side storages could therefore be part of a realistic use case scenario as the analysis showed the potential buildings could have for the power grid.

After the analysis of bigger groups of buildings and their potential the work concentrated on single buildings and how each of them could be integrated into the proposed system. The first question to answer was: “Which of the processes inside a building is a possible and technical feasible candidate for load shedding?” Due to their long time constants, controllability by existing building automation and control systems and available mathematical models the heating, ventilation and air-conditioning (HVAC) subsystem was chosen as controllable load for a proof of concept analysis.

With the respective HVAC system the parameters of temperature and the level of CO_2 in the building’s inside air is controllable. On base of these parameters the concept of virtual storing inside a building is shown and appropriate prediction models for the temperature development especially inside unheated (or not cooled) buildings are introduced. These simulation and prediction models are necessary to synchronize the load shedding demand of the power grid with the internal state of the buildings. It is shown that the simulations and prediction unit can foresee possible development of the internal temperature if the building would switch off its specific loads (in this case the heat-pump) for a specified amount of time.

The predicted parameters can then be used with the help of a rule-set to decide if the load shedding is possible in the specific situation or not. An example rule-set is presented which is based mainly on the two parameters temperature and relative humidity of the inside air. The German industrial standard (Deutsche Industrie Norm - DIN) defines a so-called comfort-area for temperature and humidity. In these standards it is defined that the air parameters inside a building have to be kept inside the given limits. It is shown that these rules can be applied for the proposed usage as rule-set inside a building that acts as active node for the smart power infrastructure.

Clearly the quality of the prediction and therefore the results of the decision process are heavily depending on the underlying simulation results. To make the decision fast and the implementation possible even on low profile processing units two kinds of existing temperature models for buildings are presented and compared. It is shown that both of them bring reasonable results for the short periods of time they need to predict. But it is also shown that the more accurate of the two models (lump-based-model) needs a much higher amount of preliminary knowledge as well as computational effort. This knowledge either needs detailed information about the physical structure of the building or detailed measurement data from inside the building to calculate the appropriate information. As this is in many cases not a feasible way due to the sheer amount of information that would be needed for setting up the system another possibility could be developed. In addition also a very rudimentary model for the ventilation of buildings could be derived.

In the work it could be shown that even the most basic model for a building's temperature behavior could be used to retrieve the needed prediction data in a sufficient precision. In addition a mechanism was introduced that would keep the prediction model as accurate as possible, even if the building's physical parameters slightly (different behavior based on change of seasons) or even abruptly (new insulation/windows etc.) change over time. It therefore could be shown, that load shedding is a possible option on a static non-changeable model but certain model parameters can be introduced in an adaptable way. In this respect the calculated parameters are compared with the measured values for the appropriate point of time and if the error is too big a totally new simulation parameter can be calculated. This self-adapting ability brings the advantage of a quick and easy setup for the building and an error correction in times when the calculated data is too different from the measured value.

To fulfill the task of simulating and predicting as well as the decision making a new functional unit was proposed, called the Demand Response Controller for buildings. This functional unit was located between the main building automation system that acts as control entity over the building and a central unit that manages the scheduling of the different virtual storages. The proposed demand response controller unit and its structure as well as possible application requirements were laid out in detail for later proof of concept implementations to show the feasibility of the approach. It was intentionally not defined if the demand response controller should be part of the building automation system itself or a physical unit itself. It is therefore thinkable to either provide an additional physical unit (hardware and software) that connects the smart power grid to the building automation system or integrate the controller as software unit /agent inside the building management.

A further step included a feasibility study based on a simulation framework in which the described processes were implemented and tested. The results showed that the developed workflow in regards of load shedding requests, simulating, decision making and (if necessary) adapting of the simulation parameters is working in the proposed way.

In an additional experiment the most challenging subtask of the whole process – namely the prediction of an internal parameter and the (sometimes) necessary adaption of the model parameters (the self-learning component) were also implemented in a field device of a building automation system. This experiment showed that even the most defining task of the intended functionality for a demand response controller could be realized on a "low-profile" field device. The last step was necessary to prove that the proposed solution is feasible in a technical point of view.

In conclusion it can be stated that in regard of the smart grid infrastructure and the ideas of introducing controllable buildings the efforts show that a single decision making unit could ensure the comfort of the inhabitants and users of the building while offering the buildings internal processes as virtual electricity storages to the smart power grid. The decision making unit has to be based on prediction models for all system parameters that are exploited as energy storages for demand shifting applications. These simulation models were only partly covered in the presented work, but a general mechanism was developed that could help to ensure the integrity of the used behavioral models by introducing a self-adapting algorithm into an error correction loop of the algorithm. This mechanism is intended to be used for more simple models than normally used, as the setup and maintenance of more complex building models need a greater amount of effort. A simple to setup and use model that can produce sufficient accurate values is therefore the way to go. Various other works propose the usage of building models inside so-called building agent units, but a self-adapting approach and the definition of its workflow as well as an investigation on its overall functionality (through simulation) as well as a technical implementation is clearly a big step into the direction of a full integration of commercial buildings inside the smart power grid.

6.2 Buildings as demand response storages – a chance for the smart grid

Within the presented work, today’s technical possibilities are consequently thought further and a technical feasible and also operational possible development path to include much needed additional storage capacity to the electrical power grid is laid out. The main research paradigm was to open a possibility that needs as less technical and infrastructural construction and therefore investment as possible. With including today’s possibilities of communication in combination with the existing power infrastructure a new way was found how storage capacity could be provided by interconnecting buildings and the power grid. The functionality and overall benefit was shown on the basis of a specific application scenario as well as a simulation of the workflow and an experimental approach.

It has to be said clearly that from the power grid’s point of view demand response storages and shiftable loads like buildings are very unlikely to fulfill the tasks and requirements needed for the primary grid control energy pool. This is mainly because of an overall uncertainty that never can be avoided (what if all storages are empty, what if the connections break) and the low responsiveness. But by providing much needed balancing power for renewable energy sources, buildings as storages could free balancing capabilities that are – at the moment – necessary to guarantee the load profile of renewables. This can be achieved by the possibility to schedule the activation of each storage unit. This additional pool of storages can be used to free capacities that are now necessary to provide back-up generation potentials for renewable energy source. Although the presented work improves and expands existing approaches there are still unsolved challenges and open points that deserve a more detailed analysis.

The presented work first analyzed a possible usage for demand response storages by outlining the necessity to reduce the prognosis error of wind generation for reducing the (at the moment) necessary amount control energy for the power grid. This potential is gained mainly by freeing control energy that is bound to the renewable generation profile, because its main functionality is taken over by storage units. Thus not only the grid stability could be provided but also additional balancing energy is made available and therefore a financial benefit could be generated.

While the stability issue and questions on how to schedule the load shifting optimally were covered in detail within the work, the financial aspect was only investigated very shortly. The work mostly covered a bare bone estimation based on financial approximations for the stabilizing energy. A more detailed analysis on how the presented approach could affect the energy prices on the market for control energy is necessary. In this context it has to be pointed out that the direct influence of the described approach on the power market was also not part of this work and surely needs a deeper analysis. By freeing up balancing power some kind of "backlash" on the market can be assumed. As the work was focused on the technical aspects of the approach a number of questions regarding the monetary side of the approach had to be excluded. The power grid itself as dynamic system shows heavily influences from the power market side (especially since the liberation of said markets) even without the communication interconnections that a smart power grid provides between all stakeholders. So it is safe to assume that there is a hidden layer of influences from the market side that goes further than the challenge to "simply" stabilize the power grid by balancing demand and generation.

A smart grid that supports and interacts on the power market has to provide possibilities e.g. to transfer electrical power over inter-continental distances. The shortcomings on deep analysis at the market side of the whole system "smart grids" cannot be held against this and other similar works as also in other works on similar topics, this side is – deliberately – left out. Different causes can be made out, one of them most prominently (and this is also the case for this work): In most cases the evaluated systems, approaches and models are in a development status that focuses on questions of stability and feasibility from a technical point of view. The question here is if the intended application can be implemented and a solution can be presented and if the proposed system is simply possible and feasible operationally and technically. Without technical solutions for parts and aspects of the system smart power grid - in itself difficult to understand and grasp - that at least show how the intended application could work, most expected and unexpected side effects would not be made visible as stimulatory evaluations lack the granularity and accuracy to fully display all processes inside a smart power grid. This should show that without the technically evaluated and developed concepts ready, some aspects (in this case the economical side and its effects on the power infrastructure) cannot be evaluated.

Experimental approaches with partly implemented applications and heavily equipped with measurement devices are necessary to evaluate the approaches and some of these experiments have already come to fruition. As the smart grid itself is not just an additional component for an existing system but more an upgrade for a (extremely complex) technical system each of these experiments have to be executed with caution and foresight to avoid the introduction of flaws and instabilities into a balanced system. Some of said experiments will show a benefit (some of the experiments that were influenced by the authors work the funded projects [Bed12] and Building2Grid-B2G [33]) some might not. All of the results must be evaluated thoroughly and the right conclusions have to be drawn. In this case "right" does primarily stands for "have a benefit in comparison with the existing solution". Introducing smart grid applications and all their additional entities, workflows and processes into the power infrastructure has to be done carefully and in awareness of the fact that the probabilities for unforeseen faults and errors rises with the number of included units. The benefits gained have to significant and the experimental approaches have to show that.

Business models in itself are an open point of sorts in this whole approach. The questions if and how building operators can benefit from the fact that the processes inside the buildings are opened for smart power applications can still not be seen as solved. But from another point of view it is also thinkable that there does not have to be a discussion on this point at all. If the approaches prove realistic and feasible it is thinkable that new standards, laws or regulatory requirements demand certain flexibilities in terms of load profile of newly built buildings. Planned commercial buildings with a predicted high peak demand of energy could be constrained to include a certain amount of storage capacity to help flatten out the load peaks. In this case the building operator has no other choice and has to provide the communication interfaces for meeting these requirements. In this context a possible requirement could be that every building has to provide a communication link that follows an open and clearly defined interface specification and has to provide its internal capacity for regulatory issues on demand response base. This scenario would make the participation mandatory.

Another way could be to hope for a voluntary participation by providing certain benefits. Here it would be important that users do not feel cheated - providing special tariffs for users that agree to connect their building to the smart grid would be a way. If the possibility should exist that users are able to “opt-out” if some commands do not fit into their internal strategy is part of another discussion. Financial incentives could help to increase the number of possible demand response storages up to a critical mass that really can make an impact. Before that the whole mechanism could be implemented in smaller grid section to show its feasibility on grander scale to counteract surely existing feelings that the normal processes and procedures inside the building as well as the user’s comfort are not harmed in any way.

The communication links between all entities has to be optimized and brought up to an industry-like standard in terms of pure technical details (e.g. availability, bandwidth etc.). But that is not enough. Another open point can be pointed out by ensuring the existence of open standards for guaranteeing interconnection and interoperability of all the different grid components. Especially if the inclusion to a smart power grid becomes more or less mandatory – a scenario that at least is still a possibility. It has to be said clearly that in this special point it surely is not enough to just define the rules and lay them out in extensive specification documents, but at least some kind of reference technology has to be developed. As this is a restriction for the different stakeholders it is necessary to build an open consortium that takes care of the definition. But not only the grid regulators and grid operators as quasi-monopolists in their (geographic) area have to take part in that process but also vendors from the domain of building automation and building design and other domains that may be part of this challenge (e.g. car companies with the electrical vehicles). It is even thinkable that the connection to the smart power grid opens up whole new concepts and ideas that different units (e.g. buildings or cars) are designed in a different way than today – not only optimized for their “intended” use but with a strong secondary focus on a special ability that is needed by the smart power grid and could provide an additional income for the operators of said units. Energy storing technologies that are provided for the smart power grid would be one of those “secondary” abilities that could generate a benefit. Buildings that do not only include the necessary storage capacity for the “normal” usage but include a surplus capacity to gain an advantage when used as demand side storage for the smart power grid could be the future. In fact within the smart grid model region in Salzburg a state of the art residential building called “Rosa Zukunft” was developed that includes (besides other smart grids test applications) bigger-than-necessary storages for warm water (in comparison to conventional dimensions) especially to support demand response applications [31,32].

In actual models of power grids every connected unit has one specific and distinct role. Most of the units either act as consumers and a smaller number as generation units. Only some units unite these two aspects and can either act as consumers or generators. The last category mainly consists of storage units. But storage capacity is not necessary to unite the two different role models in one unit - buildings with installed renewable energy sources (e.g. photovoltaic) and inject the surplus into the grid during day and take the necessary energy from the grid during night would fall into this category. These buildings have a load profile as well as a generation profile. Without storage capacity these two profiles cannot be exchanged in short order, nevertheless is the unit a load during night and a generation unit during the day. Even without information exchange and smart grid applications the strict role models are somewhat softened and changing. The interconnection of different units, stakeholders and participants - either autonomous or manual controlled - starts to make these changes even faster and more visible. It is obvious that the power infrastructure is changing as a whole. The description of the single units and their abilities, behavior and requirements also needs some kind of streamlining. Maybe the model presented in this work for shiftable energy demand could be adapted for this purpose in the future. It is thinkable, that not only the demand can be modeled in such a way but also the generation.

The energy infrastructure is changing but it is not a revolutionary change. The old infrastructure is not torn down and a totally new structure is built. The old and the new have to interact and coexist and in the end the new smart grid has to take over most functionality a traditional power infrastructure provides. All of these changes have to be made more or less transparent, in a way that all existing (and not adaptable) participants still have the same experience as before, while innovative and new participants can share the benefits of a smart power grid with all its advantages. So it cannot be named revolution as this implicates an abrupt change of the state.

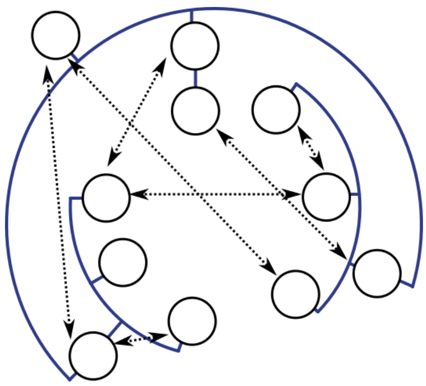


Figure 6-1: Communication between nodes in a hierarchical power grid

The whole process needs therefore the characteristics of an evolution of the grid. This implicates the change from steep hierarchical structures with strictly defined role models to a flatter or even nonexistent hierarchy with softer role models, which could be even changed on a daily or even shorter basis. While the main power infrastructure with power lines, transformers, etc, will and has to stay as it is, the different entities will come closer to each other as it will be possible for them to communicate with each other on a peer-to-peer basis across all hierarchical borders. In Figure 6-1 this expected scenario is illustrated and it is shown how the different entities are still hierarchically connected via the conventional power infrastructure (solid) whereas communication exchange (dotted) is allowed across all layers.

The information exchange between the units will make newer and more complex application scenarios possible and the smart grid then can be really named “smart”. As it is based on an existing infrastructure these changes might not be visible from the start, but in a few years the power grid will have made another evolutionary step to an infrastructure that interconnects its participants on an equal basis to enable energy and information exchange for stabilizing the power grid itself and include a majority of renewable energy sources. Some of the mechanisms that were developed in this thesis might be part of this future grid.

References on scientific publications

[ANSI07] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (2007), *Addendum e to ANSI/ASHRAE Standard 135-2004*

[Bar04] Barton J.P., Infield D.G., *Energy storage and its use with intermittent renewable energy*, Energy Conversion, IEEE Transactions on , vol.19, no.2, pp. 441- 448, June 2004, ISSN 0885-8969

[Bed12] Hettfleisch C.; Pollhammer K.; Kupzog F.; *Bed - Balancing Energy Demand with Buildings*; Schriftenreihe 29/2012 "Berichte aus Energie- und Umweltforschung", Hrsg. BMVIT; http://www.hausderzukunft.at/results.html/id5937 [2013/06/26]

[Bra06] Brauner, G. et al.: *Verbraucher als virtuelles Kraftwerk*, Berichte aus Energie- und Umweltforschung 44/2006, BmVIT, Vienna, 2006

[Bra13] Bramauer J., *Adaptive Regelkonzepte für Smart Buildings*, Bachelorthesis, German, Technical University Vienna, 2013

[Bur04] Burgstaller W., Rausch T.: *Gatewayless Communication between LonWorks and BACnet*, Proceedings of IEEE International Workshop o Factory Communication Systems 2004, 2004, pp. 361-364

[Dei08] M. Deindl, C. Block, R. Vahidov, D. Neumann, “Load Shifting Agents for Automated Demand Side Management in Micro Energy Grids”, Second IEEE International Conference on Self-Adaptive and Self-Organizing Systems, 487-488, 2008

[Deu13] T. Deutsch, T. Leber, F. Kupzog, Ö. Karacan, and A. Einfalt, “Versuchsanlage Intelligentes Niederspannungsnetz - German Paper,” IEWT 2013, Vienna, Austria, 2013.

[Die97] Dietrich D., Loy D., Schweinzer H. (Hrsg.): *LON-Technologie – Verteilte Systeme in der Anwendung*, Verlag Hüthig, Heidelberg, 1997, ISBN 3-7785-2581

[Die01] Dietrich D. (Hrsg.), Fischer P. (Hrsg.): *LonWorks®- Planerhandbuch*, Berlin, Offenbach: VDE Verlag, 2001, ISBN 3-8007-2599-1

[DIN13779] DIN, EN. "13779: Lüftung von Nichtwohngebäuden–Allgemeine Grundlagen und Anforderungen an Lüftungs-und Klimaanlagen." Berlin: Beuth (2005).

[DIN15288] DIN, EN. "15288 (2008): Schwimmbäder – Teil 2: Sicherheitsanforderungen an den Betrieb“, Berlin: Beuth (2008).

[DIN15251] DIN, EN. "15251 (2007): Eingangsparameter für das Raumklima zur Auslegung und Bewertung der Energieeffizienz von Gebäuden–Raumluftqualität, Temperatur, Licht und Akustik." Berlin: Beuth (2007).

[Ein12] A. Einfalt, F. Kupzog, H. Brunner, and A. Lugmaier, “Control Strategies for Smart Low Voltage Grids – The Project DG DemoNet-Smart LV Grid,” 2012.

[Ern07] Ernst, B., Oakleaf, B., Ahlstrom, M., Lange, M., Moehrlen, C., Lange, B., Focken, U., and Rohrig, K. (2007). *Predicting the Wind*. IEEE Power and Energy Magazine 5, 78–89.

[Fab05] Fabbri, A., Gomez San Roman, T., Rivier Abbad, J., and Mendez Quezada, V.H. (2005). *Assessment of the Cost Associated With Wind Generation Prediction Errors in a Liberalized Electricity Market*. IEEE Transactions on Power Systems 20, 1440–1446.

[Fan13] Fan, Z. ; Kulkarni, P. ; Gormus, S. ; Efthymiou, C. ; Kalogridis, G. ; Sooriya-bandara, M. ; Zhu, Z. ; Lambotharan, S. ; Chin, W.: Smart Grid Communications: Overview of Research Challenges, Solutions, and Standardization Activities. In: Communications Surveys and Tutorials, IEEE (2013), Feb., pp. 21-38. { ISSN 1553-877X

[Fas13] M. Faschang and F. Kupzog, "Interfacing vehicle charging systems with user and grid requirements," Informatik-Spektrum, vol. 36, no. 1, pp. 27–34, 2013.

[Fis09] Fischer P. (Hrsg.): *Gebäudeautomation – Die unsichtbare Effizienz*, Promotor Verlags- und Förderungsges. mbH, Karlsruhe, 2009

[Gam11] Gamauf, T., Leber, T., Pollhammer, K., and Kupzog, F. (2011). *A generalized load management gateway coupling smart buildings to the grid*. In AFRICON, 2011, pp. 1–5.

[Gra07] Granzer W., Kastner W.: *BACnet over KNX*, Prceedings of the Konnex Scientific Conference, 2007

[Gen82] G. Genta, *Spin tests on medium energy density flywheels*, Composites, Volume 13, Issue 1, January 1982, Pages 38-46, ISSN 0010-4361, 10.1016/0010-4361(82)90169-0.

[Ger11] C. Gerdenitsch, J. Schrammel, S. Dobelt, and M. Tscheligi, "Creating Persuasive Technologies for Sustainability Identifying Barriers Limiting Target Behavior," 6. th Annual Conference on Persuasive Technology, 02.-05.06.2011, Ohio, 2011.

[Ham11] Hambeck C., Mahlknecht S., Herndl T., *A 2.4μW Wake-up Receiver for wireless sensor nodes with −71dBm sensitivity,* Circuits and Systems (ISCAS), 2011 IEEE International Symposium on, vol., no., pp.534-537, 15-18 May 2011, E-ISBN : 978-1-4244-9472-9 Print ISBN: 978-1-4244-9473-6

[Han07] Handa, T.; Roesener, C.; Ichimura, J.; Nishi, H.; , *KNIVES: Network based Demand and Supply Control System - Enhancement for Network and Environmental Affinity*, Industrial Informatics, 2007 5th IEEE International Conference on , vol.2, no., pp.1171-1176, 23-27 June 2007

[Her12] Herzig H., *Algorithmus zum Scheduling von Demand-Responsefähigen Energiespeichern*, Master thesis, German, Technical University Vienna; 2012

[Heu07] Elektrische Energieversorgung : Erzeugung, Übertragung und Verteilung elektrischer Energie für Studium und Praxis ; mit 36 Tabellen und 75 Aufgaben mit Lösungen / Klaus Heuck ; Klaus-Dieter Dettmann ; Detlef Schulz. - 7., vollst. überarb. u. erw. Aufl. . - Wiesbaden : Vieweg, 2007. - XXIII, 762 S. . - (Studium und Praxis) ISBN 978-3-8348-0217-0 -

[Hub04] Hube W.; *Prädiktive Wärmeflussregelung solaroptimierter Wohngebäude mit neuartigen Verschattungs- und Speichersystemen*, 2004, Dissertation Universität Kaiserslautern

[IEA08] International Energy Agency: World Energy Outlook 2008, IEA 2008, Paris,

[IEAE08] Institut für Elektrische Anlagen und Energiewirtschaft, TU Wien (2008). Vorbereitung der Implementierung eines österreichischen virtuellen Ökostrom Kraftwerks – Technisch-wirtschaftliche Konzeption eines modernen Energieversorgungsunternehmens - Endbericht, Projektnummer 811261.

[Jun12] M. Jung, T. Hofer, S. Döbelt, G. Kienesberger, F. Judex, and W. Kastner, "Access control for a Smart Grid SOA," in Proceedings of the 7th IEEE Conference for Internet Technology and Secured Transactions, London, UK, Dec. 2012.

[Kam10] M. Kamachi, H. Miyamoto, and Y. Sano, "Development of Power Management System for Electric Vehicle i-MiEV," in Power Electronics Conference (IPEC), 2010 International, 2010, pp. 2949–2955.

[Kas04] Kastner W., Palensky P., Rausch T., Roesener Ch.: *A Closer Look on Today's Home and Building Networks*, Proceedings of the 7th Conference in Africa, AFRICON, 2004, Vol. 2, pp. 1239 - 1245

[Kas05] Kastner W. et al.: *Communication Systems for Building Automation and Control*, Proceedings of the IEEE, Vol. 93, No. 6, June 2005

[Kie11] G. Kienesberger, M. Meisel, and A. Adegbite, "A Comprehensive Information Platform for the Smart Grid," in Proceedings of IEEE AFRICON 2011, Livingstone, Zambia, September 2011.

[Kre10] S. Kreutz, H.J. Belitz, C. Rehtanz,"The impact of Demand Side Management on the residual load", Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES, pp. 1-5

[Klo07] Klobasa, M., Erge, T., and Wille-Hausmann, B. (2007*). Integration von Windenergie in ein zukünftiges Energiesystem unterstützt durch Lastmanagement*. Endbericht im Auftrag des Bundesministeriums Für Umwelt, Naturschutz und Reaktorsicherheit, Karlsruhe: Fraunhofer Institute Für System-und Innovationsforschung.

[Kol13] A. Kollmann, C. Amann, C. Elbe, and V. Heinisch, “Lastverschiebung in Haushalt, Industrie, Gewerbe und kommunaler Infrastruktur– Potenzialanalyse für Smart Grids-LOADSHIFT,”¨ IEWT 2013, Vienna, Austria, 2013.

[Kup06] F. Kupzog, “Self-controlled Exploitation of Energy Cost saving Potentials by Implementing Distributed Demand Side Management,” in Industrial Informatics, 2006 IEEE International Conference on, 2006, pp. 375–380.

[Kup07] F. Kupzog, C. Roesener, *A closer look on load management*, Industrial Informatics, 2007 5th IEEE International Conference on}, vol. 2, pp. 1151—1156, iss. 1935-4576, 2007

[Kup08] Kupzog F.: *Frequency-responsive load management in electric power grids*, PhD Thesis, Technische Universität Wien, 2008

[Kup11] Kupzog F., Sauter T., Pollhammer K., *IT-Enabled Integration of Renewables: A Concept for the Smart Power Grid*, EURASIP Journal on Embedded Systems, vol. 2011, Article ID 737543, 8 pages, 2011. doi:10.1155/2011/737543

[Kup11_2] F. Kupzog, H. J. Bacher, M. Glatz, W. Pruggler, A. Adegbite, and G. Kienesberger, “Architectural options for vehicle to grid communication,” Elektrotechnik und Informationstechnik, vol. 128, no. 1-2, pp.47–52, 2011.

[Kup13] F. Kupzog, T. Leber, G. Zucker, F. Judex, and L. Lippert, “Practical Utilisation of the Load Shifting Potentials in a Rural Austrian Municipality – Evaluation and Conclusions,” in 8. Internationale Energiewirtschaftstagung an der TU Wien – IEWT 2013, Vienna, Austria, February 2013.

[Leb11] T. Leber, M. Meisel, T. Gamauf, M. Pongratz, and F. Kupzog, “Preparations for Demand Response on a Municipal Level,” in AFRICON, 2011, 2011, pp. 1–5.

[Loy01] Loy, D. [Hrsg.]; Dietrich, D. [Hrsg.]; Schweinzer H.-J. [Hrsg.].: *Open Control Networks: LonWorks/EIA 709 Technology*; Springer US; Auflage: 1 (31. Juli 2001); 2001; ISBN 978-0792374060

[Lug09] Lugmaier A., Fechner H., Prüggler W., and Kupzog F., “National Technology Platform - Smart Grids Austria,” in Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on, 2009, pp. 1–3.

[McD04] McDowall, J.: *High power batteries for utilities - the world's most powerful battery and other developments*, Power Engineering Society General Meeting, 2004. IEEE, vol.2, no., pp.2034-2037 Vol.2, 10-10 June 2004, Print ISBN: 0-7803-8465-2

[Mei13] M. Meisel, T. Leber, K. Pollhammer, F. Kupzog, J. Haslinger, P. Wachter, J. Sterbik-Lamina, M. Ornetzeder, A. Schiffleitner, and M. Stachura, “Erfolgsversprechende Demand-Response-Empfehlungen im Energieversorgungssystem 2020 – German Paper,” Informatik-Spektrum, vol. 36, no. 1, pp. 17–26, 2013.

[Min09] Mine, G., Handa, T., Tachikawa, T., Watanabe, Y., Ichimura, J.I., and Nishi, H. (2009). Evaluation of cooperative demand control system on micro grid. In Industrial Electronics, 2009. IECON’09. 35th Annual Conference of IEEE, pp. 3593–3598.

[NeC92] Neuron C Programmer’s Guide – Revision 2, Echelon Corporation Inc., 1992

[Nit00] Nitsch J. et al.:Klimaschutz durch Nutzung erneuerbarer Energien : Forschungsbericht 298 97 340 / von Joachim Nitsch .... - Berlin : Erich Schmidt, 2000. - XVI, 519, 37 S. . - (Berichte / Umweltbundesamt ; 2000,2) (Umweltforschungsplan des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit), ISBN 3-503-05888-5 - . - Rep.: UBA FB 99 126

[Nov08] Novak T.: *Functional Safety and Security in Building Automation and Control Systems*, PhD Thesis,Technische Universität Wien, 2008

[Pal11] Palensky, P., and Dietrich, D. (2011). *Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads*. IEEE Transactions on Industrial Informatics 7, 381–388.

[Pall11] Palloti, E. ; Mangiatordi, F: Smart Grid Cyber Security Requirements. In: Environment and Electrical Engineering (EEEIC), 2011 10th International Conferenceon (2011), May, pp. 1-4. ISBN 978-1-4244-8779-0

[Par07] Park T. J., Chon Y. J., Park D. K., Hong S. H.: *BACnet over ZigBee - A new approach to wireless datalink channel for BACnet*, Proceedings of the 5th IEEE International Conference on Industrial Informatics, INDIN, 2007, Vol. 1, pp. 33-38, Vienna, June 23-27 2007

[Pol11] Pollhammer, K., Kupzog, F., Gamauf, T., and Kremen, M. (2011). *Modeling of demand side shifting potentials for smart power grids*. In AFRICON, 2011, pp. 1–5.

[Pol12] Pollhammer, K.; Wendt, A.; *BED - Balancing Energy Demand with Buildings*; in Tagungsband ComForEn 2012 (invited); 2012, S. 110 - 115.

[Pol13] Pollhammer, K., Kienesberger, G., Faschang, M., Meisel, M., Wendt, A., Leber, T., & Dimitriou, P. (2013, November). Smart energy grids in Austria-innovative solutions and concepts. In Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE (pp. 7050-7055). IEEE.

[Ras11] Rasmussen, C.N. (2011). *Energy storage for improvement of wind power characteristics*. In PowerTech, 2011 IEEE Trondheim, pp. 1–8.

[Reb02] Rebhan E.: Energiehandbuch – Gewinnung, Wandlung und Nutzung von Energie; Energiehandbuch : Gewinnung, Wandlung und Nutzung von Energie; 202 Tabellen / Eckhard Rebhan (Hrsg.). - Berlin [u.a.] : Springer, 2002. - XXXV, 1161 S. . - (Engineering online library)(VDI-Buch), ISBN 3-540-41259-X -

[Rei07] Reinisch, C., Kastner W., Neugschwandtner G., Granzer W., *Wireless Technologies in Home and Building Automation*, Proceedings of the 5th IEEE International Conference on Industrial Informatics, INDIN, 2007, Vol. 1, pp. 93-98, Vienna, June 23-27 2007

[Rei09] Reißenweber B., *Feldbussysteme zur industriellen Kommunikation*, 3. Auflage, Oldenbourg Industrieverlag, München, 2009

[Roe05] Roesener, C.; Palensky, P.; Weihs, M.; Lorenz, B.; Stadler, M.; , *"Integral resource optimization network - a new solution on power markets,"* Industrial Informatics, 2005. INDIN '05. 2005 3rd IEEE International Conference on , vol., no., pp. 578- 583, 10-12 Aug. 2005

[Rya89] Ryan J.L., *Home Automation*, Electronics & Communication Engineering Journal, Vol.1, Iss. 4, pp. 185-192, July/August 1989

[Sau01] Sauter, T. [Hrsg]; Dietrich, D. [Hrsg], Kastner, W. [Hrsg].:*EIB: Installation Bus System;* Publicis Publishing; Auflage: 1. Aufl. (21. Dezember 2001); ISBN 978-3895781759

[Sau11] Sauter, T., Soucek, S., Kastner, W., and Dietrich, D. (2011). The Evolution of Factory and Building Automation. IEEE Industrial Electronics Magazine 5, 35–48.

[Sch11] J. Schrammel, C. Gerdenitsch, W. Reitberger, and M. Tscheligi, “Supporting Domestic Energy Reduction vis Persuasive Technology,” CIRED 2011 The 21st International Conference and Exhibition on Electricity Distribution, Frankfurt, 2011.

[Sch12] S. Schütte, S. Scherfke, and M. Sonnenschein, “mosaik - Smart Grid Simulation API,” in Proceedings of SMARTGREENS 2012-International Conference on Smart Grids and Green IT Systems, edited by B. Donnellan, JP Lopes, J. Martins, and J. Filipe, 2012, pp. 14–24.

[See12] Seewald, M.G., "Benefits of end-to-end IP for cyber and physical security," Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES , vol., no., pp.1,6, 7-10 May 2012, doi: 10.1109/TDC.2012.6281494

[Sko12] F. Skopik, T. Bleier, M. Kammerstetter, and G. Kienesberger, “Smart Grid Security Guidance: Eine Sicherheitsinitiative für intelligente Stromnetze,” in Proceedings of the 42. annual conference of the German computer society, Braunschweig, Germany, 2012.

[Sno03] Snoonian D.: *Smart Buildings*, IEEE Spectrum, Vol. 40, Iss. 8, Aug. 2003, pp. 18 – 23

[Sta07] M. Stadler, F. Kupzog, and P. Palensky, “Distributed Energy Resource Allocation and Dispatch: an Economic and Technological Perception,”International Journal of Electronic Business Management, vol. 5, no. 3, pp. 182–196, 2007.

[Sta09] Statistik Austria, Bundesanstalt Statistik Österreich, Statistisches Jahrbuch Österreichs 2009 (Jg. 59), Chapter 22, pp. 355-365, 2009, ISBN: 9783902587725

[Sta15] Statistik Austria, Bundesanstalt Statistik Österreich, Statistisches Jahrbuch Österreichs 2015, Chapter 22, pp. 372-386, 12/2014, ISBN: 978-3-902925-43-5

[Sti11] Stifter, M., Bletterie, B., Brunner, H., Burnier, D., Sawsan, H., Andren, F., Schwalbe, R., Abarth, A., Nenning, R., Herb, F., et al. (2011). *DG DemoNet validation: Voltage control from simulation to field test*. In 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe), pp. 1–8.

[Su09] Su, G.; Tan, Z.; Su, J.; *Improved lumped models for transient heat conduction in a slab with temperature-dependent thermal conductivity*; 2009; Applied Mathematical Modelling; Volume 1 Number 1, 274-283

[Tar12] Tariq, M. ; Grijalva, S. ; Wolf, M.: Towards a Distributed, Service-Oriented Control Infrastructure for Smart Grid. In: Cyber-Physical Systems (ICCPS), 2011 IEEE/ACM International Conference on (2012), April, pp. 35-44. ISBN 978-1-61284-640-8

[Val10] Vale, Z.; Morais, H.; Faria, P.; Khodr, H.; Ferreira, J.; Kadar, P.; , *Distributed energy resources management with cyber-physical SCADA in the context of future smart grids*, MELECON 2010 - 2010 15th IEEE Mediterranean Electrotechnical Conference , vol., no., pp.431-436, 26-28 April 2010

[VCO09] VCÖ [Hrsg.].: *Potenziale von Elektro-Mobilität.* VCÖ - Verkehrsclub Österreich. Wien. 2009. ISBN 3-901204-61-X

[Wan11] Wanf, J. ; Leung, V.: *A Survey of Technical Requirements and Consumer Application Standards for IP-based Smart Grid AMI Network*. In: Information Networking (ICOIN), 2011 (2011), Jan., pp. 114-119. ISSN 1976-7684

[Zig08] ZigBee Standards Organization (2008), *ZigBee Smart Energy Profile Specification*

Internet references

[1] Goldschmidt I., *The development of BACnet*, available at http://www.bacnet.org/Bibliography/SPEE-11-98.html [10/02/2010]

[2] http://www.enocean.com/en/faq/ [11/03/2011]

[3] Statistik Austria http://www.statistik.at/web_de/statistiken/preise/verbraucherpreisindex_vpi_hvpi/hauptgruppen_und_details/index.html [02/04/2010]

[4] Austrian Power Grid http://www.apg.at/ [01/08/2012]

[5] Statistik Austria http://www.statistik.at/web_de/statistiken/wohnen_und_gebaeude/bestand_an_gebaeuden_und_wohnungen/022983.html [04/06/2010]

[6] ENERGYbase http://www.energybase.at/ [01/05/2012]

[7] TRNSYS – Transient System Simulation Tool http://www.trnsys.com/ [18/12/2013]

[8] US Departement of Energy Efficiency & Renewable Energy
Main page: http://energy.gov/
Deep link: http://apps1.eere.energy.gov/buildings/energyplus/?utm_source=EnergyPlus&utm_medium=redirect&utm_campaign=EnergyPlus%2Bredirect%2B1 [18/12/2013]

[9] “Wie ein Windstoß das Stromnetz erglühen ließ”
Main page: http://www.kurier.at
Deep link: http://kurier.at/wirtschaft/marktplatz/wie-ein-windstoss-am-sonntag-das-stromnetz-ergluehen-liess/34.256.859 [05/11/2013]

[10] “Österreich hilft Deutschland mit Strom aus“
Main page: http://www.derstandard.at
Deep link: http://derstandard.at/1325485715183/Nachbarschaftshilfe-Oesterreich-hilft-Deutschland-mit-Strom-aus [03/01/2014]

[11] http://www.sipforum.org/component/option,com_docman/task,doc_view/gid,375/ [2014/01/04]

[12] Internet Engineering Task Force. Scalable Routing Design Principles, April 2013. http://tools.ietf.org/rfc/rfc2791.txt [2014/01/04]

[13] Open Automated Demand Response – Communications Specification (Version 1.0), Laurence Berkeley Laboratories, April 2009. http://openadr.lbl.gov/pdf/cec-500-2009-063.pdf [2014/02/01]

[14] U.S. Federal Enery Regulatory Comission (FERC). Assessment of Demand Response and Advanced Metering, Staff Report, January 2013. http://www.ferc.gov/legal/staff-reports/09-07-demand-response.pdf . [2014/02/01]

[15] DNP Users Group. DNP3 Secure Authentication. http://www.dnp.org/ Lists/Announcements/Attachments/7/Secure%20Authentication%20v5%202011-11-08.pdf . [2014/04/30]

[16] DNP Users Group. A DNP3 Protocol Primer. http://www.dnp.org/ . http://www.dnp.org/aboutus/dnp3%20primer%20rev%20a.pdf [2014/08/20]

[17] ZigBee PRO Smart Energy API User Guide. Revision 3.3. 14 January 2013. NXP Laboratories UK 2013 . http://www.jennic.com/files/support_files/JN-UG-3059-ZigBee-PRO-Smart-Energy.pdf [2014/09/01]

[18] Shop: WLT900 Wireless LONWORKS® Transceiver. http://www.aic-wireless.com/wlt900-wireless-lonworks-transceiver/ . [2014/08/31]

[19] Shop: LonWorks® LONG RANGE WIRELESS I/O POWERED BY AIC WIRELESS®. http://www.functionaldevices.com/pdf/datasheets/AIC_LON.pdf . [2014/09/01]

[20] (2013) Smartgrids Austria - Die österreichische Technologieplattform zum Thema Smart Grids – German Page. [Online]. Available: http://www.smartgrids.at/

[21] A. Lugmaier et al., "Roadmap Smart Grids Austria – Der Weg in die Zukunft der elektrischen Stromnetze," National Technology Platform Smart Grids Austria, Tech. Rep., December 2009, http://www.smartgrids.at/?download=254.pdf.

[22] (2013) V2G-Strategies - "*Aufbau von Vehicle 2 Grid bezogenen Entwicklungsstrategien fuer oesterreichische Entscheidungstraeger*". [Online]. Available: http://www.eeg.tuwien.ac.at/index.php?option=com wrapper&view=wrapper&Itemid=136

[23] H. Brunner. (2013) "DG DemoNet Smart LV Grid Increasing the DER Hosting Capacity of Distribution Networks - Voltage Control from Simulation to Field Test". [Online]. Available: http://www.klimafonds.gv.at/assets/Uploads/Veranstaltungen/Die-Evolution-der-Elektrizittsnetze/05120417-Die-Evolution-der-Elektrizittsnetze-Ein-Status-QuoBrunner.pdf

[24] European Commission, "Standardization Mandate to European Standardisation Organisations (ESOs) to support European Smart Grid deployment,"2011, http://ec.europa.eu/energy/gas electricity/smartgrids/doc/2011 03 01 mandate m490 en.pdf.

[25] European Commission, "Standardization Mandate to European Standardisation Organisations (ESOs) to support European Smart Grid deployment,"2011, http://ec.europa.eu/energy/gas electricity/smartgrids/doc/2011 03 01 mandate m490 en.pdf.

[26] CEN-CENELEC-ETSI Smart Grid Coordination Group, "Smart Grid Reference Architecture," ftp://ftp.cencenelec.eu/EN/EuropeanStandardization/HotTopics/SmartGrids/ReferenceArchitecture final.pdf, November 2012.

[27] The Smart Grid Interoperability Panel Cyber Security Working Group, "Guidelines for Smart Grid Cyber Security: Vol. 1-3, Smart Grid Cyber Security Strategy, Architecture, and High-Level Requirements," 2010, http://csrc.nist.gov/publications/nistir/ir7628/nistir-7628 vol1.pdf.

[28] Bundesamt für Sicherheit in der Informationstechnik (Germany), "Protection Profile for the Gateway of a Smart Metering System, V.1.2," March 2013, https://www.bsi.bund.de/DE/Themen/SmartMeter/SchutzprofilGateway/schutzprofil smart meter gateway node.html.

[29] Bundesamt für Sicherheit in der Informationstechnik (Germany), "Protection Profile for the Security Module of a Smart Metering System, V.1.0," March 2013, https://www.bsi.bund.de/DE/Themen/SmartMeter/Schutzprofil Security/security module node.html.

[30] Bundesamt für Sicherheit in der Informationstechnik (Germany), "Technische Richtlinie BSI-TR-03109, V.1.0," March 2013, https://www.bsi.bund.de/DE/Publikationen/TechnischeRichtlinien/tr03109/index htm.html.

[31] Smart Grids Modellregion Salzburg, http://www.smartgridssalzburg.at/, April 2015

[32] Rosa Zukunft, http://www.rosazukunft.at/, April 2015

[33] S. Raudaschl, B. Kaiser, R. Braun, F. Judex, G. Zucker, A. Wendt, G. Kienesberger, M. Pichler, K. Nadeje, B. Strasser; "Smart Grids Modellregion Salzburg – Building to Grid": Endbericht, Österreichische Forschungsförderungsgesellschaft mbH FFG, Juni 2013, http://www.smartgridssalzburg.at/fileadmin/user_upload/downloads/Endbericht_Building_2_Grid.pdf , April 2015

[34] Sunpower Solar Panels, http://us.sunpower.com/solar-panels-technology/x-series-solar-panels/, April 2015

Curriculum Vitae

Klaus Pollhammer
* 11.09.1982, Steyr, Austria
Nationality: Austria
Breitenfurterstrasse 378/3/28
A-1230 Vienna, Austria

Work Experience

2013-present	Research Project Engineer for "SWARCO FUTURIT Verkehrssignale Ges.m.b.H."
Dec. 2011	Guest lecture at University of Applied Sciences "FH Johanneum / Kapfenberg", Student laboratory lecture and supervision: "Field Bus Systems"
2010-2013	Teaching at University of Applied Sciences "FH Campus Wien", Full Lectures "Digital Systems" and "Microcontroller"
2008-2013	Research Assistant at the Institute of Computer Technology (ICT), Vienna University of Technology. Involvement in various research projects regarding the area of "Energy&IT" with industrial and academic partners. Topics: development of strategies and algorithms for the communication and control of future smart grids. Co-Organization and co-lecturer of the lecture "Informationstechnik Bachelorvertiefung" Supervision of BSc and MSc thesis and seminar works Student laboratory supervision: "Field Bus Systems" and "Java Smart Card Programming" Lectures: "Digitale Systeme, Übung" (main lecturer Dipl.-Ing. Dr.techn. Friedrich Bauer)
2002-2006	5 months internship at Siemens GmbH, Department PSE AS LO. Development and improvement of a Database- and JSP-based web-application for enhancing the quality management of a department of the Siemens GmbH. Development and implementation of different functionalities for Java-based applications.

Education

Feb 2009	Start of PhD studies, Technical University of Vienna (supervisor: O. Univ. Prof. Dipl.-Ing. Dr.techn. Dietmar Dietrich).
Jun 2008	Master studies Electrical Engineering/Computer Technology - Graduation from Technical University of Vienna
Oct 2006	Start of Master studies Electrical Engineering/Computer Technology Technical University of Vienna, Karlsplatz 13, A-1040 Vienna

	End of Bachelor studies Electrical Engineering - Graduation from Technical University of Vienna
Oct 2001	Start of Bachelor studies Electrical Engineering Technical University of Vienna, Karlsplatz 13, A-1040 Vienna
May 2001	1 month English language school in Vancouver/Canada
April 2001	Completion of mandatory military service
June 2000	School leaving examination (BG Untere Bachgasse Mödling)

Scientific Experience

2008/2009	Start of research activities for the PhD-thesis. PhD thesis working title: "Automated Buildings as Energy Storages", how to instrument existing building automation systems for using the thermal capacity of functional buildings as distributed energy storages.
2008	Master thesis at the Institute of Computer Technology (O. Univ. Prof. Dipl.-Ing. Dr.techn. Dietmar Dietrich, Dipl.-Ing. Dr.techn. Friederich Kupzog) Technical University Vienna „Analyse und Benchmarking von Energieverbrauchsdaten" ("Analysis and Benchmarking of Energy Consumption Data"), covers the possibilities for the arithmetical processing of energy consumption data.
2007	Seminar work in the areas of operational systems and programming microprocessors
2006	Bachelor thesis at the Automation & Control Institute (ACIN) and the Solid State Electronics Institute (FKE) at the Technical University Vienna: „Untersuchung der Steuerung eines omnidirektionalen Roboters im Zeitbereich" (ACIN, supervisor Em.O.Univ.Prof. Dipl.-Ing. Dr.techn. Alexander Weinmann) „ESD Modelle und Testmethoden" (FKE, supervisor Ao.Univ.Prof. Dipl.-Ing. Dr.techn. Dionyz Pogany)

Scientific Publications

Novak, T., Pollhammer, K. *Traffic-Adaptive Control of LED-Based Streetlights.* Industrial Electronics Magazine, IEEE 9.2 (2015): 48-50.

Novak, T., Pollhammer, K., Zeilinger, H., Schaat, S. *Intelligent streetlight management in a smart city*. In Emerging Technology and Factory Automation (ETFA), 2014 IEEE (pp. 1-8). IEEE.

K. Pollhammer, G. Kienesberger, M. Faschang, M. Meisel, A. Wendt, T. Leber, P. Dimitriou, *Smart Energy Grids in Austria - Innovative Solutions and Concepts*, in Proceedings of the IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, S. 6, Wien, 2013.

K. Pollhammer, G. Kienesberger, *Using vector-metrics for the comparison of communication technologies in smart grids*, in Industrial Electronics Society, IECON 2013 - 39th Annual Conference of the IEEE, S. 4, Wien, 2013.

G. Kienesberger, M. Berger, K. Pollhammer, *Smart Synergies - Synergetischer Ausbau von IKT-Infrastruktur für Smart Grids,* Presentation: Smart Grids Week - Salzburg 2013, Salzburg.

G. Kienesberger, M. Berger, K. Pollhammer, F. Kupzog, J. Wendlinger, M. Meisel, *Synergiepotentiale in der IKT-Infrastruktur bei verschiedenen Smart-Grid-Anwendungen*, tech. report, Institute of Computer Technology, Vienna University of Technology, 2013.

A. Wendt, M. Faschang, T. Leber, K. Pollhammer, T. Deutsch, *Software Architecture for a Smart Grids Test Facility*, in IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, S. 6, Wien, 2013.

M. Meisel, T. Leber, F. Kupzog, K. Pollhammer, M. Ornetzeder, J. Haslinger, J. Sterbik-Lamina, P. Wächter, A. Schiffleitner, M. Stachura, *Lastmanagement für intelligente Stromnetze in Österreich (Smart Response)*, tech. report, Institute of Computer Technology, Vienna University of Technology, 2013.

K. Pollhammer, A. Wendt, *BED - Balancing Energy Demand with Buildings*, in Tagungsband ComForEn 2012 (invited), 2012, S. 110 - 115.

K. Pollhammer, F. Kupzog, C. Hettfleisch, *Balancing Energy Demand with Buildings - Project BED*, in Nachhaltige Gebäude - Ansprüche, Anforderungen, Herausforderungen - Band 16, 2012, S. 85 - 90.

A. Wendt, K. Pollhammer, *Turning Buildings into Active Participants of a Smart Grid, in Tagungsband ComForEn 2012 (invited)*, S. 74, Wels, 2012.

M. Meisel, T. Leber, K. Pollhammer, F. Kupzog, J. Haslinger, P. Wächter, J. Sterbik-Lamina, M. Ornetzeder, A. Schiffleitner, M. Stachura, *Erfolgsversprechende Demand-Response-Empfehlungen im Energieversorgungssystem 2020*. Informatik-Spektrum, Bd. 19, Nr. 19, 2012, S. 17 - 26.

M. Meisel, T. Leber, F. Kupzog, K. Pollhammer, M. Ornetzeder, P. Wächter, J. Sterbik-Lamina, J. Haslinger, A. Schiffleitner, M. Stachura, *Erfolgsversprechende Demand Response Empfehlungen im Energieversorgungssystem 2020*, in Presentation: D-A-CH-Konferenz Energieinformatik 2012, Oldenburg, Deutschland.

K. Pollhammer, F. Kupzog, T.J. Gamauf, M. Kremen, *Modeling of demand side shifting potentials for smart power grids*, in Proceedings of the 10th IEEE Africon (2011), S. 5, Zambia, Afrika, 2011.

K. Pollhammer, G. Zucker, *Demand Side Management with Buildings - Introducing the projects Building2Grid and BED*, in Tagungsband ComForEn 2011, 2011, S. 28 - 32.

S. Zerawa, K. Pollhammer, T. Turek, D. Bruckner, *Simplifying routine tasks using contactless smartcards*, in Proceedings of the 10th IEEE Africon (2011), S. 6, Zambia, Afrika, 2011.

M. Pongratz, K. Pollhammer, A. Szep, *KOROS Initiative: Automatized Throwing and Catching for Material Transportation*, in Proceedings of the 1st International ISoLA Workshop on Software Aspects of Robotic Systems, S. 9, Wien, 2011.

F. Kupzog, T. Sauter, K. Pollhammer, *IT-Enabled Integration of Renewables: A Concept for the Smart Power Grid*. EURASIP Journal on Embedded Systems, Bd. 2011, 2011, S. 1 - 8.

T.J. Gamauf, T. Leber, K. Pollhammer, F. Kupzog, *A Generalized Load Management Gateway - Coupling Smart Buildings to the Grid*, in Proceedings of the 10th IEEE Africon (2011), S. 5, Zambia, Afrika, 2011.

K. Pollhammer, F. Kupzog, *Vereinfachte thermische Modelle - Grundlage für Lastverschiebung bei Gebäuden*, in Nachhaltige Gebäude Planung - Betrieb - Bewertung Band 14 (invited), 2010, S. 63 - 69.

F. Kupzog, K. Pollhammer, *Automated Buildings as Active Energy Consumers*, in Proceedings of 8th IFAC International Conference on Fieldbuses and neTworks in Industrial and Embedded Systems (FeT 2009), 2009, S. 212 - 217.