Demand Response Interoperability for the residential European Energy Market

Master Thesis

Identifying Standardization Gaps between a Demand Response pilot project and a proposed best practice

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STADTWERKE WOLFHAGEN

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Preface

This thesis concludes my life as a student at the University of Twente in Enschede for the almost eight years that have passed since I first started in 2009.

When I began with the topic about a year ago, I was not familiar with smart grids and how this topic will shape our future electricity consumption. I have learned a lot in the past year, I was especially reading paper after paper to get an understanding of this diverse issue. I was talking to companies, standardization institutes and professors, and combining all the knowledge helped me to finally finish this thesis.

All of this would not have been possible without the help and support of my graduation committee. In the beginning of my thesis I started with Maya Daneva as my first supervisor. Due to time constraints on her side we decided that I look for another supervisor. With Klaas Sikkel and Hans Moonen I found two supervisors who were patient with me and easily accepted the difficulty of me conducting my research from Berlin while they were living in Enschede. I am very grateful for your constant help and flexibility throughout this project, and for the earlier courses that we shared throughout my studies.

I further want to thank my former employer Markus Löcker, for bringing this topic to my knowledge and always helping me whenever I had anything on my mind. Your support during this thesis, but also during my work, has always been valuable.

Markus Huntzinger, project manager at Stadtwerke Wolfhagen, where I conducted part of this study, has been very friendly and open while I was analyzing their project. He always found time to help me get the information I needed and gave me valuable insight into this topic beyond what I was asking.

I especially want to thank Johann Hurink at the University of Twente for proof-reading my thesis. Your effort has been remarkable. I have not been a student of yours and still you took so much time to read through my whole work. Thank you very much.

At last, I want to thank all my friends and my family for motivating me to work on this and for giving feedback when I needed it. Special thanks goes to my roommate Patrick, for being lazy when I was so that I wouldn't feel bad, but always pushing me when you knew I needed it.

With great relief I finish this last sentence, thanks to all of you for making this possible.

Matthias

Abstract

The transformation to a smart grid is a crucial step in this century and is supported and accompanied by regulations to encourage a reduction in energy consumption and investment in intelligent infrastructure. One prominent example is the European Union effort to reduce greenhouse gas emissions by 20% compared to the 1990 levels and increase the share of energy produced to 20% by 2020. With an increase in distributed renewable energy sources, the efficiency of production decreases as these sources are to a large extend uncontrollable. The goal of reducing energy consumption can be achieved by shifting the energy consumption to times in which renewable production is high. This can be achieved with demand-side management (DSM), especially by establishing demand response (DR) programs. DR ranges from dynamic prices for energy that vary over time or incentives that are paid for load shifting at the consumer premises.

These programs require the consumer to actively change his consumption pattern and are therefore subject to automation to increase the likeliness of participation. To circumvent a vendor-lock for these automation systems, the communication between the energy supplier and the consuming household has to be standardized.

In this thesis, the DR program at Stadtwerke Wolfhagen was examined to spot the level of standardization within the program and reveal existing standards in DR communication, with the goal to increase the interoperability of the Wolfhagen program towards a DR communication standard. To achieve this, the SGAM framework to describe smart grid use cases was facilitated to describe the use case in Wolfhagen. During the work of this thesis it turned out that there is not yet a standard for DR communication. Nonetheless, by choosing a reference specification as a likely future standard, we analyzed the Wolfhagen use case and the reference specification, OpenADR, with the same underlying framework, to examine the level of interoperability with the reference specification. The result showed that Stadtwerke Wolfhagen has several interoperability gaps to OpenADR. These results are demonstrated by an interoperability matrix that has emerged during this research. It shows that the interoperability levels used to distinguish the level of interoperability are either not sufficiently distinguishable or that the use cases that have been mapped in this thesis need further decomposition to make the result of the matrix more descriptive.

Further, the research revealed that the future market model of the European smart grid is yet to be established. There is no agreed upon standard for Demand Response communication in Europe, there is uncertainty about the future market model, and standardization in parts of the smart grid are still missing. Based on these facts, Stadtwerke Wolfhagen is advised to improve interoperability towards a reference specification by specifically improving on communication semantics.

Table of Contents

Glossary

AMI	Advanced Metering Infrastructure
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
DR	Demand Response
DSM	Demand Side Management
DER	Distributed Energy Resources
DG	Distributed Generation
DS	Distributed Storage
DSO	Distribution System Operator
ESO	European Standardization Organization
ETSI	European Telecommunications Standards Institute
EU	European Union
GHG	Greenhouse Gas
GWAC	GridWise Architecture Council
HEM-RM	Harmonized Electricity Market Role Model
IOP	Interest of Interoperability
NIST	National Institute of Standardization and Technology
PV	Photovoltaic
RES	Renewable Energy Sources
RA	Reference Architecture
RS	Reference Specification
SG-CG	Smart Grid Coordination Group
SGAM	Smart Grid Architecture Model
TSO	Transmission System Operator
VRES	Variable Renewable Energy Sources (Syn. RES)

Chapter 1

1 Introduction

The electricity grid has an aging infrastructure that reaches the limits of its capabilities. With the introduction of renewable energy sources like wind turbines and solar panels that are added decentralized to the grid, the complexity of the grid increases and puts additional stress on the infrastructure [1]. Due to the inefficiency of storing electricity, the production and consumption of electricity has to be in balance at all time and the regulators are confronted with new challenges due to the additional renewable resources to keep the balance of energy demand and supply. Next to investing in new infrastructure, one solution to increasing the efficiency of balancing demand and supply is to encourage consumers of electricity to shift their consumption in times of low electricity production to times of high production. This concept is part of DSM[1] (Demand Side Management), specifically Demand Response (DR). DSM includes everything on the demand side of the energy market. High levels of automation shall encourage the consumer to change his consumption pattern while maintaining a similar level of comfort. To enable this automation, the system at a consumer must be able to communicate with the systems at the energy supplier – in other words, both systems must be interoperable.

The goal of this thesis is to improve the interoperability between a consumer system, which we define as a system residing at the consumer premises that handles the communication with the outside world as well as having access to control the consumer appliances, and an energy distribution system operator (DSO) system in a typical DR program. To identify typical interoperability issues a case study will be performed at an actual DR pilot project to show how to recognize interoperability gaps and provide recommendations based on these findings to the organization involved.

To first understand the necessity for DR we have a look at the challenges of the contemporary electricity grid and how the advances in information technology can address them.

Electricity demand and supply

The electricity infrastructure and supply has been put at a continuously increasing stress in the past years. Electricity usage has increased steadily and is very fluctuating [2]. These fluctuations result in demand peaks that define the minimal requirements of the electricity chain. In other

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[1] DSM is described in detail in Chapter 3

[2] DR programs are part of DSM and are discussed in detail in Chapter 3

words, due to increase in electricity demand, the minimal grid requirements have increased as well. On top of that, energy demand varies per day and season and is largely unpredictable [1]. The balance of demand and supply is crucial to prevent power outages. Therefore it is necessary to always have generation capacity that is able to meet maximum peak demand.

The usage of renewable energies is one of the most important challenges in the world. Directives in the European Union require all their states to contribute to the overall target of 20% of energy production from renewable sources by 2020 [3]. Those renewable resources come from external, sun, water and wind power and are to a large extent uncontrollable. The generation based on these sources may have some similarities with the demand patterns, but in general they are far from being equal [4].

With an overall increase in renewable generation, the fluctuations in energy supply increase as well and it is even more challenging to balance demand. Since power outages can have existential consequences on society and have to be prevented, having sufficient generation capacities is crucial [5]. Furthermore, as technology advances, even more energy is used. With fast charging technologies for electric vehicles and a growth in electricity powered vehicles, demand in electricity will continue to rise and fluctuations with them [6]. Due to the nature of the renewable sources uncontrollability, costly supplemental production is necessary to jump in when renewable production is missing, which results in low utilization those traditional power plants. Next to the financial drawback of additional generation capacity and low utilization, the grid capacity is another alarming factor. Shifting demand from peak periods to times of lower usage can be a less expensive alternative to investments in new grid infrastructure [7, 8]. To be able to recognize a shift in demand of consumers, it is necessary to measure accurately. This prerequisite allows for financial rewards and can be achieved with new technology in the electricity infrastructure. The result is called the '*smart grid*'.

Smart grids

Affordable communication infrastructure makes it possible to add smart controlling mechanisms to the energy infrastructure. This basically means that modern communication technology is added to various parts of the electricity grid [9]. With a development towards "smart grids", communication between consumer and grid operator gets bi-directional [8]. This is achievable through advanced metering infrastructure (AMI), in which smart meters are installed at the consumer to communicate energy usage to the grid operator. According to Faruqui et. al.[10], investing in smart metering has the following benefits:

> *"This investment is likely to yield improvements in the way that electricity flows through the grid by eliminating meter reading costs, allowing for faster detection of power outages, permitting remote connect/disconnect of service and minimizing power theft."*

Additionally, with the technology to monitor energy usage, DSOs have the opportunity to participate in Demand Response[2] (DR) programs which aim to optimize energy consumption by reshaping the energy profiles of the consumer [4].

Demand Response

One of the fundamental ideas of demand response is to provide price signals that reflect the actual cost of power [11]. With dynamic prices, consumers can decide whether to buy (consume) energy at times of high costs (during peak demand periods) or to shift load to times of lower costs. Information technology in home appliances enables automation of such load shifting while preserving the comfort of residents. Therefore a controller at the household is necessary that switches appliances on or off based on the residents preferences. By shifting demand from peaks, the necessity of higher marginal cost generation and grid reinforcement investment is reduced and therefore electricity prices could significantly drop [12].

[2] DR programs are part of DSM and are discussed in detail in Chapter 3

1.1 Problem Statement

The need for standardization

System operators and energy suppliers can profit significantly from renewable energy technologies, even more if energy production and consumption is adapted to actual prices on the energy markets [13]. However, lacking interface standardization results in vendor lock-ins and inhibits new players to enter the market. According to a report from the USEF Foundation [13], standardization of such interfaces is essential to introduce smart energy systems on a global scale:

> *"A prerequisite for large-scale market introduction of smart energy systems for small and medium-sized enterprises (SMEs) and residential end users is the commoditization of products, services, and solutions so that they become commercially viable; that is, it is essential to reduce the cost to serve those end users and reduce the cost to connect their appliances. Standardization of both market access conditions and interfaces will enable the mass production of the technology and IT systems required to build the energy system of the future."*

The European Committee for Electrotechnical Standardization (CENELEC) is responsible for standardization in the electrotechnical engineering field and aims to create market access in the European as well as international level, adopting international standards wherever possible. Due to many different actors along the smart grid value chain, standardization is seen as a key issue by the CENELEC [14]. By the end of 2014, the group finalized a report requested by the European Commission stating a set of standards that support smart grids deployment. As of 2014, especially the sector of demand response management lacks fully featured standards [15]. A key issue is therefore to support standardization.

European developments

In Europe many efforts have already been made to push smart energy infrastructure and demand shifting to the consumer [16]. The EU co-funded a list of projects across the continent (among others EcoGrid.EU [17], ADDRESS [18], web2energy [19], MIRABEL [20], E-Energy [21], eFlex, Grid4EU [22], FINESCE [23])[3]. Some of them strive to define communication standardization across multiple actors and appliances. Furthermore there have been several smaller pilot projects in European countries that aim to test smart grids and DSM features in the field (Jouw Energie Moment [24], Wolfhagen [25], EnergieKoplopers [26], among others)[4]. These smaller pilot projects

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[3] This is a sub-set of all co-funded EU smart energy projects, these are chosen based on their participation in DSM programs

[4] This is not a comprehensive list, just an indication of example projects

need smart energy controllers, home appliances and communication tools to enable their demand side management programs.

There is not yet a European standard for the communication of demand response programs, but numerous specifications have been released as results from longstanding, nation-spanning research programs across the EU [16]. Interoperability between key market players and newly created solutions is a prerequisite to an integrated, smart energy market.

The market for DR programs, especially in Europe, is still unclear. The market roles have not been defined definitely. New market players are rather likely to create individual solutions than building on existing solutions due to the uncertainty in the market and a missing set of standards. A lack of knowledge about market developments further contributes to this problem. While these individual solutions can be used in a field study, they are unlikely to be capitalized due to the regulated nature of the electricity market. The aim of this thesis is to provide an overview of existing specifications to DR communication and highlight a method to create or adapt a project with interoperability towards these specifications in mind.

1.2 Research setting

This research is done in collaboration with Stadtwerke Wolfhagen GmbH as part of my graduation within the master program *Business Information Technology* at the University of Twente.

The Stadtwerke Wolfhagen is a DSO in Germany and has started their "Wolfhagen 100% EE – Entwicklung einer nachhaltigen Energieversorgung für die Stadt Wolfhagen" project (Wolfhagen 100% renewable energy – development of sustainable energy supply for the city of Wolfhagen) which aimed to generate 100% of the actual power consumption from renewable sources. This goal has been reached in 2015 and since then a pilot project in DSM has been established. Within this project price signals are exchanged between participating residents and the DSO to encourage load shifting to times of high renewable generation. This project has been developed based on individual requirements. To be able to put their product to market in the long-term, it is necessary to ensure interoperability in the market structure and information technology that is developed around the globe.

The traditional energy grid architecture has been established decades ago [9]. As the industry faces the emerging fundamental changes towards a smarter infrastructure, Stadtwerke Wolfhagen has introduced its Demand Side Management pilot project to stay ahead of the competition while further benefitting from the high amount of renewable production. The project won the national "Energy Efficient City" competition, resulting in national funds which support the creation of the DSM pilot project including residential households and the development of an individual technological solution [27].

In the long term, Stadtwerke Wolfhagen aims to monetize the outcome by selling the developed energy management system on a broader scale. But to be able to monetize the soft- and hardware requires compliance with nationwide standardization requirements.

This thesis is laying a narrow focus on the communication between DSOs and consumers (as both are the actors represented in the Wolfhagen solution) and the accompanying data exchange. We aim to find a suitable ICT solution as a reference for the DSM project, compare the results and lay out gaps in terms of interoperability. The outcome should save time and money when developing future functionality and an adapted solution benefits the consumers as they can use appliances built upon standards that integrate smoothly with other energy suppliers.

The resulting advice will guide Stadtwerke Wolfhagen to improve interoperability with its DR solution and further contribute to a coherent smart energy grid of the future by introducing a method to simplify gap analysis with DR standards.

1.3 Scope

This thesis shows how smart grid developments can be compared and standardization gaps can be identified. It focuses on the communication between DSO and residential consumers, which is the context in which Stadtwerke Wolfhagen has established its DSM project. It leaves out the communication between producers and transmission system operators (TSO) as well as the communication between TSOs and DSOs, as it is not of primary interest for Stadtwerke Wolfhagen and would considerably broaden the scope, which is not feasible over the time of this research. It further does not research the standardization issues between the automation system and the smart appliances, like washing machines or freezers, as these facilitate a different standard and have a different set of requirements. This is illustrated in Figure 1.

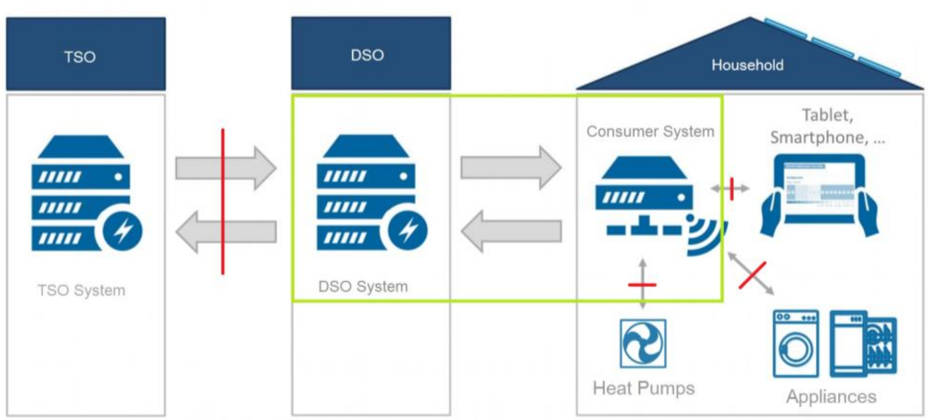

Figure 1 – Scope of this thesis

Chapter 2

2 Research Design

First the research objectives are outlined. The research questions are then given in the context of the objectives. After that, the research methodology is explained which helps to answer the research questions. In the final section, the methods are described as to how the objectives are going to be achieved.

2.1 Research Objectives

The purpose of this thesis is to shed light on the standardization of Demand Response communication and the specifications that have been developed. With regards to an actual field project in Wolfhagen, it is determined how interoperability in the project can be improved by comparing the field case with the available specifications based on a well researched smart grid framework. The resulting guidelines help Stadtwerke Wolfhagen to decide on further steps in their Demand Side Management development and to lower the time-to-market. To have a common understanding of what a smart grid framework and interoperability is, both terms are explained below.

2.1.1 The concept of Interoperability

Interoperability is *the ability of two or more systems or components to exchange information and to use the information that has been exchanged* [28].

2.1.2 The concept of a smart grid framework

Comparing the level of interoperability between two systems requires a common structure (or universal presentation schema) in which all the concepts, use cases and data flows of the systems are illustrated. Such a universal presentation schema has been developed in the form of a set of several architectures, aggregated into a common framework, called Smart Grid Architecture Model (SGAM) [29].

2.1.3 Main objective

The main objective of the current research can be described as:

"To define guidelines for improving interoperability of two systems in DR programs by highlighting interoperability gaps through comparison of an actual DR case to a DR reference specification by means of the Smart Grid Architecture Model"

Demand Response is a subset of Demand Side Management. Even though DSM also includes energy efficient appliances, this is of no concern in this thesis. When the term DSM is used in this thesis, it can be understood as interchangeable for DR.

Following the research objective, the next section describes the research questions that are derived from the goal.

2.2 Research Questions

This chapter describes the research questions based on the research objectives. The research questions are explained in short and each of them contributes to a delivery that is mapped according to the research design by Verschuren and Doorewaard in the following section [30].

As was indicated in the previous chapter, the main goal is to provide guidelines for improving interoperability in the exchange of DR signals. To tackle this problem, the following main question is answered.

How can Stadtwerke Wolfhagen improve interoperability of their DR program in its Demand Side Management pilot project?

This main research question is supported by the following 6 sub-questions.

1) What is Demand Response? What are the current developments in Demand Side Management and DR?

To be able to improve interoperability, it is necessary to understand what Demand Side Management and Demand Response actually is and what the current developments in the field are.

2) *Which framework can be used to efficiently analyze DR interoperability?*

To find interoperability gaps, it is necessary to understand how two systems can be compared in terms of interoperability. The concept of interoperability and the theoretical grounds to compare different systems need to be elaborated. Therefore, a framework is needed that is tailored to the demands of the smart grid and the comparison of two systems in terms of interoperability.

3) *To what extent have the identified DR methods been implemented in the Wolfhagen DR project?*

While the first question explains the ideas of DR identified by research, these may not represent what is actually implemented in the field. Analyzing the DSM pilot project yields an actual implementation of DR that can later be used to determine interoperability with a reference specification.

4) *What standard developments in DSM have been undertaken that can function as a reference specification?*

Finding a reference specification requires having an overview of existing solutions first. The answer to this question results in a reference specification chosen from a list of specifications that attempt to deliver DR concepts that can be compared to the pilot project to give insights in the level of interoperability. The list is based on literature review.

5) *To what extent aligns the observed pilot project with the reference specification?*

The previous sub-questions have us left with a reference specification and the Wolfhagen implementation of DR between households and DSOs. To determine the level of interoperability, both have to be compared using the SGAM framework and different terms of interoperability.

6) *What steps can be taken to improve interoperability?*

The gap analysis is based on the information derived from the Wolfhagen case, the decision on the reference specification and their mapping on SGAM. These results will be interpreted and form the basis for recommendations for Stadtwerke Wolfhagen to improve the interoperability in their pilot project. Based on these findings, general recommendations are derived.

2.4 Research Methodology

This thesis follows the research design by Verschuren and Doorewaard [30].

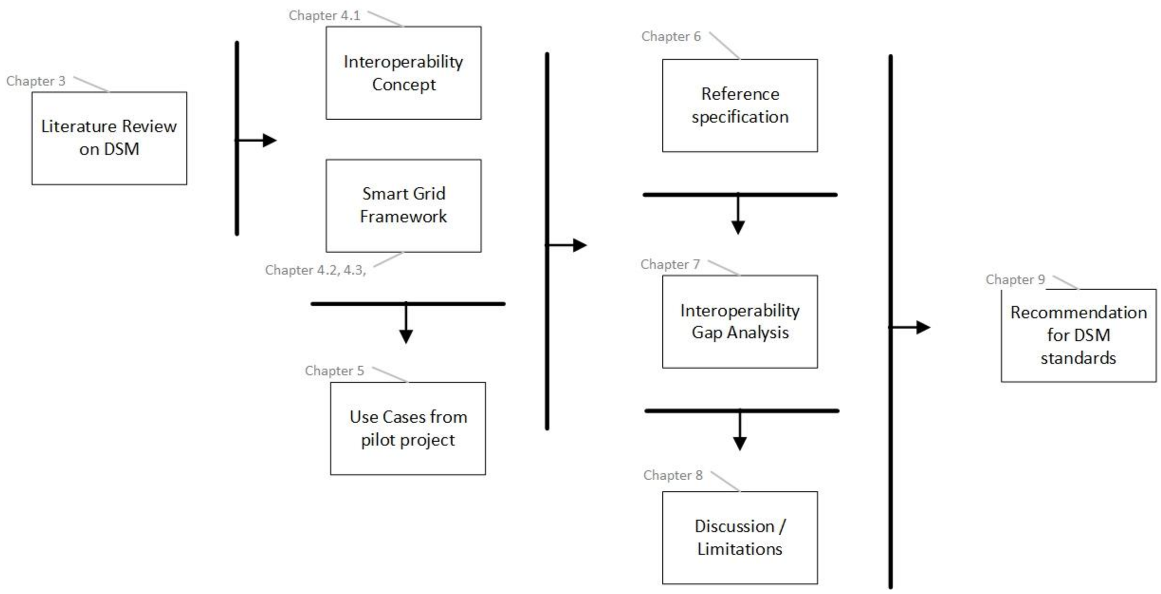

Figure 2 - Research deliverables following Verschuren & Doorewaard's research model

Figure 2 shows the deliverables that result from the research questions with additionally linking them to the chapters of this thesis. In this research model, the approach is linear. The vertically aligned deliverables can be worked out in parallel, while an arrow requires the previous deliverables to be done first. The evaluation is done by an expert interview and proof-reading by a domain expert to give a validated guideline in improving interoperability in DR in the context of the analyzed pilot project.

2.5 Research Methods

This section elaborates on the research methods and the steps taken to answer the research questions.

The goal of this thesis is to deliver guidelines to improve interoperability of a DR system by revealing gaps. These gaps will be identified by putting the implementation in context of a smart grid framework and comparing it to a reference specification (RS). To achieve this goal, five steps are performed sequentially and each of them has its own deliverables, as outlined in Figure 2. These steps can be seen in Figure 3. In the subsequent sections, each phase is described briefly.

Figure 3 - Methods to achieve goals

2.5.1 Literature review (DSM)

The first literature review is divided over 2 chapters. In this part of the thesis, the results of current research are outlined, the concept of interoperability is described and the smart grid architecture model explained. This contains the following points.

1. The methods and programs that have evolved from case studies and research with respect to Demand Side Management. This gives an overview over what DSM is and its value for the energy sector.

2. The concept of interoperability. This explains what defines interoperability and how we can define different levels of interoperability between two systems.

3. Smart Grid Framework. The insights of the pilot project implementation and a proposed specification need to be compared based on the same set of rules. To define clear boundaries a framework is needed that enables comparison with special attention towards interoperability.

2.5.2 Pilot project interview

During this research, a case study has been performed in the city of Wolfhagen in Germany. The engineering manager, responsible for the project has been interviewed in a semi-structured way to reveal how the project has been established and how soft- and hardware was developed and chosen. The result is a list of uses cases and requirements that are derived from the actual implementation in the field. These use cases are mapped to the framework that helps to identify standardization gaps by comparison with a reference specification.

2.5.3 Literature review (Reference specification)

Based on the use cases from the pilot project, suitable contenders for comparison in terms of interoperability need to be identified. By searching research databases with a defined set of search strings, DR specifications have been found for comparison. Based on a defined set of criteria a reference specification is chosen that is mapped to the framework and compared to the implementation.

2.5.4 Gap analysis

To define the level of interoperability it is essential to know to what extent all use case functions are covered by the reference specification. The reference specification from literature review is confronted with the implementation in the field case to reveal the coverage of their functionality. The result is a newly created matrix based on interoperability layers outlined by the smart grid framework and the key terms of interoperability described in this thesis.

2.5.5 Validation

To validate the findings of this thesis, the results will be validated by external experts in the respective field. There will be a semi-structured interview held to validate the description of field data with a leading manager at the pilot project and the usage of the research methods and the framework is validated by a domain expert in smart grid research through proof-reading of this thesis.

Chapter 3

3 Literature Review

The energy sector is one of the pillars of growth, competitiveness and development for modern economies. This chapter covers the concepts and methods that have been identified by research under the term Demand Side Management and Demand Response, how smart grid developments encourage them and the role of distributed energy resources within this context. To make DSM programs possible, a change in the electricity infrastructure is necessary. This will be described in the first section.

3.1 Transforming to a smart grid

In the past century, the goal of electricity production was to be reliable and to be performed at reasonable costs, which until liberalization in the 1990s was mostly a state affair [31]. The current infrastructure has been in place for decades and while its aging poses challenges for the reliability of electricity transfer, additional environmental impacts of production and utilization gain importance in social and political perspective [32]. Electricity usage has increased steadily and is very fluctuating [2]. These fluctuations result in demand peaks that define the minimal infrastructure and generation requirements of the electricity chain. Figure 4 shows the increase in production and consumption of energy in million tonnes of oil equivalent (Mtoe[5]) over almost the past 20 years.

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[5] One Mtoe corresponds to about 11.63 terawatt-hours (TWh) [33]

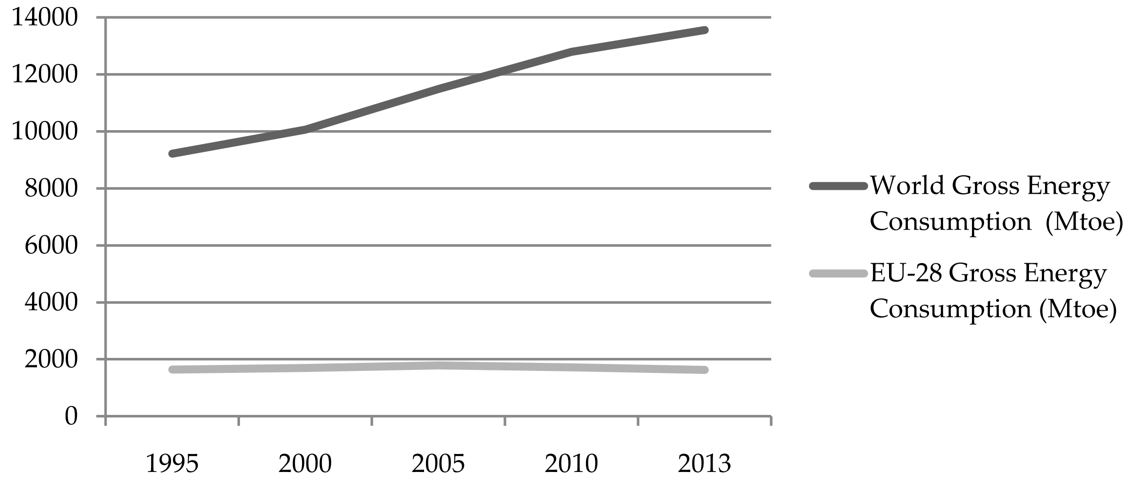


Figure 4 – Worldwide and EU-28 Consumption in Mtoe [34]

On top of a worldwide increase in energy consumption, energy demand varies per day and season and is largely unpredictable [1]. The balance of demand and supply is crucial to prevent power outages. Therefore it is necessary to always have generation capacity that is able to meet maximum, peak demand.

The aging infrastructure is a problem itself considering the increase in consumption, but next to that the European Union has set environmental and energy efficiency goals to encourage a climate change. These include an overall target of 20% reduction in Greenhouse Gas (GHG) emissions by 2020 and 50% by 2050, a reduction of 20% of energy consumption by 2020 and an increase in the amount of produced energy by renewable sources to 20% [35]. Although the 28 EU member states have not experienced the same relative increase in energy consumption (in fact, there is a slight decrease in EU-28 member states consumption) compared to the world, the challenge of decreasing consumption by 20% is still ambitious.

Energy efficiency therefore plays a key role in achieving these targets. Energy powers our societies and economy, therefore over the past years the energy consumption had a coherent relation with the economic growth [36]. In recent years, the EU was able to decouple energy consumption from economic growth, as can be seen in figure 5.

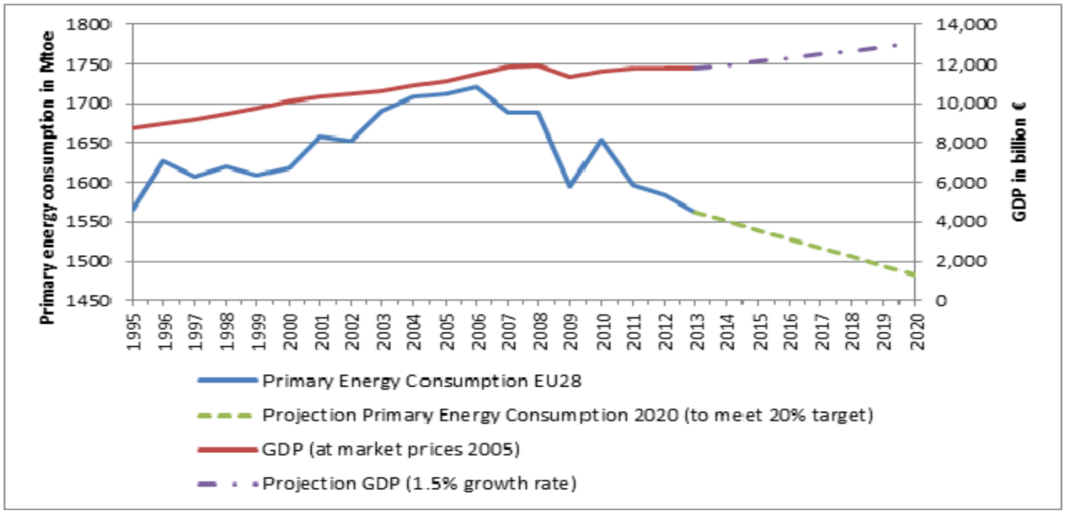


Figure 5 – Decoupling between Energy Consumption and GDP Growth [36]

The figure shows that the EU might be able to deliver on the new Energy paradigm. The developments are supported by numerous energy efficiency measures. As a result of these, buildings are consuming less energy, inefficient equipment is being phased out from the market and labels applied to household appliances such as televisions and boilers have enabled consumers to make informed purchasing choices, among others [36].

Although there are directives towards the industry concerning production restrictions in energy consumption, as well as labeling and awareness for consumers, there are also directives towards the renewing of the power grid. EU Directive 2009/72/EC expects its member states to "*encourage the modernisation of distribution networks, such as through the introduction of smart grids, which should be built in a way that encourages decentralised generation and energy efficiency*", further stating that "*in order to promote energy efficiency, Member States or, where a Member State has so provided, the regulatory authority shall strongly recommend that electricity undertakings optimise the use of electricity, for example by providing energy management services, developing innovative pricing formulas, or introducing intelligent metering systems or smart grids, where appropriate.*" As a final remark, the directive states that in cases "*where roll-out of smart meters is assessed positively, at least 80 % of consumers shall be equipped with intelligent metering systems by 2020*" [37].

The electricity network is therefore faced with challenges from different sectors:

1) *Environmental challenges:* traditional energy production is the largest human-caused source for CO2 emission and needs to be reduced in accordance with the EU policies,

2) *Infrastructure challenges*: the network congestion of the grid reaches its limit through an increase in electricity demand and the aging infrastructure of the grid [38] and

3) *Innovation technologies:* the existing grid lacks compatibility to new advances in communication technologies and advanced power electronics

The "smart grid" is a term that describes the attempt of the power industry to process the technology advances into the power grid and make it more intelligent [38]. To deploy a smart grid it is necessary to couple electricity delivery infrastructure with sensing and telecommunication technology to catch up with the developments in commerce and entertainment, among other sectors [9].

With these few information technology enhancements, system operators are enabled to control energy flows on the grid with more precision, increase automation and control of substations on the distribution network, increase the connectedness of distribution networks, reduce the number of customers interrupted by small-scale contingencies and allow for remote or automated control of individual customer loads [9].

It is therefore obvious that renewing the aging grid will come hand in hand with adding modern communication technology to the power infrastructure, as its capabilities are another added value to reach the goals set by EU directives.

3.2 Distributed Energy Resources

In the traditional electricity system there are four sectors: generation, transmission, distribution and consumption [1]. Distributed Energy Resources (DER) can be defined as small-scale power generation or storage units that are located close to the point of consumption [9].

Traditionally, differences in demand and supply of electricity have been balanced by monitoring the demand side and controlling the generation. The variations in demand (*variability*) and the *uncertainty* of sudden loss or change in generation units had to be controlled by generation to ensure balance. With an increase in variable supply sources, new ways to balance supply and demand need to emerge. The term *flexibility* gained importance in power systems and its services include *up regulation*, which means providing additional power as needed, and *down regulation,* which means the opposite by reducing the power availability in the system. The need for more flexibility comes with the introduction of more distributed energy resources (DER), small- to medium-scale energy resources that are connected to the distribution grid. DER can be divided in distributed generation (DG) and distributed storage.

Distributed generation is the term describing power generating technologies in distribution grids that are decentralized. The category comprises dispatchable resources, e.g. variable renewable energy sources that depend on fluctuating energy sources like wind or solar [39]. It is desirable to manage and optimize the efficiency of DG as its share in power production will steadily increase according to EU policies [1]. This can be done by encouraging consumption close to the physical point of production to decrease transportation losses.

One option to balance demand and supply is active power control of renewable power plants. Active power control refers to adjusting the production in various timeframes. A regulation signal can be sent to PV installations and wind turbines and they have the ability to respond fast. Down regulation can be provided by curtailing power production, while operating units generating below their maximum generation level provides the possibility for up regulation. Both operations come at the expense of an overall reduction in output of renewable energy sources (RES) [39].

To increase the efficiency of distributed generation, it can make sense to group together several households and their distributed generators into a *microgrid*. In a microgrid, the group of houses tries to optimize their combined import and export from and into the grid [4]. These microgrids can, instead of exchanging power directly with the operator, also form a cooperative group with other microgrids. This coalition could constitute a local energy exchange market. Microgrids can have several advantages: by transferring power locally among themselves they reduce power losses and improve the autonomy of the network. With closely located microgrids the power is transferred over shorter distances, thus reducing transferring losses. Further, local power exchange helps avoiding losses at the level of the operator. Recapitulating, these microgrids have a mutual benefit in cooperating so as to trade power locally within their network [40].

Distributed storage (DS) describes the technology to store energy in small scale on distribution grid level. This technology enables the consumer to shift his consumption pattern and therefore provide flexibility. Storage mediums are e.g. batteries, flywheels, pumped hydro storage or compressed-air energy storage [39].

According to the U.S. Department of Energy, in 2012/2013 about 340 MW of storage were installed worldwide [41]. This rate could increase to 6 GW per year by 2017, achieving a total of 40 GW installed in 2022 [41, 42]. Although this includes industrial storage as well, GTM Research expects in the U.S. alone that between 2014 and 2020 720 MW of distributed storage capabilities will be deployed [43].

3.3 Demand Side Management

The previous sections have given insight in the change in technology that enables smart controlling of energy consumption and the influence of distributed generation on the overall challenges of balancing demand and supply. This chapter highlights the demand side and shows how the term Demand Side Management (DSM) combines the aforementioned technologies and methodologies.

Energy demand varies, depending on the time of the day and time in the year. Recalling from chapter 3.1, these fluctuations define the maximum, peak demand and form the requirements on generation capacity. Together, the uncertainty of supply and variability in demand lead to inefficiencies in power generation, with power generation plants having a utilization far below the optimum [1]. The increased share of RES in energy production also introduces variability to supply. Since demand and supply always have to be in balance, this variability needs to be coped with. Demand Side Management is the term that describes everything that is done on the demand side of the energy system, which can range from using more energy efficient appliances to incorporating sophisticated energy management systems [7]. Hu et. al. have stated a severe definition for DSM [44]:

> *"Demand-Side Management refers to leading power users to scientifically and rationally use power and save power by taking effective measures to improve power energy utilization efficiency, optimize resource allocation, protect environment, and accomplish power consumption management activities carried out with power service at the lowest cost."*

The energy consumption patterns in residential homes vary depending on the time of the day and the time during the year. Figure 6 (a) shows the daily electricity consumption over 2002, aggregated over a set of data from 702 Finnish households. Figure 6 (b) shows the hourly, mean consumption values over each day of the same data set.

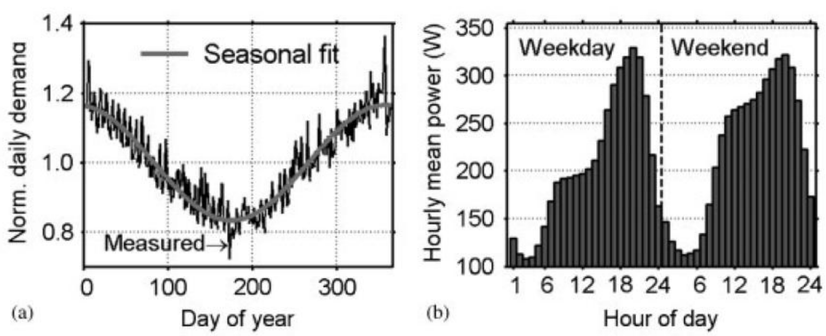


Figure 6 – Average demand patterns in residential home [45]

Pombeiro et al. show in a more recent study that Portuguese households have similar demand, although only the months June and July have been taken into account. In their work, peak demand occurs at 22:15 while lowest demand is around 5:15 [46]. Figure 7 shows that residential energy consumption accounts for the second biggest group of energy consumers, with transport being the number one and industry following behind [34].

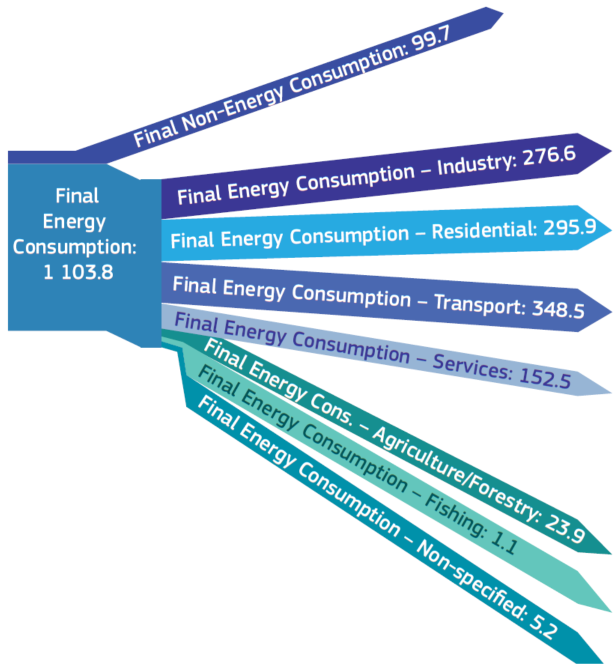


Figure 7 – Energy consumption in 2013 in mtoe [34]

Therefore the production to about 27% of the overall energy consumption in Europe has to factor in these huge fluctuations in residential consumption, where e.g. minimum demand in summer nights accounts to only about 30% of the peak demand in winter [1]. Generation plants need to be able to serve peak demand and therefore have to reduce production in times below peak consumption. This is especially the case for power plants with high flexibility. There is a significant spread among different generation technologies when it comes to utilization, since some power sources are not easily regulated (e.g. nuclear power plants operate around 100% and can not easily be turned off). Therefore the conventional plants with a higher flexibility have to lower their production in off-peak times and increase production towards peak consumption periods. Some of these plants only run a couple of hours a year and hence have a bad return on investment for the company in charge [1, 2, 4].

With EU policies requiring a twenty percent stake of renewable production, this results in uncertainty in supply. Figure 8 shows operational timeframes and examples of how renewable energy sources affect the production of energy.

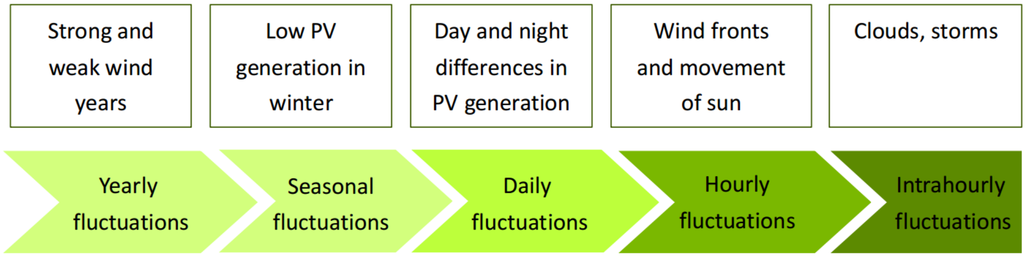


Figure 8 – Examples of fluctuations in RES [39]

To deal with this uncertainty it is necessary for the power system to provide increased amounts of energy reserve to secure the supply. This reserve needs to adapt to the unpredictable fluctuations in renewable production and therefore require high flexibility. As was mentioned before, the conventional plants with high flexibility are the ones with the least utilization since they are only used when peaks are high and or renewable sources are not available [1].

A solution to this problem can be different methods that are identified in Demand Side Management. DSM can be categorized in the following [7]:

a) Energy Efficiency (EE)
b) Time of Use (TOU)
c) Demand Response (DR)

Energy Efficiency includes all permanent changes on equipment (light bulbs, washing machine …) to newer, more energy efficient appliances. These changes are immediately measurable and are the most welcome method.

Time of Use describes variable energy prices that depend on the time. In times of low production, energy prices rise to penalize the consumer and encourage him to (re)arrange his processes, while prices are low in times of high production. It is shown that a DSM program with TOU tariffs can lead to reductions in costs and emissions while maintaining energy security [47]. It should be noted that Time of Use refers to a scheme in which the prices vary over time (e.g. hourly rates), but that these rates are set based on historical data and therefore for a long period ahead. Hourly fluctuations cannot be taken into consideration since the rates are not dynamically adjustable.

While TOU tariffs are sent beforehand to allow the consumer to adapt to the new prices, *Demand Response* signals have a more direct impact on the processes of the consumer. The goal of demand response, as with TOU, is to shift the demand from peak to off-peak times. This reduces the fluctuations in demand and therefore contributes to the efficiency of flexible conventional power plants. There are different kinds of *DR* methods identified, and all of them build upon a concept of price incentives to encourage the consumer to participate. Some examples are real time pricing, direct load control or emergency demand response programs [7].

These different DR programs can be categorized as either:

Market DR: real-time pricing, price signals and incentives, and

Physical DR: grid management and emergency signals

To make use of these DR signals and time of use tariffs in an automated way, usually an energy controller is installed at the house to automatically switch appliances on or off based on personal preferences. These preferences can be expressed in rules and priorities to preserve the comfort level of the resident while still shifting demand and therefore saving money.

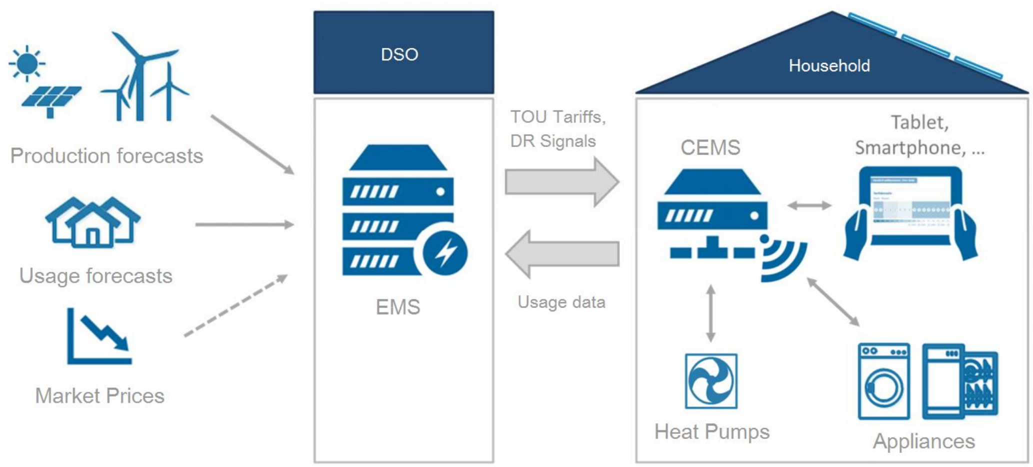


Figure 9 – Typical DR scenario between DSO and household[6]

In the scenario depicted in figure 9, the Energy Management System (EMS) at the DSO exchanges its DR messages based production forecasts, usage forecasts and market prices to the Customer Energy Management System (CEMS). These messages can for example be day-ahead price tariffs. The CEMS, based on preferences and priorities set by the consumer, then decides when to reduce or shift consumption and the consumption is sent back via the smart meter.

But there are also critics on day-ahead pricing, and other models have gained significant attention in recent pilot projects and research. The implementation of time dependent local tariffs would apply to both the controllable and uncontrollable load. Because of that, the USEF foundation states

[6] The original graphic was developed by Stadtwerke Wolfhagen and was modified and translated in accordance with the creator

that *"in principle uncontrollable loads could change their load pattern and end-users could change their behavior patterns but the financial benefits are so low that such price signals are ineffective for uncontrollable loads. As a result, the end-users pay a disproportional part of the costs to resolve the congestion and those who really contributed significantly to resolving it are barely rewarded."* [13]. The solution should be a new market model based on the concept of *flexibility*.

The concept of flexibility should offer consumers the possibility of active participation in the EU energy transition. The role of the consumer therefore requires a fundamental change on the electricity market [13]. The market model should consider all stakeholders involved in the electricity chain and regard their different needs:

While a DSO would like to reduce the consumption, or at least flatten the load profile, of its network to maximize utilization, a wind farm operator would like to see consumption following his production pattern. A consumer on the other hand would like to consume energy when he desires and not be limited by the consumption patterns of other consumers or the availability of sun and wind. These wishes can obviously be contradicting. Somehow, these stakeholders must share the flexibility that results from the different needs of the other stakeholders in the grid.

Since those wishes are not equally important, the optimal solution depends on the importance of each wish, which is depending on the alternative that is presented to a stakeholder. A consumer for example can decide to charge his car later and take the bus. To assess the importance of its own wish, the stakeholder monetizes his wishes and thereby creates a basis for evaluation. It enables stakeholders to compare the desired flexibilities with the costs of their alternatives and assess a value to it. That way, the ones that benefit the most from consumption will compensate the others that had to shift their load. In theory, that should result in an optimal solution [13, 48].

Therefore, in the flexibility concept, a consumer of energy determines his ability to reduce consumption. This potential reduction is termed his flexibility and can be sold to a flexibility aggregator, who buys the flexibility of the different consumers and sells it to the grid operators. Figure 10 illustrates this. It shows how the prosumer, a consumer who also produces energy or at least wants to participate in the energy market by selling his flexibility, makes his flexibility available to the aggregator who creates services based on his accumulated flexibility and offers it to the different market players. The received value in turn is shared with the prosumer as an incentive to shift his load.

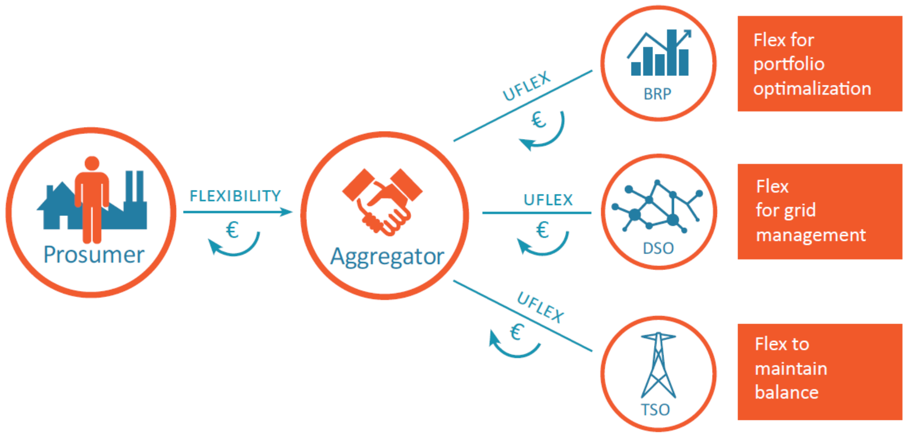


Figure 10 – The flexibility concept as outlined by USEF Foundation [13]

There are several reasons to make use of Demand Side Management. For one, EU policies state that *"in order to promote energy efficiency, Member States or, where a Member State has so provided, the regulatory authority shall strongly recommend that electricity undertakings optimise the use of electricity, for example by providing energy management services"* [37]. DSM falls by definition under the umbrella of energy management services. Another factor is that it is more cost efficient to intelligently influence load than to build a new power plant [7].

3.4 Summary

The transformation to a smart grid is a crucial step in this century and is supported and accompanied by regulations to encourage a reduction in energy consumption and investment in intelligent infrastructure. With the increase in distributed renewable energy sources, the goal of reduced energy consumption can be achieved by focusing on demand-side management, especially by establishing demand response programs. DSM ranges from energy efficient appliances to newly created energy markets in which prices for energy vary per time or incentives are paid for load shifting at the consumer premises.

Generally, DSM techniques improve energy efficiency, controllable loads and local generation through its system of diverse generation sources, supplying energy across the grid to a large set of demand-side users with possibilities for improving energy efficiency and local generation [49].

The benefit of DSM is clear, but the implementation of such programs in Europe requires regulation to achieve an international standard in terms of communication and an agreed-upon market model. The following chapters address the efforts made towards a regulated, coherent European Smart Grid.

Chapter 4

4 The road to standardization

System operators and energy suppliers can profit significantly from renewable energy technologies, even more if energy production and consumption is adapted to actual prices on the energy markets [13]. However, lacking interface standardization results in vendor lock-ins and inhibits new players to enter the market. According to a report from the USEF Foundation [13], standardization of such interfaces is essential to introduce smart energy systems on a global scale:

> *"A prerequisite for large-scale market introduction of smart energy systems for small and medium-sized enterprises (SMEs) and residential end users is the commoditization of products, services, and solutions so that they become commercially viable; that is, it is essential to reduce the cost to serve those end users and reduce the cost to connect their appliances. Standardization of both market access conditions and interfaces will enable the mass production of the technology and IT systems required to build the energy system of the future."*

It is obvious that standardization is essential to implement DSM solutions on a broader scale. In its M/490 mandate, the European Union requested the development of a framework to enable continuous standard enhancement and development in the field of smart grids by European Standardization Organizations (ESOs) [50]. In accordance with the mandate, the Smart Grid Coordination Group (SG-CG) was established by a cooperation between CEN (European Committee for Standardization), CENELEC (European Committee for Electrotechnical Standardization) and ETSI (European Telecommunications Standards Institute) [14]. This coordination group has been responsible to develop a framework that enables ESOs to continuously develop standards in the field of smart grids.

In the first section, the general concept of standardization and interoperability is explained, while the following sections outline the results of the SG-CG towards a uniform framework.

4.1 Interoperability

To standardize interfaces and communication between two systems, it is necessary to make those systems interoperate. Interoperability is *the ability of two or more systems or components to exchange information and to use the information that has been exchanged* [28]. Two systems capable of communicating data are exhibiting *syntactic interoperability*. Data formats (e.g. JSON) and communication protocols (e.g. TCP/IP) are building the groundwork to achieve syntactic interoperability, as well as low-level data formats like a format used to store alphanumerical data (e.g. ASCII) between different systems. To achieve further interoperability, syntactic interoperability is a necessary condition [51]. The concept of interoperability is illustrated in figure 11.

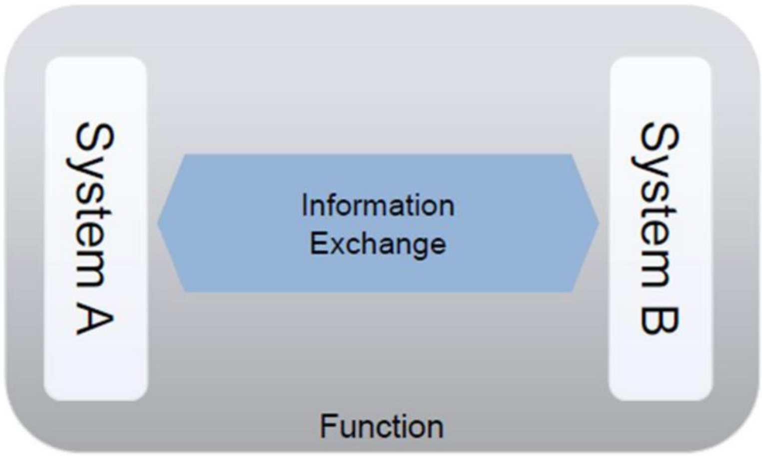
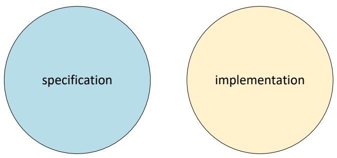


Figure 11 – Interoperable systems performing a function [51]

Standardization is responsible for a clear definition of the formats used on low-level to high-level so that different systems that follow a specific standard are interoperable.

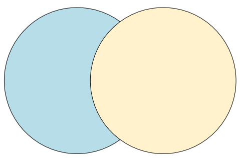
4.1.1 Key levels of Interoperability

The following list shows the key levels of interoperability that are used within this thesis to describe the extent of interoperability between systems, based on [51]:



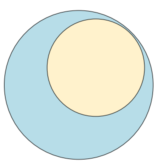
Irrelevant

The implementation has no features in common with the specification.



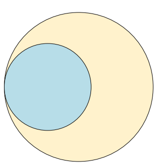
Consistent

The implementation has some features in common with the specification, but some specifications have not been implemented.



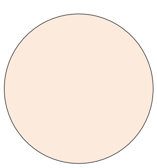
Compliant

Some features in the specification are not implemented, but all implemented features are covered by the specification.



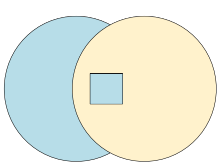
Conformant

All features in the specification are implemented in accordance, but some more features are implemented not in accordance.



Fully Conformant

All features from specification are implemented in accordance to specification and there are no features that have not been specified.



Non-Conformant

Any of the above in which some features are implemented not in accordance with the specification

It is in the interest of interoperability (IOP) that a standard is written in a way that allows to assess the level of conformance to its requirements by describing the function rather than the design and giving precise, measurable specifications [51].

Comparing the level of interoperability between two systems requires a common structure in which all the concepts, systems, use cases and data flows are illustrated. Such a universal presentation schema has been developed by the SG-CG in the form of a Reference Architecture (RA). This RA is a set of several architectures, aggregated into a common framework, called SGAM [29].

4.2 The Smart Grid Architecture Model

The Smart Grid Architecture Model (SGAM) consists of a methodology, a conceptual model and a Reference Architecture [29]. The conceptual model addresses a high-level view of the main actors of the smart grid and their interactions. The Reference Architecture (RA) copes with a variety of stakeholders, combines power system management requirements with expanded interoperability requirements and allows for various levels of description from top-level to more detailed views [29].

4.2.1 The SGAM methodology

This section gives a brief overview of the SGAM methodology concepts used in the architecture and is relevant for the following sections [52].

> *The goal of the Smart Grid methodology is to support international standards development for Smart Grid technologies, products, components, and systems and their interfaces, to support and boost the large-scale deployment of Smart Grids and smart markets in Europe. The methodology provides tools for the identification and structuring of requirements for new Smart Grid standards and provides a framework for their development [52].*

An important concept in this methodology is the concept of roles and actors. They form the basic components in the conceptual model, the SGAM model as well as use cases. By defining them in terms of responsibilities that are independent from certain market structures they allow for the development of market structure agnostic standards. This is necessary to guarantee a Smart Grid standards design that is compatible with evolving markets.

The market models in Europe define which activities are regulated and therefore allowed. Those activities of different smart grid parties are defined by their responsibilities and roles. The allocation from roles to parties may be subject to legislation / regulation [52]. Standards that support roles are the fundament of a standard that spans across all EU members states by being market independent and therefore applicable in different European market models.

Having an agreed upon list of actors and roles and a common understanding hereof is essential to ensure interoperable system design. The *European Network of Transmission System Operators for Electricity* (ENTSO-E), the *European Forum for Energy Business Information Exchange* (eBIX) and the *European Federation of Energy Traders* (EFET) created a clear definition of the market roles within the various electricity markets of the EU. These are modeled in the *Harmonized Electricity Market Role Model* [53].

A unique mapping between use case actors and roles and European market models based on the same set of roles support the applicability of standards to different market structures. Figure 12 illustrates this.

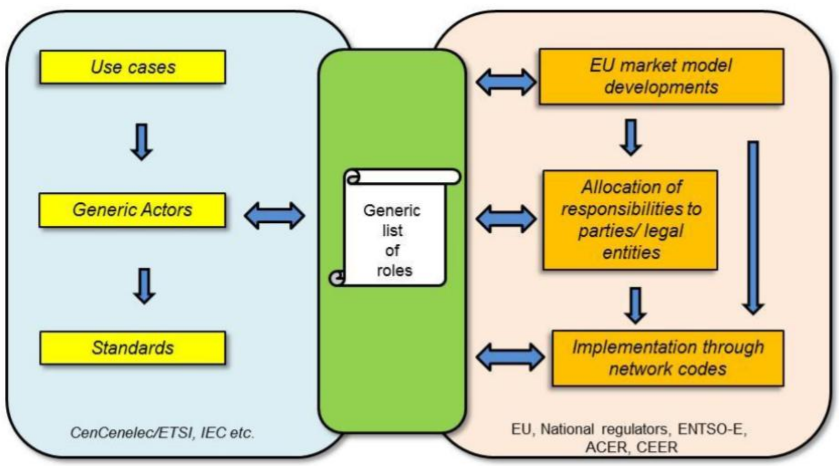


Figure 12 – Alignment between standards and market models [54]

The SG-CG aims to support the aforementioned goals by providing a generic actor list which 1) is the basis of all market model developments, 2) use case actors can be uniquely mapped to, 3) can be used by DSOs and TSOs and 4) is aligned with the European network codes (ENTSO-E) [55]. This list can be found in [56], however we outlined relevant actors for DR in Annex A.1.

The Smart Grid involves different disciplines with each having its own vocabulary and viewpoints. The SG-CG defines concise definitions based on TOGAF, Archimate, SGAM and the Harmonized Electricity Market Role Model (HEM-RM) to enable modeling in a market-independent way. These definitions can be found in Annex A.2. Figure 13 illustrates a meta model showing the relationships between the different terms actor, role, responsibility and party as described above [52].

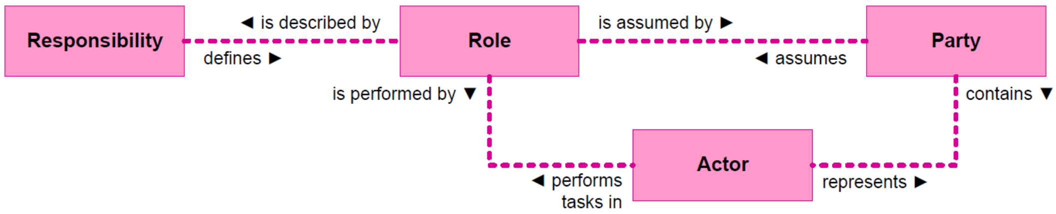


Figure 13 – Meta-Model of the concepts related to actors [52]

To deepen the understanding of how actual actors of use cases can be associated in the actors-role concept, the following example shows the meta-model from the perspective of a consumer using an energy management system.

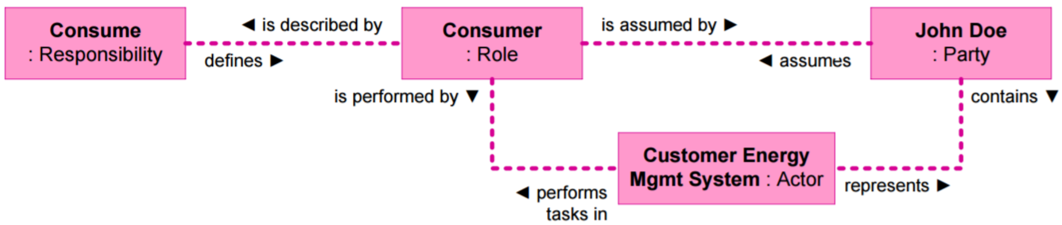


Figure 14 – Meta-Model example [54]

4.2.1 The Conceptual Model

The power grid in the EU has numerous heterogeneous but interconnected participants involved. While every participant builds and operates its part of the network, these parts still have to work together. The EU Conceptual Model deals with the centralized and decentralized aspects of the new grid infrastructure and is based on the work of the National Institute of Standards and Technology (NIST) [54].

It is essential to assure seamless collaboration between the different stakeholders involved and enable integration between communication technology and operational technologies in their power system management.

> *"The conceptual model essentially seeks to serve as a common framework, thereby enabling the convergence and facilitation of the dialog between all these stakeholders, and thus make an important contribution to aligned and consistent smart grid deployment within Europe."* [54]

This alignment is guaranteed by building upon the Harmonized Electricity Market Role Model. The SG-CG further defines the following principles, which also form the acceptance criteria for the conceptual model from which architecture and standards can be derived.

- It is possible to extract business roles and actors from the EU conceptual model since the conceptual model is organized in conceptual domains. These domains group the aforementioned roles and hence ensure compatibility between market and technology. Figure 15 illustrates the meta-model.

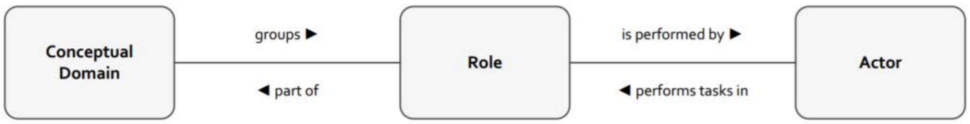


Figure 15 – Meta-Model for the conceptual model [54]

- It is in alignment with European electricity market by grouping the roles identified in the harmonized electricity market role model and therefore support the initial understanding of the European electricity market at a more abstract level.
- It supports central and distributed power system development, micro grids, a Pan European Energy Exchange System (PEEES) and the concept of flexibility [54].

Based on these principals, or requirements, the EU conceptual model has been developed which is illustrated in figure 16.

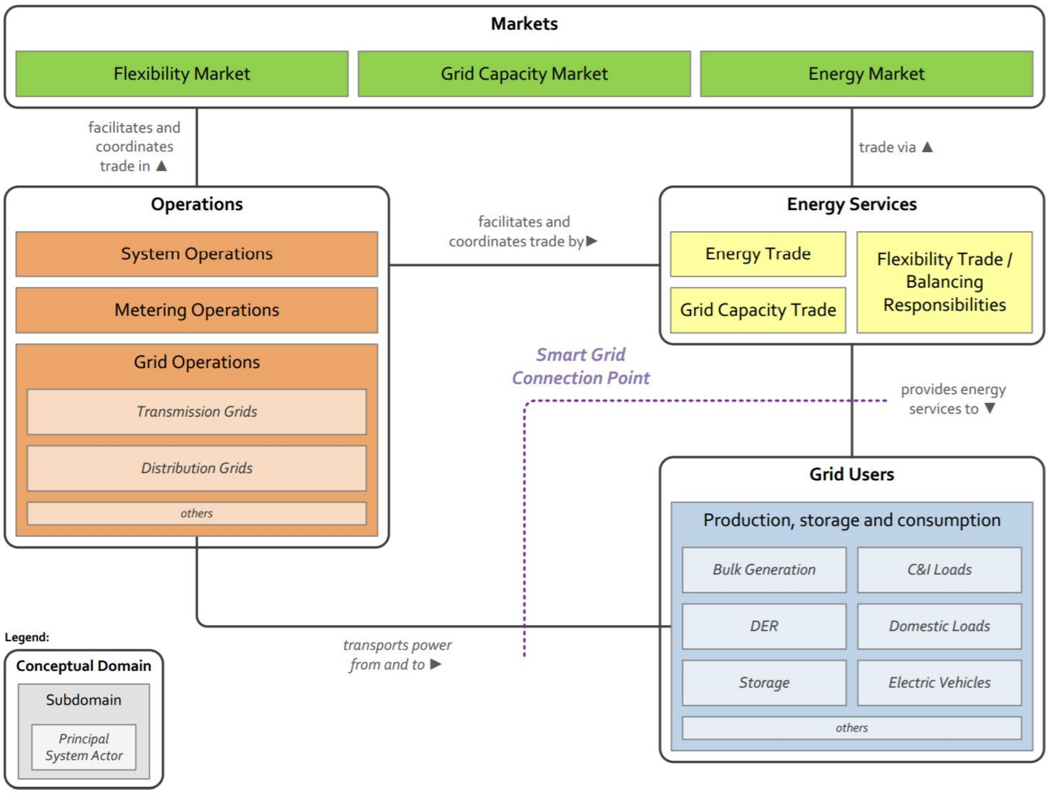


Figure 16 – EU Conceptual Model for the Smart Grid [54]

The conceptual model is defined by grouping the roles and actors in line with the European market. It consists of four conceptual domains which are *Markets*, *Energy Services*, *Operations* and *Grid users*.

This approach, with its high-level result, helps to classify use cases and further supports consistency among the solutions from different stakeholders in the smart grid. Based on the Conceptual Model, the Reference Architecture has been developed.

4.2.2 The Reference Architecture

According to the SG-CG, the RA was developed based on the motivation to create *a blueprint for the development of future systems and components, providing the possibility to identify gaps in a product portfolio*. Further it helps to structure a smart grid domain and provide a communication foundation between different domains that need to interoperate. In addition, it should ensure that the RA supports identifying standardization gaps in the field of smart grid developments by providing an appropriate methodology [29].

4.2.2.1 Interoperability Layers

Interoperability is seen as a key enabler of smart grid developments and consequently the SGAM framework addresses interoperability inherently. The SG-CG built upon the widely accepted GridWise Architecture Council (GWAC), which represents a methodology to describe requirements necessary to achieve interoperability between systems or components [29]. The GWAC introduced eight interoperability categories divided among three drivers, "Technical", "Informational" and "Organizational". To realize an interoperable function, a standard or specification has to exist for each category. The interoperability categories are *Basic Connectivity, Network Interoperability, Syntactic Interoperability, Semantic Understanding, Business Context, Business Procedures, Business Objectives, Economic / Regulatory Policy* [57].

To simplify the architecture model, a clearer presentation is anticipated and therefore the categories from GWAC are aggregated into five abstract interoperability layers, shown in figure 17.

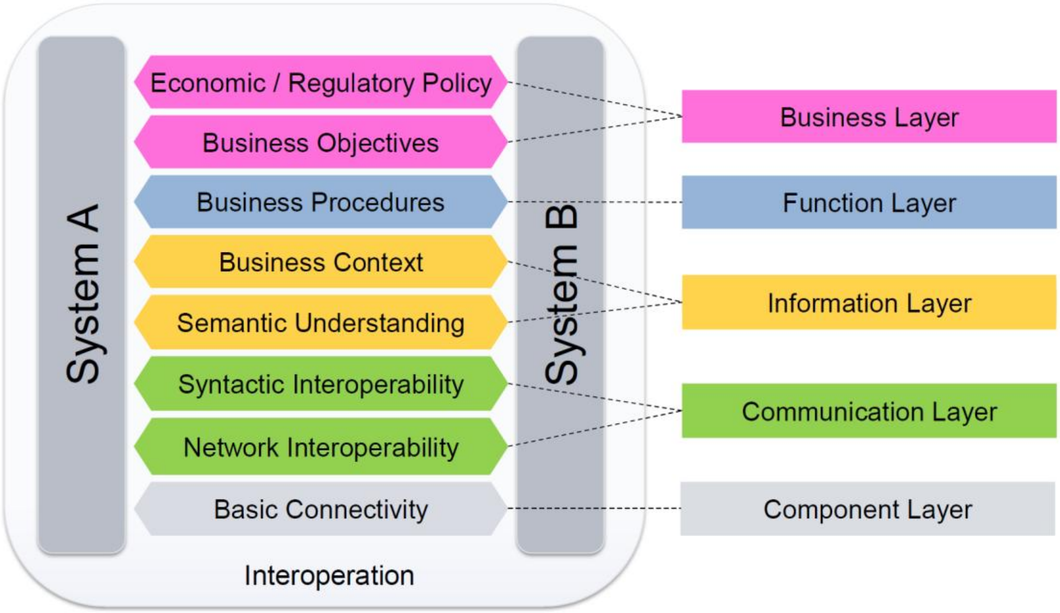


Figure 17 – SGAM interoperability layers [29]

The business layer represents the business view on information exchange while the function layer represents an architectural view of the functions involved. The information layer contains the information objects, like data models, while the communication layer describes the protocols used for the exchange of this information. Finally the component layer emphasizes on the physical components used.

A more detailed overview of the different interoperability layers is given in Annex A.3.

4.2.2.2 The Smart Grid Plane

Power System Management separates between electrical process and information management viewpoints. These can be split into the hierarchical zones for the management of electrical processes and the physical domains of the energy conversion chain [29]. By using the EU Conceptual Model and applying it to this concept, the Smart Grid Plane has been founded, which is shown in figure 18. It enables the representation and separation on which levels the domains interact.

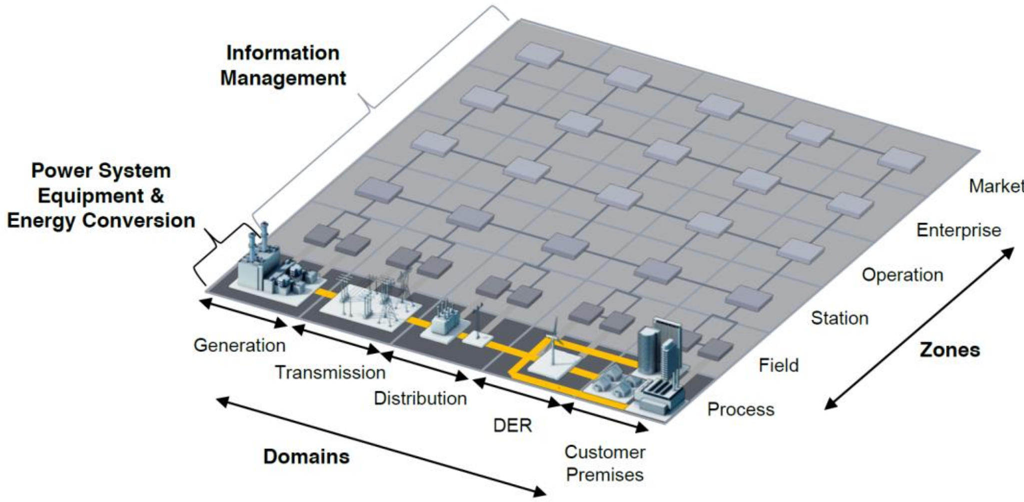


Figure 18 – Smart Grid Plane with domains and zones [29]

The zones from the smart grid plane represent hierarchical levels of power system management and reflect a model that considers the concept of aggregation and functional separation based on IEC 62357.

While the *process* zone includes physical or spatial transformations of energy and the equipment involved, *field* includes equipment to control or monitor the process of the power system. The *station* zone represents areal aggregation for the field zone while *operation* is the host for power system control operations in the respective domain. In the *enterprise* zone, commercial and organizational processes as well as infrastructure for enterprises is mapped while the *market* zone reflects the market operations along the energy chain [29].

Annex A.4 and A.5 provide further detail into the domains and zones of the smart grid plane, respectively.

An organization can have actors in different zones and domains. A transmission utility might cover all zones from the transmission domain, from process through to market. Another example might be a service provider offering weather forecasts for DSOs and DER operators. The service provider is likely mapped to the market zone, interacting with DSO and DER domain in the operation zone [29].

4.2.2.3 The SGAM Framework

The final SGAM Framework is derived by merging the interoperability layers defined in 4.2.2.1 with the smart grid plane from the previous chapter 4.2.2.2. The result is a three dimensional model, represented in figure 19.

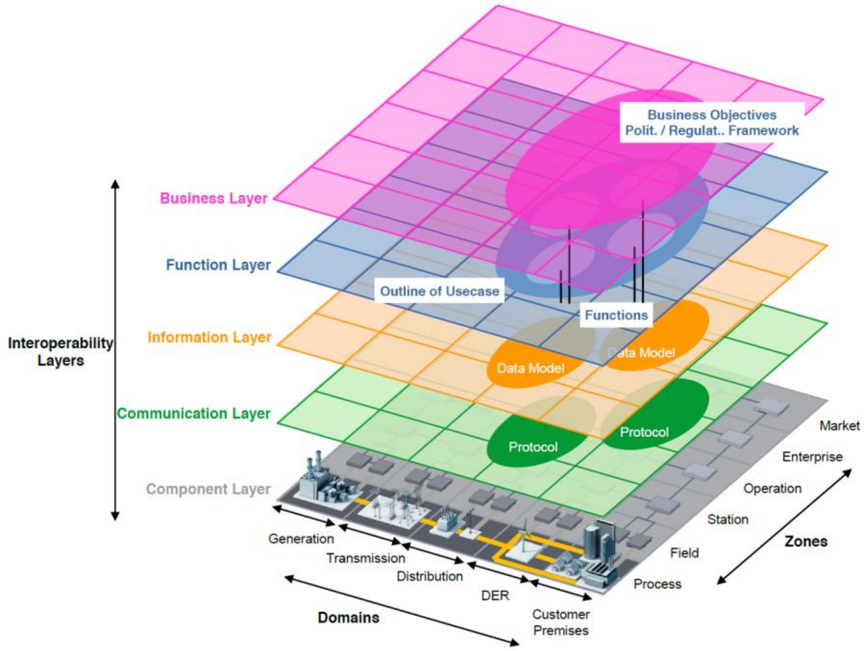


Figure 19 – SGAM Framework [29]

The final SGAM Framework maps entities and their relationships to the hierarchical information management zones and in the context of their domain while considering interoperability aspects through the five interoperability layers. The framework follows the principal of *Universality*, in accordance to which the SGAM is intended to represent smart grid elements in a common and neutral view. Its fundamental idea is to place entities in an appropriate location in the interoperability layer and on the smart grid plane. This comprehensive view on entities and their relation to other entities is termed as *Localization*. It is important to have a *consistent* interpretation on the mappings on SGAM. An empty layer means there is no specification available to support the use case. This means that there is a need for a specification or a standard on that particular layer. It is *flexible* in the sense that use cases are independent of the zone. The same functions might be in the field zone in decentralized systems or in operation zone for centralized systems. Functions can also be nested in different components. Further, addressing specific requirements can be mapped in multiple ways between the communication and information layer. Since SGAM reflects the entire Smart Grid, it is *scalable* in the way that it can either show specific functions in a detailed view or show everything in a specific scenario. It is *extensible* in a way that the layers can be de-aggregated to get further insight or new zones or domains might be added in a future yet-unknown state of the smart grid [29].

4.3 A Use Case Template for SGAM

The SG-CG gives an explanation on how to map use cases to its SGAM Framework. This enables the performing organization to validate the support of their use cases by current standards and identifies gaps with respect to standards. According to the SG-CG, a use case is mapped on SGAM by starting with a use case analysis. From the analysis, the component layer is developed, following the business layer, function layer, information layer and finally the communication layer [58]. Figure 20 illustrates this development.

4.3.1 Use Case Analysis

A use case needs the necessary information and therefore has to be verified to have sufficient information. This includes *name, scope* and *objective*, *use case diagrams*, *actor names* and *types*, *preconditions, assumptions* and *post conditions*, *use case steps, the information which is exchanged* among actors as well as *requirements*. In this thesis, the Use Case Template provided by [59] will be used. This template contains all aforementioned fields and is compliant with IEC 62559-2:2015, as well as it follows the guidelines defined by SG-CG in [56].

The following sections explain in short how the different interoperability layers are developed based on the values from the use case template [58].

4.3.2 Component Layer

The use case information on actors forms the basis for the component layer. Although use case actors can be devices, applications, persons and organizations, the component layer originates from the technical devices. These can be associated to the domains and the zones in which they reside.

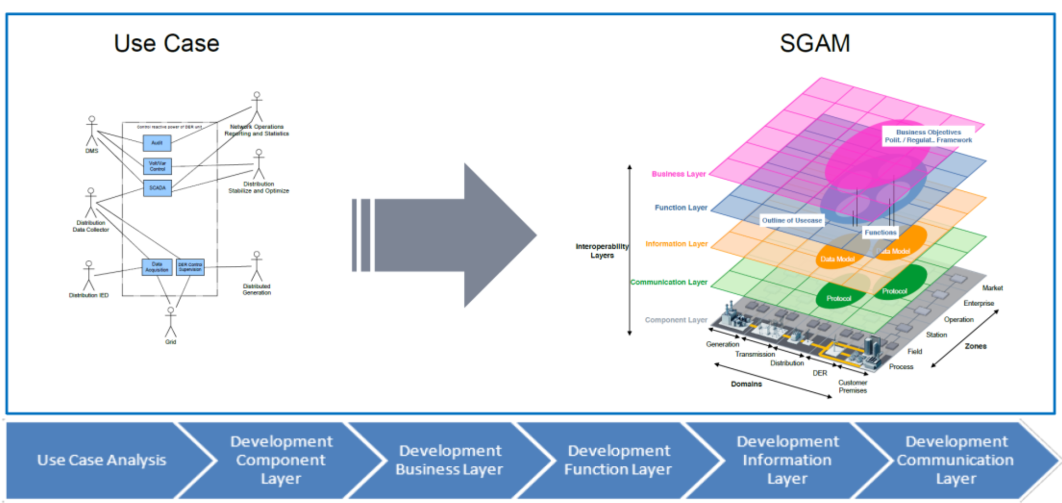


Figure 20 – Mapping of use case to SGAM [29]

4.3.3 Business Layer

The business layer hosts business processes, services and organizations. They can best be derived from business use cases, but also non-technical actors, narrative or step-by-step analysis can reveal the parts in the business layer. It also includes business objectives as well as economic and regulatory constraints.

4.3.4 Function Layer

By extracting functionality from use cases functions can be developed that map on the function layer. A use case might consist of sub use cases that can be transformed to functions by formulating them in an actor independent and abstract way. Other information sources are the narrative, objectives and nature of the use case.

4.3.5 Information Layer

The information layer describes the information objects which are used and exchanged between actors. Those can motsly be derived from the steps, sequence diagrams, the narrative as well as the scope. The underlying data models should be identified by analyzing available standards.

4.3.6 Communication Layer

Interoperable exchange of information is emphasized in the communication layer by describing protocols and mechanisms used for the exchange between actors. Appropriate protocols are identified based on the information objects and data models.

4.3.7 Overview

Figure 21 summarizes the previous sections in a graphical overview, showing how the different sections of an IEC 62559-2 compliant use case are mapped on the interoperability layers of the SGAM framework.

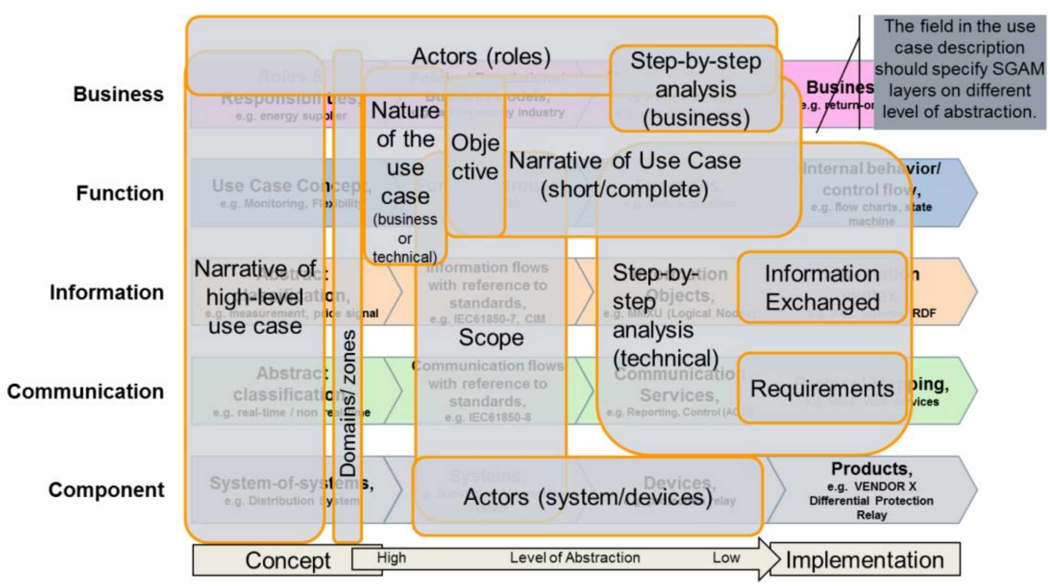


Figure 21 – Mapped IEC 62559-2:2015 Use Case Fields to SGAM [58]

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Chapter 5

5 DSM in the field

During the work in this thesis we have analyzed a pilot project covering DSM concepts at a German DSO called Stadtwerke Wolfhagen GmbH. This chapter outlines the results found in their DSM implementation, wrapped in a use case according to the template described in Chapter 4.3 and mapped to the SGAM Framework accordingly.

5.1 The pilot project

The project at Stadtwerke Wolfhagen is termed "Wolfhagen 100% EE - Entwicklung einer nachhaltigen Energieversorgung für die Stadt Wolfhagen" (Wolfhagen 100% Renewable Energy – Development of sustainable energy supply for the city of Wolfhagen), which will simply be referred to as the project throughout this chapter.

5.1.1 General information

Stadtwerke Wolfhagen has 40 employees and supplies energy, water and light to 14.000 people in 11 districts. Part of the project is the initiative "Demand Side Management" which aims to harmonize demand and supply locally[7]. To evaluate the extent to which Demand Side Management concepts are accepted by households, a set of 35 households have been equipped with smart devices to enable the consumer to automatically adapt their consumption based on price signals and personal preferences. The project has been supported financially by the German *Bundesministerium für Bildung und Forschung* (Federal Ministry of Education and Research), as well as either financially or through other resources by several other parties, e.g. the renowned Fraunhofer Institute and the University of Kassel.

[7] The concept of microgrids and islanding is referred to in chapter 3.3.

5.1.2 Goals

Stadtwerke Wolfhagen had the goal to produce more than 100% of the energy that has been consumed in a whole year by renewable sources. This has been achieved in 2015 and Stadtwerke Wolfhagen is therefore one of the first DSO in Germany that has achieved such a goal in its own district. In 2015, the energy consumption in the district Wolfhagen has been 47,6 million kW/h while its production from renewable energy resources has been 50,4 million kW/h [25]. The consumers are nevertheless not independent from traditional power sources, as the supply and demand are not always in balance. In times of high production, the surplus will be fed to the grid while in short supply energy has to be taken from the grid. This is demonstrated in figure 22, where the red line indicates the consumption, and the dashed area the production.

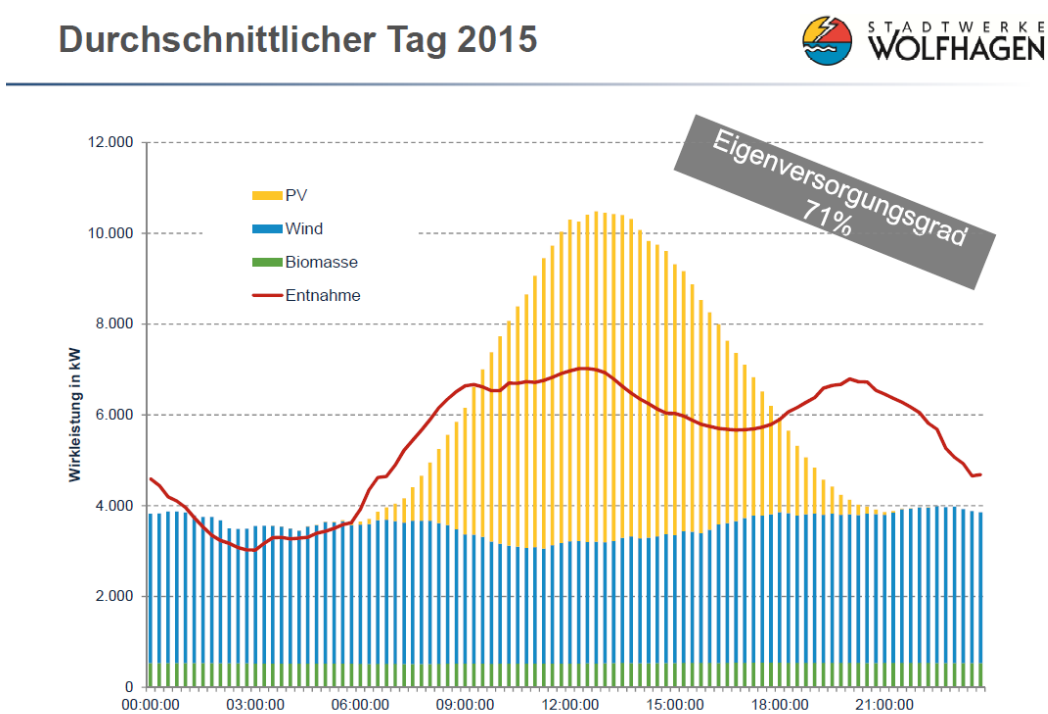


Figure 22 – Self-Sufficiency-Ratio, Supply and Demand – Source: Stadtwerke Wolfhagen

In Wolfhagen, the degree to which the consumption is covered by local renewable production is termed as the *Eigenversorgungsgrad* (Self-Sufficiency-Ratio). In 2015, Stadtwerke Wolfhagen managed a 71% ratio but aims at 90% by 2025. To achieve this, the concepts of DSM were taken into account to shift demand in times of low production to times of higher renewable production. The following figure illustrates the idea of demand shifting.

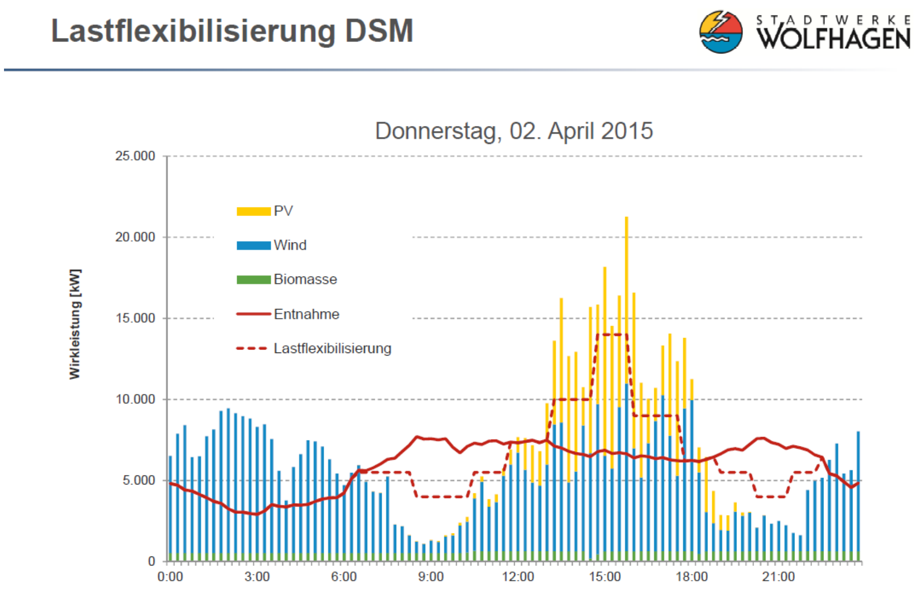


Figure 23 – Load shifting concept visualized – Source: Stadtwerke Wolfhagen

Figure 23 depicts the idea of load shifting to achieve a higher self-sufficiency-ratio. To achieve load shifting it is necessary that consumers change the way they consume energy by e.g. using home appliances at different times. In Wolfhagen, this should be achieved by providing a flexible, or, dynamic energy tariff.

It is in the interest of Stadtwerke Wolfhagen to develop new business models for the future smart grid. One idea is to sell the customer an energy management controller that was developed in the project, another to offer monitoring services for the DSM enabled smart grid. To be able to sell the smart controller to other households, or to be able to monitor devices from other manufacturers, it is important that they are compliant with the protocols and data exchange that are likely to be communication standard in the near future in Germany and Europe.

5.1.3 Wolfhagen DSM Concept

Stadtwerke Wolfhagen receives production forecasts from an external service provider. This data is uploaded once a day at 9:00 to an FTP[8]-Server. Data is then imported into a BelVis-System. Based on the consumption of the previous year, a consumption forecast is created. Both forecasts create values for each 15 minutes of the next days. The consumption and production forecast form the basis for the dynamic tariff that is created. The BelVis-System creates this dynamic tariff based on an algorithm that aims for high prices in times of short supply and low prices in times of

[8] File Transfer Protocol, a network protocol standard

expected energy surplus.[9] This tariff is again uploaded to an FTP-Server and includes the dynamic prices for the following two days. These tariffs will be downloaded once a day by the smart energy controller at the residential households, termed in the project as *Optimierungsrechner* (Optimization Computer). This device, which is running Linux, is able to communicate with smart appliances in the household and can turn them on or off based on the consumers preferences and the dynamic prices. All forecasts and prices are saved as CSV files.

Further, every household has a smart meter installed that determines the total consumption in 15 minute intervals. This data is communicated with the *Zählerfernauslesung (ZFA)* (Remote Meter-Reading) once a day at 4:00 via GSM[10].

5.2 The use case scenario

This chapter describes how the use case was created based on the information that has been available at Wolfhagen. The use case was created from the information that was gathered through an interview with the project manager of the DSM project in Wolfhagen.

5.2.1 A common understanding of actors and roles

The project description from the previous chapter uses specific terms for devices and systems although there might be systems at other companies that perform the same functions but are termed differently. It is therefore essential to have a common understanding and definition of the actors and roles involved. As was outlined in Chapter 4.2.1, Actors perform roles (a list of roles and systems and their definition is given in Annex A.1). The following table shows the mapping between the Wolfhagen terms and the actor list given in [56].

Actor Wolfhagen	Description	Actor Mapped	Definition
Optimization Computer	Smart Energy Controller that adjusts consumption based on customer preferences and price	Customer Energy Manager, CEMS	The CEM is a logical function optimizing energy consumption and or production based on signals received from the grid, consumer‟s settings and contracts, and devices minimum performance standards.

[9] It is assumed that a consumer seeks the lowest electricity bills and therefore adapts his consumption pattern in order to minimize his costs.

[10] Global System for Mobile Communications, a telecommunication standard

	signals		
FTP-Server	Receives and supplies price information	Energy Management Gateway	An access point (functional entity) sending and receiving smart grid related information and commands between actor A and the CEM, letting the CEM decide how to process the events.
BelVis-System	Receives forecasts and creates dynamic tariffs.	Actor A, Demand Response Management System	External actor (Smart Grid Market Role) interacting with the system functions and components in the home or home automation network through the energy management communication channel. Examples of such market roles are the Energy Provider, the Energy Services Provider, the aggregator, etc.

Table 1 – Mapping Wolfhagen Actors to generic actors

In the set of standards identified by the SG-CG, high level use cases are defined and organized in clusters. The cluster "Demand and production (generation) flexibility" defines the high level use case "*Receiving metrological or price information for further action by consumer or CEM"* which we see as the best fit to identify the functionality outlined above in the Wolfhagen project [15]. To fall into the high level use case, all functionality that does not relate to the generic use case is left out of scope. This includes specifically the reading of meter data.

5.2.2 Use Case diagrams

The following figure shows a simple sequence diagram showing the flow of information between the actors involved in the project.

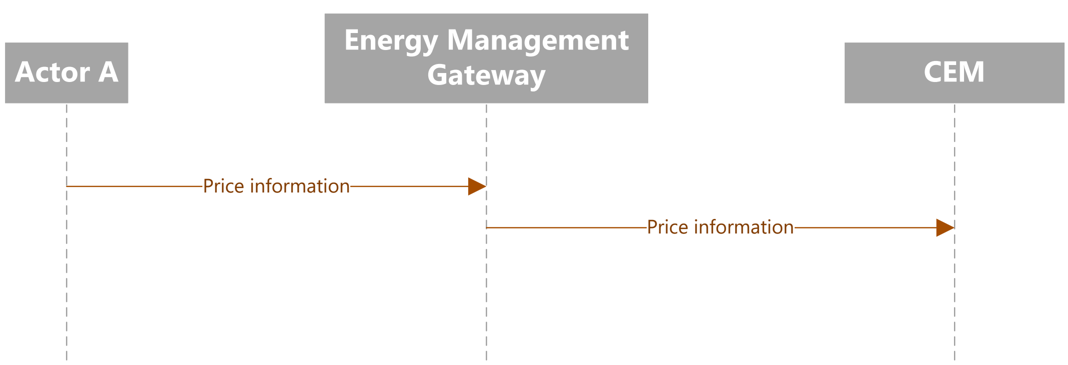


Figure 24 – Sequence Diagram showing flow of price information in Wolfhagen project

5.2.3 The final use case

All content in the use case has been developed in collaboration with Stadtwerke Wolfhagen and represents to our best knowledge the actual implementation. The focus lies on the technical implementation; therefore the business side is left out of scope. This is due to the fact that a definite market model for DR as well as legal and regulatory standards has yet to be established and the current model in Wolfhagen is therefore not able to be put to market as of now. The legal and regulatory issues will be discussed in more detail as part of our guidelines in chapter 9.

The complete use case can be found in Appendix B.

5.3 Mapping the Use Case on SGAM

The use case from Appendix B is mapped on SGAM to create a model of the current situation in Wolfhagen according to Chapter 4.3. The Microsoft Visio template available through DISCERN has been used to visualize the SGAM architecture [59]. All models are created in accordance with the description provided by DISCERN to emphasize a common understanding of the notations [60].

5.3.1 Component Layer

The component layer describes the devices that are stated in the actor list. This breaks down to the Customer Energy Management System, the Energy Management Gateway and the Demand Response Management System (DRMS) which in this case represents the BelVis-System, as outlined in Table 1. The DRMS and the Energy Management Gateway are located at Stadtwerke Wolfhagen and therefore reside in the Distribution zone. Since the CEMS is located at the residential household, it resides in the customer premises. The component layer is modeled in figure 26.

5.3.2 Function Layer

The use case does distinguish between two steps and these are translated into two distinct functions. The first is the upload of the CSV file to the FTP Server, the second the download by the CEM. This simple setup is illustrated in figure 27.

5.3.3 Information Layer

The CSV format is used with an underlying data model as shown in figure 25. The columns, in the respective order, describe 1) the date of validity, 2) the time of the day at which the price starts, 3) the end time, 4) the price per kW/h in €, 5) a tariff-number, ranging from 1-5. The layer is visualized in figure 28.

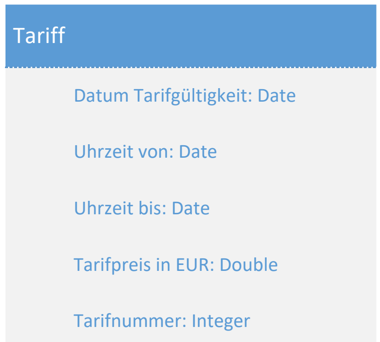


Figure 25 – Data Model

5.3.4 Communication Layer

Data is exchanged via FTP which builds upon TCP/IP. The file is uploaded once a day to the FTP server and from there it is distributed to the different households' CEMS. The process facilitates a "push and pull" architecture; data is first pushed to the gateway server and in a regular interval data is pulled from that intermediary server to the households. The concept is modeled in figure 29.

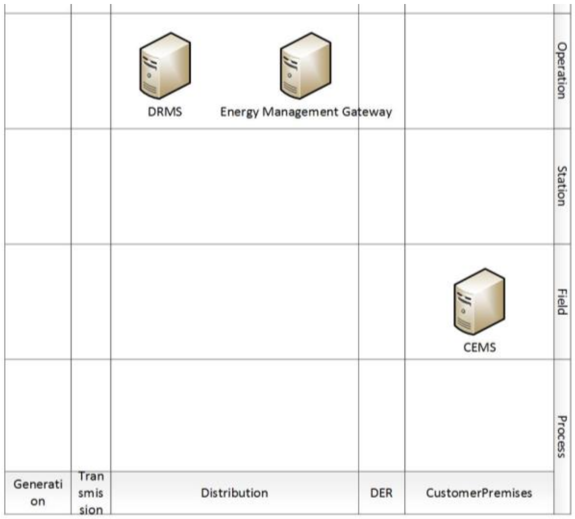


Figure 26 - Component Layer Wolfhagen

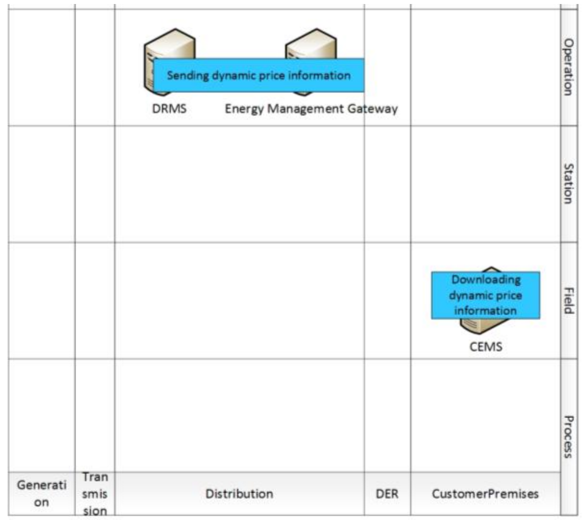


Figure 27 – Function Layer Wolfhagen

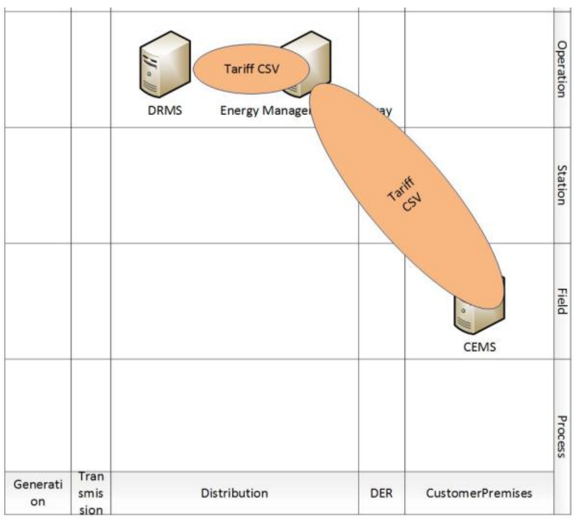


Figure 28 – Information Layer

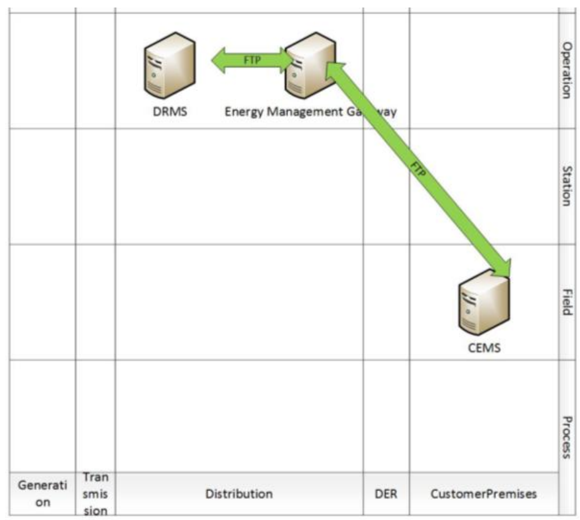


Figure 29 – Communication Layer

5.4 Review

5.4.1 Summary

Stadtwerke Wolfhagen have implemented a "push and pull" architecture for the concept of day-ahead dynamic prices. While the component and communication layer utilizes standardized protocols and systems, the information and function layer are designed individually according to the needs of the project. Nonethtless, the goal of the project is to monetize the development by bringing the custom developed CEMS to market. To realize this new business model, it is crucial to be compliant with communication and information standards in a future European smart grid.

5.4.2 Validation

Although the information has been gathered in a semi-structured interview at Stadtwerke Wolfhagen, there has been an additional interview with the head of the Wolfhagen DSM project to verify the situation has been designed correctly and according to the actual implementation. Especially chapter 5 has been audited by the expert and in general the situation was represented accurately. There have been minor changes based on the remarks, which are summarized in this section.

- The number of employees has changed since the first interview
- He especially outlined again the missing regulatory framework to make the project suitable for practice, which has been specifically mentioned but was planned for a later chapter
- The BelVis System has been mapped to the DMS (Distribution Management System) Actor. This has, in mutual agreement, been corrected to the Demand Response Management System, as the former is mere responsible for monitoring the grid, while the latter is more accurate when describing a system that controls forecasts and creates dynamic prices

Chapter 6

6 Attempts on European standardization

This chapter covers the efforts that have been identified in research to develop a common ground for demand response communication. It therefore strives to answer research question four.

We have been granted access to the Use Case Management Repository hosted by DKE (Deutsche Kommission Elektrotechnik, Elektronik und Informationstechnik (German Commission for electrical engineering, electronics and information technology)) and used by members of the SG-CG. Although the use cases have not been published yet, the DR use case for information exchange in price data has not been changed since August 2015 and is referred to as *final*. Nonetheless, the use case does not describe an actual implementation. The actors are generic, there is no information on semantic details or communication protocols given. Therefore, detailed specifications have to be considered.

In order to achieve a list of DSM specifications that cover similar functionality as the Wolfhagen case, a systematic literature review has been conducted based on the steps outlined by Kitchenham [61] to get a distinct list of DSM specifications.

6.1 Systematic literature review

Scopus was selected as the source for publications as it contains major journals and proceedings which should be representative for the current state of knowledge in Demand Side Management research. The initial search term was *"Demand Side Management communication protocol"* in article keywords, title or abstract. The result set was sorted by the number of citations and in case not all results have been reviewed, the number of results is based from the first result until the number of results reviewed. After manual review of some of the resulting articles it was obvious that the set of publications were not relevant to the actual problem. As was outlined in Chapter 3, Demand Side Management can be divided in different categories, one among them "Energy Efficiency" [7]. Energy efficiency has nothing to do with the actual implementation in Wolfhagen and is of no relevance for improving interoperability. The term *demand side management* was therefore exchanged in favor of *demand response*, which more accurately describes the efforts made in Wolfhagen. The new search term, *"demand response communication protocol"* delivered closer results, but a manual review again showed that results were either too general or served a different purpose than expected.

Results were often about general standardization or applicability of technical protocols on the OSI transport layer. In one of the resulting papers, Fan et. al. [62] describe that instead of focusing on a particular technology like wired or wireless communication techniques it is envisaged to "*achieve agreement on usage and interpretation of interfaces and messages that can seamlessly bridge different standards or technologies*". According to the paper, the main aim of communication standardization should be achieving interoperability between components rather than defining them. The search term was therefore further refined to *"demand response interoperability standards"*, which resulted in a set of 745 publications (search performed on 13-02-2017). To further restrict the number of publications, only those in the area of "Energy" or "Computer Science" have been reviewed. This reduced the set to 505 publications.

Gungor et. al. [63] define the smart grid as comprising of three different layers, the application-, power- and communication layer, in which the application layer covers demand response management and its interoperability. It further defined home energy management as the power management on consumer premises. As outlined in chapter three, the energy management system is the application responsible for sending/receiving the DR signals. Therefore, the search term was adapted to include *energy management system*. It was further decided to search in all fields instead of only title and abstract, as we are not looking for publications that specifically describe such interoperability specifications, but we just need an overview of the existing solutions. Therefore, a publication that, for example, describes a case study on DR dynamic pricing can be relevant if they, in some section, describe the interoperability specifications used to communicate between customer premise and utility. The new search term was "*energy AND management AND system AND demand AND response AND interoperability AND standards AND (LIMIT-TO (SUBJAREA , "COMP ") OR LIMIT-TO (SUBJAREA , "ENGI "))*", giving 295 results. The search has additionally been restricted to only cover the most recent results, filtering by publication year 2016 and 2017. The final search string is therefore "*energy AND management AND system AND demand AND response AND interoperability AND standards AND (LIMIT-TO (SUBJAREA , "COMP ") OR LIMIT-TO (SUBJAREA , "ENGI ")) AND (LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2017))* " resulting in 65 publications.

6.2 Appropriate specifications

The papers have been reviewed manually for specifications on demand response application communication. A distinct list of the results can be found in table 2.

Name of specification	Seen in
Open Automated Demand Response (OpenADR)	[64]
Flexible Power Alliance Interface (FPAI)	[65]
Universal Smart Energy Framework (USEF)	[65]
Energy Interoperation (EI)	[66]
IEC Common Information Model (CIM)	[66]
Weather Information Exchange Model (WXXM)	[66]

Table 2 – Resulting DR specifications from literature review

To decide which of the resulting solutions will serve as a reference specification we defined inclusion criteria for which the specifications have to comply with. These are (1) the specification has to be publicly available and free of charge, enabling widespread and easy implementation into the own programming solution, (2) it needs to specify the exchange of price information, and (3) the specification has to be tested in real world case studies and successfully used. If more than one specification will comply with the inclusion criteria, the most practiced solution will be used based on Scopus search results for case studies.

6.2.1 OpenADR

Open Automated Demand Response (OpenADR) is an open and standardized way to communicate DR signals between electricity providers and system operators and their customers using a common language over any IP-based communications network, such as the Internet [67]. According to the OpenADR specification, the OpenADR 1.0 specification was donated to the Organization of Structured Information Standards (OASIS) to create a standard for OpenADR. The OASIS' Energy Interoperation (EI) Technical Committee (TC) developed a standard to describe "an information model and a communication model to enable collaborative and transactive use of energy, service definitions consistent with the OASIS SOA Reference Model [SOA-RM], and XML vocabularies for the interoperable and standard exchange of dynamic price signals, reliability signals, emergency signals, communication of market participation information such as bids, load predictability and generation information" [68]. OASIS EI TC defines more than DR and Distributed Energy Resources (DER), therefore profiles within the EI Version 1.0 standard were created to enable specific applications within the Smart Grid. The OpenADR Alliance used the EI OpenADR profile as the basis for the OpenADR 2.0 Profile Specification defined in this document, making OpenADR a subset of Energy Interoperation specifically for DR [69]. The specification is available for free for registered users through the OpenADR.org website. Further, existing programming examples can be downloaded to enhance the understanding of the specification.

6.2.2 Flexible Power Alliance Interface

The interoperable platform *The Energy Flexibility Platform & Interface* (EF-Pi) aims to connect a variety of appliances and support a host of Demand Side Management (DSM) approaches. It was formerly known as Flexible Power Alliance Interface (FPAI) but was not practical for international use, therefore the name was changed [70]. EF-Pi documentation, specification, source code and examples are available online [71].

6.2.3 Universal Smart Energy Framework

According to the specification, USEF "unlocks the value of flexible energy use by making it a tradeable commodity and by delivering the market structure and associated rules and tools required to make it work effectively. USEF fits on top of most energy market models, extending existing processes to offer the integration of both new and existing energy markets" [13]. The specification can be downloaded for free on the usef.info website, as well as a reference implementation is available on Github [72]. USEF describes a new market model in which the price of energy is expressed in terms of *flexibility*. The specification does not cover the exchange of price information between DSO and consumer.

6.2.4 Energy Interoperation

As mentioned in section 6.1.1, Energy Interoperation by OASIS is a superset of OpenADR, describing "an information model and a communication model to enable collaborative and transactive use of energy". Since we are aiming to improve demand response interoperability, OpenADR is the preferred choice over EI.

6.2.5 IEC Common Information Model

The Common Information Model is part of the IEC 61970 series and provides a UML model for the exchange of information in an electrical network. It defines a ontology and common vocabulary [73]. Since it is available through IEC, it is not available free of charge.

6.2.6 Weather Information Exchange Model

The Weather Information Exchange Models and Schema (WXCM-WXXM-WXXS) are designed to enable a platform independent, harmonized and interoperable meteorological information exchange covering the needs of the air transport industry [74]. A conceptual model, logical data model and exchange schema are available free of charge and can be downloaded via the wxxm.aero website. The specification does not cover the exchange of price information.

Table 3 summarizes the findings so far based on the first two inclusion criteria.

Name of specification	Inclusion Criteria (1) – available, free	Inclusion Criteria (2) – enables price exchange
Open Automated Demand Response (OpenADR)	Yes	Yes
Energy Flexibility Platform & Interface (EF-Pi)	Yes	Yes
Universal Smart Energy Framework (USEF)	Yes	No
Energy Interoperation (EI)	Yes	Yes
IEC Common Information Model (CIM)	No	-
Weather Information Exchange Model (WXXM)	Yes	No

Table 3 – Specifications and inclusion criteria

Since OpenADR is a subset of EI and specifically designed for DR, OpenADR is favored over EI. USEF and WXXM do not specify the exchange of price signals and the CIM model is not available free of charge and all three are therefore excluded and irrelevant as a reference specification.

To decide on one of the remaining solutions (OpenADR and EF-Pi) another Scopus search has been performed to determine the extent of usage of both specifications in real case scenarios. This is based on the assumption that a well-tested specification is more reliable than a mere theoretical specification.

A search for *"(fpai OR ef-pi) AND case AND study) AND (LIMIT-TO (SUBJAREA , "ENER")"* listed three results and none of them highlighted the usage of EF-PI in the sense of a communication tool. The search term was broadened by removing the restriction to "case study". The new term left us with 19 papers of which all were checked for incorporation of EF-PI. The result is that only three of those 19 papers have used FPAI in their studies, and none of them used it to exchange price information in a day-ahead use case [75-77].

A search for *"(OpenADR AND case AND study) AND (LIMIT-TO (SUBJAREA , "ENER")"* listed 59 results, removing case study from the term even resulted in 173 publications. To discard EF-Pi in favor of OpenADR requires the resulting set of publications to describe at least three case studies that are based on OpenADR communication. This is already achieved by Samad et. al. who highlight the state of practice in Demand Response and describe four high profile case studies based on OpenADR. These include a pilot project in China by Honeywell and supported by the U.S. Trade and Development Agency, the China Electric Power Research Institute and the Tianjin Economic Technological Development Area. Further, it highlights a microgrid project for the Food and Drug Administration campus in White Oak, an LA Air Force Base Project to explore the usage of DR with electrical vehicles and finally the Thames Valley Vision project in the United Kingdom which envisages a high quality and affordable future electricity network by allowing customer and utility greater control as to how and when electricity is used [78].

6.3 The reference specification OpenADR

Open Automated Demand Response (OpenADR) is an open and standardized way for electricity providers and system operators to communicate DR signals with each other and with their customers using a common language over any existing IP-based communications network, such as the Internet [67]. It was developed at the Demand Response Research Center (DRRC) as part of an ongoing effort to help building and facilities managers implement automated demand response within their facilities. It was designed to allow buildings to invoke pre-planned demand shedding strategies quickly and automatically when requested by utility operations. It also enabled utilities to promote commercial and industrial participation in new power pricing programs that leverage automated demand response behavior from end users [79].

OpenADR provides non-proprietary, standardized interfaces to enable electricity service providers to communicate DR and Distributed Energy Resource (DER) signals to customers using a common language and existing communications such as the Internet. These OpenADR data models facilitate price-responsive and reliability DR. This is achieved through open Application Programming Interfaces (APIs) that provide two-way communications between the service provider (Utility/ISO) and customers (Sites) through a logical interface of an OpenADR server (called a Demand Response Automation Server, short DRAS) [80].

6.3.1 The OpenADR systems

To improve interoperability in the Wolfhagen case we need to adapt our process towards the use case as specified by OpenADR.

OpenADR uses the definitions of Virtual Top Nodes (VTNs) for the DRAS and Virtual End Nodes (VENs) for the clients as actors for communication. Any signal exchanged is between a VTN and one or more VENs, while VTNs and VENs do not directly communicate with each other. Generally in an interaction, the VTN acts as the server, providing information to the VEN, which themselves respond to the information [68].

The latest OpenADR specification defines the two actors as follows [68]:

Virtual Top Node (VTN): *An entity that is responsible for communicating grid conditions (e.g., prices, reliability events, etc.) to other entities (i.e., VENs) that control demand side resources. The VTN is able to communicate with both the Grid and the VEN devices or systems in its domain.*

Virtual End Node (VEN): *The VEN has operational control of a set of resources and/or processes and is able to control the electrical energy demand of these in response to an understood set of Smart Grid messages (i.e., DR signals). The VEN may be either a producer or consumer of energy. The VEN is able to communicate (2-way) with a VTN receiving and transmitting Smart Grid messages that relay grid situations, conditions, or events.*

The specification defines two types of communication, being *push* and *pull*. In the first, the VTN pushes new event information to the VEN, while in pull mode the VEN asks the VTN for event information. Since the Wolfhagen case itself uses a push type of communication towards the households, we will consider only the OpenADR push communication.

6.3.2 The OpenADR messages

OpenADR defines its messages as a number of services conforming the Energy Interoperation specification. These are termed *EiRegisterParty, EiEvent, EiReport and EiOpt.* These messages are sent in XML format. The detailed definitions can be found in [68].

6.4 Mapping in SGAM

With the common understanding of the actors involved, and the knowledge of the exchange of information, we are able to map the use case of price exchange according to the OpenADR specification on SGAM and compare it with the solution provided in Wolfhagen to draw conclusions in terms of interoperability.

6.4.1 Component Layer

As outlined in 5.2.1, a common understanding of the actors involved is crucial to compare different solutions. The actors of OpenADR are therefore mapped to the common use case actors defined in Annex A.

Actor OpenADR	Description	Actor Mapped	Definition
VEN	See 6.3.1	Customer Energy Manager, CEMS	See 5.2.1
-	-	Energy Management Gateway	See 5.2.1
VTN	See 6.3.1	Actor A, DRMS	See 5.2.1

Table 4 – OpenADR actors mapped to generic actors

By the definition of OpenADR, a Customer Energy Manager is the VEN, receiving signals from the VTN and controlling consumption and production of local energy according to the VTNs signals.

Actor A, or the DRMS, has the role of a VTN, as it generates and sends the price signals to the CEMs, therefore communicating grid conditions with the consumer.

Since there is no intermediary in OpenADR and VTN and VEN communicate directly, there is no need for an Energy Management Gateway. However, it might make sense to have an Energy Management Gateway that serves as an interface to translate incoming and outgoing messages in the desired semantics – e.g. facilitating OpenADR if the sender/receiver is capable of it, and using proprietary solutions if not. In this case, the Energy Management Gateway serves as either VTN or VEN. Figure 30 illustrates the component layer.

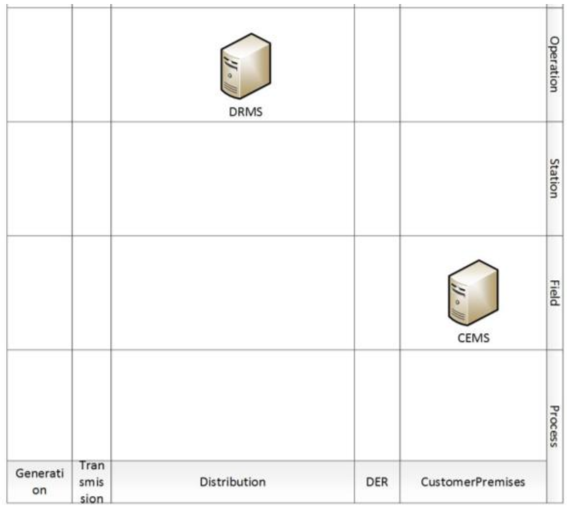


Figure 30 – Component layer

6.4.2 Function Layer

OpenADR facilitates a push pattern from the VTN to the VEN, therefore our DRMS is initiating the sending of a message to the CEMS on a daily basis and the CEMS is only a passive receiver of this information. This event is called oadrDistributeEvent and is responsible for sending event information to the receiver. Figure 31 illustrates this simple single function.

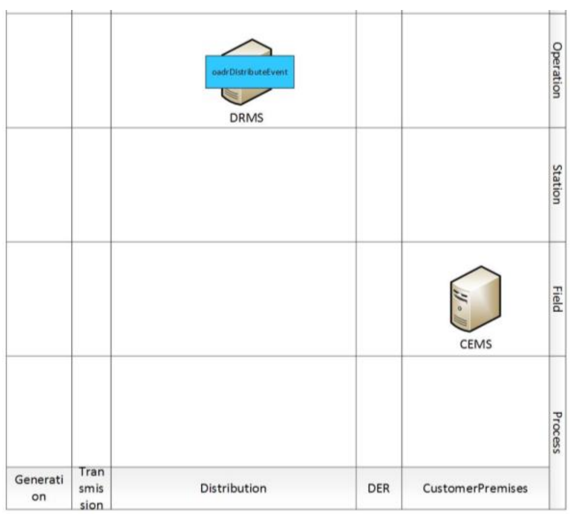


Figure 31 – Function layer

6.4.3 Information Layer

The information layer contains the data model and therefore also the data semantics. In OpenADR, information is exchanged in XML format [68]. The data model is shown in Appendix C.1. The information layer is visualized in figure 32.

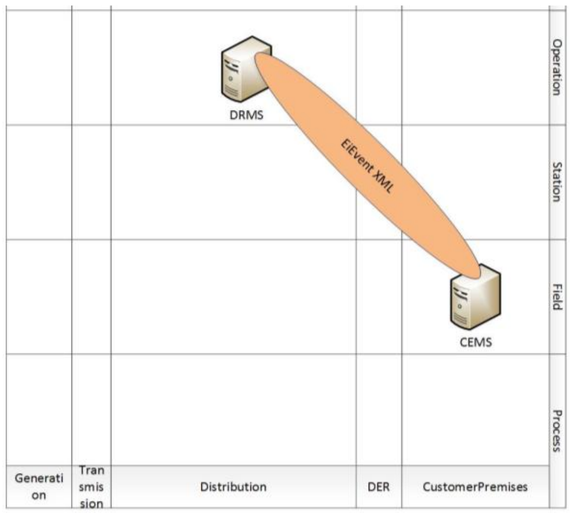


Figure 32 – Information layer

6.4.4 Communication Layer

In OpenADR, data is exchanged via HTTP or XMPP protocol. While the VTN must support both, the VEN can support either of it [68]. The communication layer is shown in figure 33.

Figure 33 – Communication layer

Chapter 7

7 Towards improved interoperability

While chapter five left us with a SGAM model of the current practice in Wolfhagen, chapter six shows the same use case on SGAM according to OpenADR specifications . To determine to what extend the Wolfhagen solution is interoperable with OpenADR, the different SGAM layers will be compared individually to determine the level of interoperability and the necessary work that has to be done to achieve interoperability.

7.1 The SG interoperability layers

To achieve a comprehensive overview of interoperability we will be determining for each interoperability layer the interoperability level according to the terms identified in 4.1.1. This results in an interoperability matrix, with the rows representing the interoperability layers and the columns the interoperability levels. The interoperability layers from the bottom to the top are likely depending on one another like the foundation of a building: if a bottom part breaks, the layers on top of it break too. If, e.g., the components in a system are different, it is highly likely that the communication layer differs and that might also affect the information and function layer. Therefore we can assume that the earlier in a bottom-up approach interoperability breaks, the costlier the achievement of interoperability will be. We therefore start the comparison with the component layer and move up the SGAM layers.

7.1.1 Component Layer

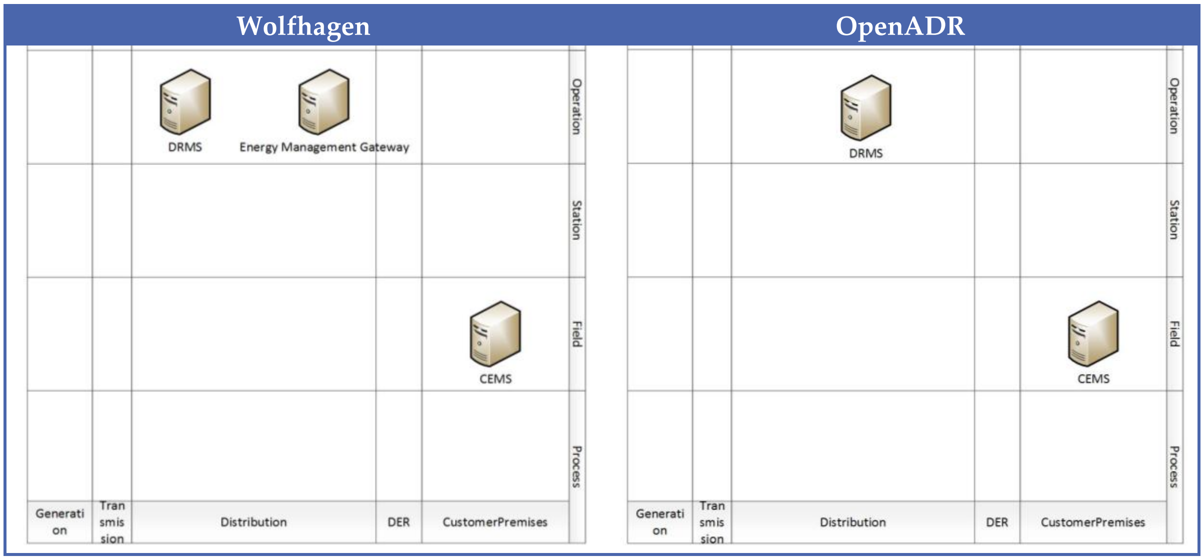


Table 5 – Component layers of the Wolfhagen DR program and OpenADR

According to the specification, OpenADR *"is intended to specify the various functions that must exist in a compliant server. It is not intended to specify the precise technology or implementation details of each of the functions in the interface."* For example, although the specification may specify that HTTP communication has to be used and an XML schema is given for the interface, no specific language or computing platform has to be used to actually implement this [81]. The VTN and VEN communicate either through XMPP or HTTP, both of which lay in the application layer of the IP stack. Since the DRMS and CEMS in Wolfhagen run on Linux and are currently exchanging information with the Energy Management Gateway via FTP, it can be deducted that both are technically capable of communicating via HTTP or XMPP protocol. This is due the fact that FTP also lays in the application layer of the IP stack, therefore already employing the hardware necessary for OpenADR communication [82]. Both component layers are confronted in table 5.

The conclusion is then that the Wolfhagen component layer is **conformant** to the OpenADR layer, as all requirements from OpenADR are met by the Wolfhagen infrastructure. It could be argued that this also fits the term fully-conformant, although it is likely possible that the current infrastructure is implementing hardware beyond what is specified in OpenADR.

7.1.2 Communication Layer

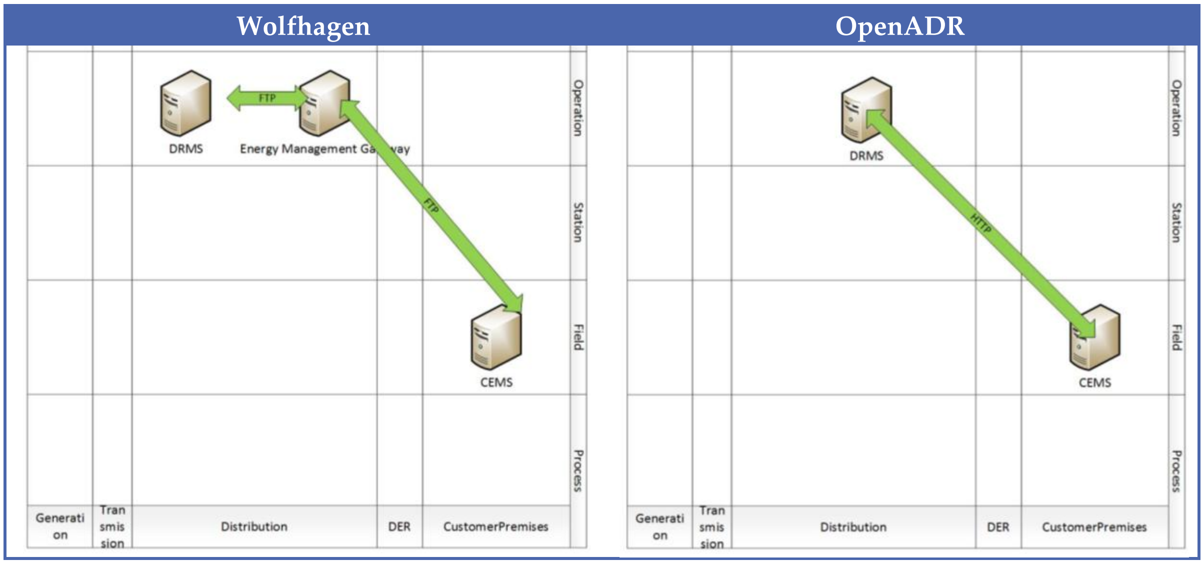


Table 6 – Communication layers of the Wolfhagen DR program and OpenADR

Within the Wolfhagen case, the current communication protocol is FTP. It lies in the application layer of the Internet Protocol stack, on top of TCP. OpenADR uses a different approach for communication, namely HTTP or XMPP. Both share the usage of TCP/IP and therefore maintain the same protocols in transport-, internet- and network access layer. Nonetheless, differences in the application layer require adaption to realize compliance with OpenADR. The Wolfhagen project is therefore **consistent** with OpenADR for the the first three layers of the IP stack, but **non-conformant** since it employs FTP instead of HTTP and XMPP. Both communication layers are confronted in table 6.

7.1.3 Information Layer

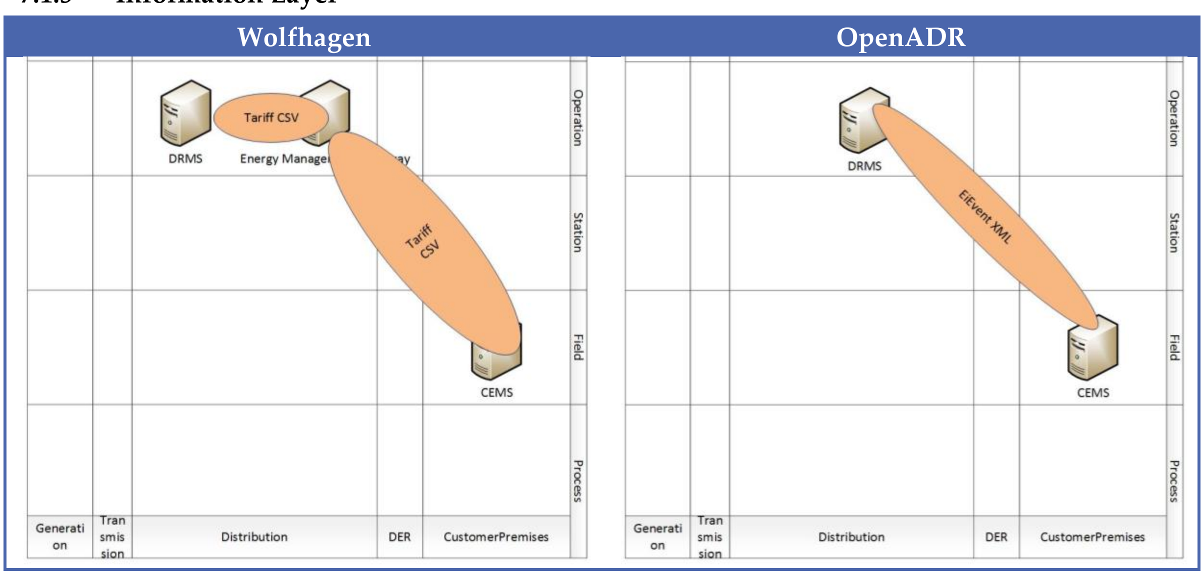


Table 7 – Information layers of the Wolfhagen DR program and OpenADR

Within the Wolfhagen case, the current datamodel is very simple. It represents one table with information on hourly prices, as outlined in 5.3.3. The data is send and received in CSV format. An example dataset (for illustration purposes we reduced the hourly rates with 8-hour rates) is illustrated below.

```
Datum Tarifgültigkeit;Uhrzeit von;Uhrzeit bis;Tarifpreis in EUR;Tarifnummer
21.09.2016;00:00;08:00;0,16;4
21.09.2016;08:00;16:00;0,26;4
21.09.2016;16:00;00:00;0,36;4
```

The OpenADR data model is more abstract as it has to cover lots of different purposes. The EiEventType from the data model can describe many different messages (not only RTP but also e.g. Critical Peak Pricing (CPP)). Depending on the values within the same table the specification defines what the contents of the message describe. OpenADR allocates XML schemas that have to be followed so that sender and receiver can interpret the content. According to the schema and the requirements from the specifications, the above example dataset has been translated to an OpenADR fully-conformant xml message which can be found in Appendix C.2.

It is therefore possible to translate the data to OpenADR, as its flexibility allows for any Real Time Pricing time intervals, including the hourly day-ahead rates applied in Wolfhagen. Nonetheless, the data model itself significantly differs from OpenADR, as does the way the data is structured. In terms of interoperability, the Wolfhagen information layer is **consistent** to the OpenADR information layer in terms of the information that is exchanged, but **non-conformant** as the schema of representation has no common ground. Both information layers are confronted in table 7.

7.1.4 Function Layer

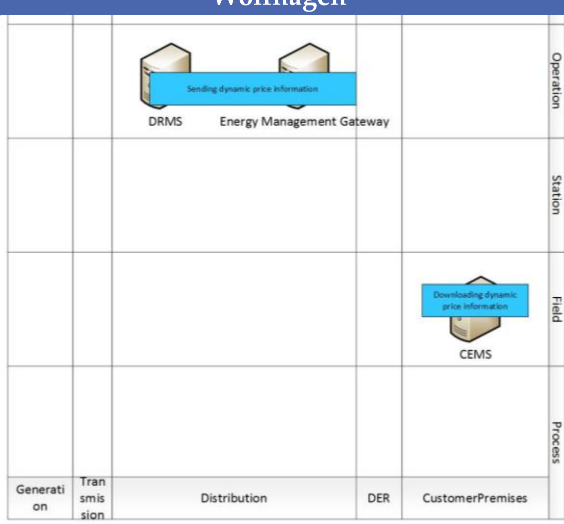
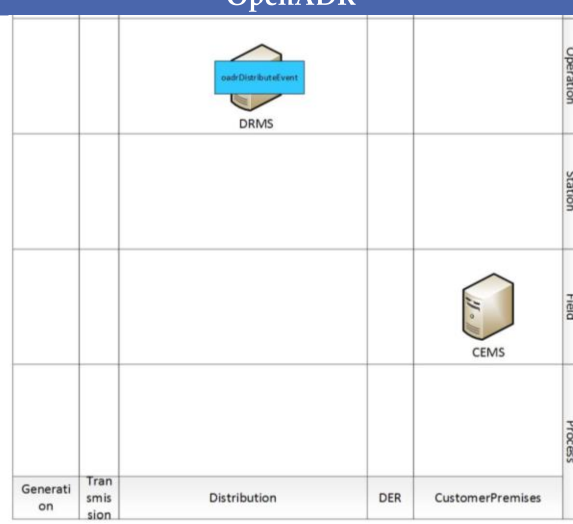
Wolfhagen	OpenADR
	

Table 8 – Function layers of the Wolfhagen DR program and OpenADR

In the current Wolfhagen DR program, there are two steps necessary to get data from the sender to the receiver. First, the sender pushes the data onto the FTP server, termed the Energy Management Gateway. At a later point in time, the receiver has to pull the data from the gateway. Within OpenADR, there can be either a pull at the receiving end, or a push from the sender. Since the DRMS first has to gather data to create the list of dynamic prices, it is desired to prefer a push pattern over a pull pattern, as the latter includes the risk of a receiver asking for data that is not yet available. In terms of use case description, the push of data from the DRMS to the receiver remains the same. The DRMS creates the dynamic prices and then sends the data to a receiver. What differs is that in accordance with OpenADR, the DRMS has to send the data for every registered receiver, while in the current situation it is only sent once and then the receiver pulled the data themselves. Therefore, this requires changes in the way the process is handled. We term the function layer therefore **consistent** since it follows the same use case description, it sends the necessary data to the receiver, but part of it is not in accordance with the specification, and therefore it is also **non-conformant**. Both function layers are confronted in table 8.

7.2 The SG interoperability matrix

The previous section indicated the interoperability levels that the Wolfhagen case has on each SGAM interoperability layer. To increase the value of the matrix that we can create from this data, it is important to understand what the interoperability levels in Chapter 4.1.1 mean for the goal of improving interoperability.

Basically, in the order stated, irrelevance, consistency, compliance, conformance and full conformance states the level of interoperability from a low level of interoperability to a high level of interoperability. The comparison of two uses cases per layer can only result in one of the previous mentioned levels of interoperability, while each level can additionally be non-conformant. That means, if the component layers of two systems are compared, they can be either irrelevant, consistent, compliant, conformant or fully conformant in terms of interoperability, but not two of them.

Please refer to 4.1.1 for the explanation of the interoperability levels.

We conclude that:

- If two systems are fully conformant, no efforts have to be done and they are interoperable.

- If the implementation is conformant to the specification, it is still interoperable as this means it has additional features that are not specified but which do no harm if the conformant system is communicating with a fully conformant system.
- If the implementation is compliant to the specification, some specifications are missing but all implementations are in conformance. This means, to become fully interoperable some additional work has to be done, but all existing work can remain untouched.
- If the implementation is consistent, some features are according to the specification. The difference to compliance is that the implementation also includes features not specified in the specification. As with compliance, additional work has to be done to become interoperable.
- If the implementation is irrelevant, all features are not according to the specification. All existing work has to be changed to become interoperable.

If on top of any of the above interoperability levels the layer is non-conformant, it means something has been implemented that does not comply with the specification. That part of the implementation has to be changed to become interoperable.

Table 9 summarizes the findings from section 7.1.

Dynamic Price Exchange	Irrelevant	Consistent	Compliant	Conformant	Fully Conformant	Non-Conformant
Function		x				x
Information		x				x
Communication		x				x
Component				x		

Table 9 – Interoperability Matrix for dynamic price use case between Wolfhagen DR program and OpenADR

7.3 Conclusion

For Stadtwerke Wolfhagen to become interoperable with OpenADR, each layer that is not conformant or fully conformant requires change or additions. The result is that the component layer can remain untouched, which represents the hardware used both at the customer premises and on the distribution site. This is crucial, as investments in the CEMS hardware remain valuable. Interoperability in the communication layer requires a change from FTP to HTTP protocol which does require software updates on both systems. This is probably the most expensive effort, since this does not only require a simple exchange of a protocol, but with the new protocol also additional requirements are introduced. The HTTP protocol requires the receiver to establish a local HTTP server, and since the receiver is residing in the consumers household it may pose additional challenges by e.g. a firewall in the local network [68]. The information layer has gaps in terms of interoperability levels, but, as shown in 7.1.3, the flexibility of the OpenADR specification makes it easily possible to translate the current data to be semantically interoperable. The function layer reveals the same level of interoperability gaps as the lower two. The way the data is exchanged requires new processes since the DRMS now has to keep hold of all receivers to be able to send the data to each CEMS. Nonetheless, it is highly likely that the DRMS already keeps track of all CEMS since it is common practice to receive the usage data from the CEMS anyway.

The total effort in changing the implementation can only be roughly estimated, as it depends on many factors, among others the software programming. If all software is written according to OOP best practices, it might be less expensive to exchange a messaging protocol. The matrix gives an overview of critical points and can help as a starting point in improving interoperability to achieve compliance with a specification, identifying the areas which need special consideration.

Chapter 8

8 Discussion

The previous chapters have given insight in the necessity of demand side management in a future European smart grid to achieve the goals set by EU policies towards a reduction of energy consumption and the generation from renewable energy sources. It was outlined that standards are necessary to encourage global application of these smart grid features and how interoperability between two smart grid systems can be compared. Based on a field study on demand response in Wolfhagen, the implementation of the DR project in Wolfhagen was compared to a reference specification, in this case OpenADR.

8.1 The interoperability matrix

The interoperability matrix evolved by the need to describe the level of interoperability between two systems. With SGAM it was possible to have a form of description for a system, a frame that is related to smart grids and therefore easily adaptable for the implementation and specification that has been investigated. But with both systems described in terms of SGAM, it was still necessary to describe the differences in terms of interoperability. The interoperability levels outlined by the SC-CG seemed to be a good way to start.

Yet there are some drawbacks with these terms. The "level" of interoperability between irrelevant, consistent and compliant can be huge. If most of the two systems in comparison is different and only a small function is the same, the level is termed as consistent. But on the other hand, if almost all of the system is compliant but a small part is not, it is also termed consistent. With that definition in place, a lot of functions or systems under comparison may be termed consistent. The comparison of the day-ahead price exchange use case between the Wolfhagen implementation and the OpenADR specification highlights this problem. Therefore it may make sense to break the system down in smaller parts. It is questionable how big these decompositions have to be to yield better results in terms of interoperability levels while still preserving the necessity to map them on different layers according to SGAM. This is especially visible in the function layer, where it is difficult to assess a level of interoperability, since even though the functionality might be the same, it cannot easily be recognized due to many factors like the name of actors or the wording of functions.

8.1 A different market model: the concept of flexibility

The decision for OpenADR was based on inclusion criteria, namely 1) that the specification is publicly available and 2) that it enables the communication of day-ahead dynamic prices. In this process, e.g. USEF was left out of scope as a reference specification, because it does facilitate a different market model and therefore does not include the direct communication of day-ahead dynamic prices between DSO and consumer. This choice was made because Stadtwerke Wolfhagen decided for their specific market model and the reference specification should only provide a documented standard for the business processes and use cases that are already in place to reduce the budget necessary to improve interoperability.

Nonetheless, it is yet unclear how the future market model of the European smart grid will look like. The European market models related to Smart Grids will be under increased discussions in the forthcoming years. The EU intends to implement a single European Market for energy, although existing models differ across EU member states and therefore a common European market model is an unlikely concept at this point in time [54]. It might be possible that future energy pricing will be based on a different model than the day-ahead pricing exercised in Wolfhagen, e.g. the concept of flexibility as outlined in Chapter 3.3.

Hence, it is difficult to give suggestions of best practices as it is still unclear how the market model will develop in the future. A different market model may involve changes to the business and function layer. This poses a dilemma for the work of this thesis, namely to define recommendations for improving interoperability in demand response: How can we improve interoperability if we do not know how the market model will affect the functionality? Since there is no definite solution in sight, there is a situation of uncertainty. In a situation of uncertainty, assumptions have to be made about a future state and based on those assumptions, recommendations can be described. In the previous chapters, our assumptions have been that the most researched and tested demand response protocol is most likely to become a global standard in the future. Based on this assumption, the level of interoperability between the current DR implementation in Wolfhagen and OpenADR as a DR specification has been compared.

To enable a market model that facilitates flexibilities instead of dynamic prices, its own trading market is required. If such a trading market would evolve, the currently deployed day-ahead dynamic price concept will not be applicable in the future [13].

The flexibility concept has been object to many pilot projects (examples are the EU funded MIRACLE [83], USEF [13] ,ADDRESS [48], eFlex [84] and Grid4EU [85]), reaching consumers in more than 20 countries and serving more than 500.000 consumers. If we assume that a future market model around flexibilities will emerge, then the level of interoperability has to be compared to a different reference specification, and the result will be different than what has been shown in Chapter 7 now.

8.2 Barriers of entry

It is important to mention that regardless of whether the future market model will promote flexibilities or day-ahead pricing, the current regulations pose barriers for either concept to succeed in the market.

The TSO and DSO are both regulated monopolies; therefore they need to comply with regulatory requirements. They should be neutral market facilitators, rather than active market participants, limiting their options regarding capturing the value streams from day-ahead dynamic prices or flexibility [39].

A SWECO report to the EU identified several different barriers for a new market model, e.g. a **lack of markets** in which, in an organized way, DER can supply services to large markets or where storage can provide services, a **lack of market access** even when there would be a market due to price barriers or technical specifications, a **lack of price pass-through** in which prices cannot be properly passed-through to the consumer because of regulatory barriers concerning regulated end-user prices that are not flexible enough. In e.g. Germany, the DSO is not necessarily the energy supplier, making it complicated to pass price incentives to the consumer [39]. A **pricing model** is also identified as one of the barriers for DR to emerge in [48]. It is further outlined that **economic regulation of DSOs** plays a significant role for the future market model. To stabilize the grid DSOs have the option of investing in physical infrastructure or solve problems with DR programs and DER. The first introduces higher investments (CAPEX) while the latter increases operational costs (OPEX). The regulatory incentives for DSOs typically don't reward CAPEX-OPEX optimization. The regulatoy models are stated to be compromises between cost-reflectiveness and incentives for efficiency, leaving the DSO with a either-or situation [39].

Other barriers identified are c**ontractual issues** that do not provide the required flexibility for using DR as a means to fulfil contractual obligations, c**onflicting interests** that can occur among e.g. DSOs / TSOs having to assess the technical feasibility of DR services [48].

8.3 Recommendations

During the phase of this research a vast knowledge has been acquired in the field of smart grids, especially in Demand Response, the standardization process, the attempts to find new market models and the technical specifications for Demand Response and therefore Demand Side Management projects. Based on this experience, several recommendations can be made towards Stadtwerke Wolfhagen to improve their interoperability.

Since there is a level of uncertainty towards the future market model and regulations that will be applied to the EU energy sector, the recommendations are split in two – a short-term and a long-term recommendation. This is backed by the fact gained during an interview in Wolfhagen that the current project is on limited budget and already some features for the current pilot project had been spared.

8.3.1 Short-term recommendations

The current solution is not future-proof, as it does not encourage any semantic interoperability towards other DR programs. The likeliness of the individually developed CEMS to become available in the market without taking into account the standardization efforts that have been undergone in EU funded programs or research is low, as it is resulting in a product that is incompatible to other energy suppliers or products. To increase interoperability, the CEMS (*Optimierungsrechner*) should incorporate a communication gateway that is able to understand different communication protocols. The fact that the hardware is compatible with OpenADR would require a cost-effective short-term effort to make the software compatible with the US standard for DR communication. Even if OpenADR is not going to be a European DR communication standard, it will be later on easier to implement additional communication standards. Even for a model facilitating flexibility, the CEMS is an integral part of the architecture. Since the CEMS is the main factor for monetization of the project , it is vital to stay ahead of the developments in the market and develop the software accordingly. As soon as a standard is defined, the time-to-market is reduced significantly. OpenADR and USEF have signed a memorandum of understanding to integrate the universal framework USEF with the DR communication standard OpenADR in 2015. By the end of 2016 OpenADR has already adopted new DR program templates according to USEF specifications [86]. The partnership with the European universal framework can be an indicator that OpenADR can become established in Europe in the long run when it comes to communicating DR signals. As we have shown in Chapter 7.1.3, translation to a OpenADR compliant XML message can be done with the data given in the current project. The development costs to become OpenADR compliant should therefore be manageable.

8.3.2 Long-term recommendations

In the long run, Stadtwerke Wolfhagen should consider a partnership with one of the global players in DSM automation. In Chapter 8.1, pilot projects that facilitate flexibility have been outlined. One of the key market players in Europe is likely USEF, where work continues to deliver a universal smart energy framework [87]. Within these different projects, the budget has been multiples of that given in Stadtwerke Wolfhagen, with consumers stretching over different European countries. These programs tested new market models and therefore cover more scenarios of the future European smart grid. To make the CEMS ready for a future market, we advise to further provide interoperability for these markets. Since in that case also the component layer will change, processes will inevitably change as well. This will include a change on many aspects of the current CEMS development. Nonetheless, it is likely that a lot of functionality that has already been invested in the CEMS can remain, e.g. the frontend design for the consumer, the administrative features, the data exchange of consumer behavior, etc.

In this situation of uncertainty it is unclear whether a specific specification will become European standard, and therefore investing in interoperability can have zero return on investment. Yet waiting for a definite standard will significantly reduce the time-to-market when the right market models are in place, which could result in a product that comes to market when it is already saturated. The best decision depends on the budget available and the ability to take risks. In this dilemma, waiting reduces costs of development but increases risks of becoming irrelevant in an emerging market. Developing ahead of a standard increases development costs because there might have been developments that are irrelevant in a future market, but that decrease the time-to-market when a standard has emerged.

Chapter 9

9 Conclusion

The current research shows the level of interoperability of a smart grid demand response program at Stadtwerke Wolfhagen compared to a reference specification, in this case OpenADR. Based on the results of this research, this chapter gives recommendations for Stadtwerke Wolfhagen to improve interoperability.

9.1 Results

As defined in Chapter 2, the main research question is:

> ***How can Stadtwerke Wolfhagen improve interoperability in their Demand Side Management pilot project?***

In order to answer this, the research question has been decomposed into several sub-questions which will be reflected on in this section.

1) *What is Demand Response? What are the current developments in DSM and DR?*

To answer the first question, a literature study has been performed to understand the terms Demand Side Management and Demand Response. To understand the necessity for DSM it was necessary to analyze the current energy grid infrastructure and the developments in information technology that enable the automation of DR.

The best description of DSM in our point of view was given by Hu et. al., whom defined that DSM *"refers to leading power users to scientifically and rationally use power and save power by taking effective measures to improve power energy utilization efficiency, optimize resource allocation, protect environment, and accomplish power consumption management activities carried out with power service at the lowest cost."* [44]. DR is a subset of Demand Side Management, relying upon a concept of price incentives to encourage the consumer to participate in programs that shift or shed the consumption of power to become more energy efficient. In a typical DR scenario, information is exchanged between the consumer and either the DSO or an aggregator. Between both parties, DR signals are sent between computer systems that influence the consumption of energy. The computer system at the consumer premises is called customer energy management system, or short CEMS.

2) Which framework can be used to efficiently analyze DSM developments?

The answer to the second research question is a necessity to achieve a common understanding of a program or project in standardized terms, making two different programs comparable. It was necessary to find a framework that would fit the individual needs of the smart grid, hence highlighting the technological and business side of a project in terms of the subject domain of the smart grid. The SGAM architecture was developed to achieve exactly that: visualization of developments in the smart grid domain and identifying standardization gaps. In accordance with a EU mandate to enable continuous standard enhancement and development in the field of smart grids, the Smart Grid Coordination Group (SG-CG) was established by a cooperation between CEN (European Committee for Standardization), CENELEC (European Committee for Electrotechnical Standardization) and ETSI (European Telecommunications Standards Institute) [16]. This coordination group has been responsible to develop the framework that enables ESOs to continuously develop standards in the field of smart grids. The framework was used to visualize the details of different DR implementations and specifications in a standardized way. The architecture consists of five different interoperability layers, smart grid domains and zones.

3) To what extent have the identified DR methods been implemented in the Wolfhagen DR project?

To answer the third research question, it was necessary to get a detailed picture of the developments of the DR pilot project in Wolfhagen. Therefore, a semi-structured interview has been conducted with the project manager of the DR project in Wolfhagen. This included the interview along with live demonstration of program from a consumer and DSO point of view.

Stadtwerke Wolfhagen implemented a day-ahead dynamic price model, in which every day at 9am hourly energy prices for the upcoming two days are sent digitally to the self-developed customer energy management system (CEMS). The CEMS decides based on consumer preferences when to best switch on or off appliances. The communication of data is developed individually and does not adhere to semantic standards.

4) What standard developments in DSM have been undertaken that can function as a reference specification?

Answering the forth question required an intensive literature review to determine what efforts have already been undertaken to develop an agreed upon standard in the communication of DR signals. According to an emerging set of keywords, the research database Scopus was searched for articles that mentioned DR specifications or projects. The resulting list of specifications was checked against inclusion criteria to reduce the number of specifications. OpenADR emerged as the best choice according to the relevant criteria.

5) To what extent aligns the observed pilot project with the reference specification?

To answer the fifth research question, it was necessary to compare the results of the implementation from RQ3 with the reference specification from RQ4. The framework that came forth from RQ2 served as the basis for comparison, along with a set of interoperability levels that have also been identified while answering RQ2. The interoperability levels, together with the interoperability layers, were formed to an interoperability matrix which visualizes the working points to improve interoperability.

After applying this method, the implementation in Stadtwerke Wolfhagen shows interoperability gaps in three of the four interoperability layers that have been examined: the communication, information and function layer. In all layers, the level of interoperability has been equally different according to the terms used. A specific *extent* of interoperability remains to be defined, as there is not one metric yet to formulate interoperability in terms of comparable numbers.

6) What steps can be taken to improve interoperability?

The interoperability matrix highlights the gaps in the different layers, giving a first indication on where to adjust the current implementation to become interoperable with the reference specification. Nonetheless, this research showed that since there is no definite standard yet, it might not be the best choice to actually improve interoperability towards one specific reference specification, since it is unclear whether the reference specification will become international standard in the future. A different market model might evolve which could mean that the currently taken DR approach of day-ahead dynamic prices will be irrelevant in the future. In such a case, the adaptions to the CEMS are significantly different to improve interoperability than what they are when adapting to a reference specification that supports the same market model.

Since the general processes for consumers remain consistent for either market model – improving energy efficiency by shifting energy load to different time periods – it may make sense to develop a communication gateway on top of the CEMS that is able to communicate in different standards. Still, a different market model, like the one utilizing flexibility, will also likely be accompanied by changes throughout the software, therefore resulting in higher costs for improving interoperability.

To **summarize** the findings and answer the main research question, we conclude that there is not one best way to improve interoperability at this moment. The decision that Stadtwerke Wolfhagen has to make will be based on the assumptions about a future market model. The research shows that the market model will change, but there is still uncertainty about the actual changes. With that uncertainty at place, there is not one reference specification that is sure to represent the future energy market. To decide for one or many specifications depends on the financial budget for new developments and the willingness to take the risk of developing in the wrong direction. Since the current implementation is unlikely to result in a product that is market-ready, it is necessary to develop towards something new. The question is wether to wait for a definite standard or stay ahead of the competition and reduce the time-to-market when a standard has established.

This thesis provides the necessary knowledge to improve interoperability by showing a way to identify the gaps in interoperability towards a reference specification. If Stadtwerke Wolfhagen is willing to become OpenADR compliant, this thesis already delivers a translation of their current data model to an OpenADR XML message. Further, it shows which layers have to get further attention for development. If, on the other hand, another specification is chosen as a reference, the thesis can be seen as a guideline towards improving the interoperability by starting with the knowledge of Chapter 5, mapping the new specification on SGAM and compare the two systems according to the interoperability matrix.

9.2 Limitation

The conclusions that can be drawn from this research are subject to limitations based on the methods involved, and of the limited timeframe that was available to conduct this research.

In chapter 5, the information about the case in Stadtwerke Wolfhagen is outlined. This information was derived from an interview with the head of the DR program. The information is therefore limited by his knowledge of the subject domain and his knowledge of actual information. It was not possible to have first hand insight in the actual programming of the software.

Further, in chapter 6, the reference specification is chosen. To retrieve a list of potential specifications, a form of literature review has been conducted to deduct the specifications. This has been based on some keywords that have been used based on best-knowledge of the field and try and error. We cannot guarantee that these keywords cover all articles that name a technical demand response program specification. Furthermore, the search was limited to the Scopus research database. This might have excluded specifications that are the result of other pilot projects that come from the field of practice and have not yet been published in the field of research. Nonetheless, there has to be some restraints to keep the level of depth and therefore amount of time manageable.

Further, the recommendations in chapter 8 are based on assumptions about a future market model that has yet to emerge. The assumptions are made based on information gained through literature but can be subject to change. Given the uncertainty, it is difficult to recommend a solution for improving interoperability, since there is always the risk of investing in a solution that is not future proof.

9.3 Contributions

This thesis analyzed a pilot project in demand response at Stadtwerke Wolfhagen and how interoperability within it can be improved. This has been done by investigating the status quo of demand response program specifications and comparing the implementation with a reference specification. To be able to compare two systems in terms of interoperability, the implementation and the specification have been mapped onto a framework in the context of smart grids, the Smart Grid Architecture Model (SGAM).

The research on SGAM as a smart grid framework is still moderate. This thesis is a working example of how a use case in practice and from a specification can be mapped upon SGAM. Further, the interoperability matrix has evolved by putting the interoperability terms defined by the Smart Grid Coordination Group [51] in context of the interoperability layers, which originated from the GridWise Interoperability Context-Setting Framework [57].

The contribution for the research field is a working example of interoperability gap analysis in the field of smart grid developments with an easy to interpret matrix that visualizes these gaps. Furthermore, the recommendations that have been derived from the matrix contribute to identify business opportunities and risks for Stadtwerke Wolfhagen when determining a future proof strategy for the demand response program.

9.4 Future research

This thesis used the SGAM framework to analyze a demand response pilot project and detect interoperability gaps towards a reference specification. From the work the interoperability matrix evolved to give an easy to understand visualization of the gaps of interoperability between two systems.

The thesis highlighted the uncertainty in the European market model. There are different market model developments but it is unclear in which direction the market will actually evolve. Quantitative research to highlight all potential market models and afterwards qualitative assessment on the likeliness of adoption will help clarify in which direction the market will develop.

This thesis used Scopus as an information basis to deduct a list of demand response specifications for comparison with the case study. This list is by no means comprehensive. Future research should build on the foundation of this small list and extend it to other information sources than Scopus alone.

The terms used in the matrix have been outlined by the SG-CG but there is still room for interpretation when comparing two systems with the terms given. To make the matrix more reliable, and therefore the conclusion drawn from its results more meaningful, it would be helpful to have a clear definition of when two functions or systems are irrelevant, consistent, compliant or conformant. A possible method could be to create a structured questionnaire that, depending on several standardized multiple choice questions, declares the level of interoperability. A possible result would be a new scale of interoperability that improves understanding and validity.

The matrix that has been developed should further, additionally to the necessary improvements in interoperability levels, be validated. Validating the expressiveness could occur by assessing several implementations that need improved interoperability towards a specific specification. By first creating the interoperability matrix for each implementation, it should be clear which implementation is close to interoperability and which implementation needs to most work. By actually working towards interoperability on each implementation and comparing the effort it took to achieve interoperability in comparable numbers (e.g. hours worked, or amount of money spent) the meaningfulness of the matrix can be validated.

Annex A - SGAM

A.1 Generic Actor List

Generic Actors / Roles, important in DR, extracted from [56].

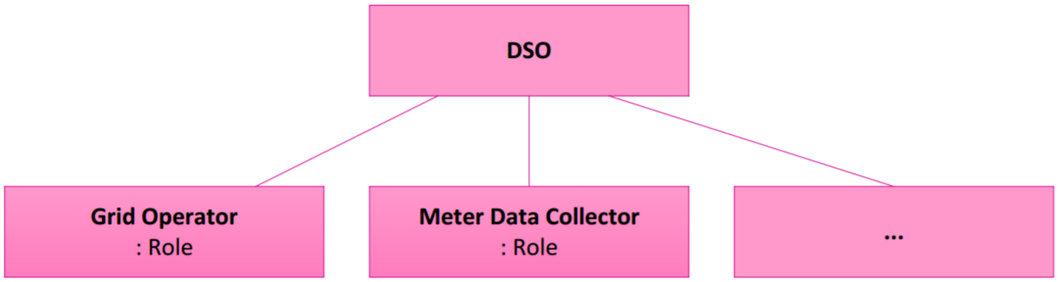
Name	Actor Type	Actor Description
Actor A	External Actor	External actor (Smart Grid Market Role) interacting with the system functions and components in the home or home automation network through the energy management communication channel. Examples of such market roles are the Energy Provider, the Energy Services Provider, the aggregator, etc.
Actor B	External Actor	External actor (Smart Grid Market Role) interacting with the system functions and components in the home or home automation network through the metering communication channel. This actor is responsible for collecting metering data. Examples of such market roles are the DSO, metering company, etc.
AMI System	System	Advanced Metering Infrastructure System
Appliances	System	Object devices
Consumer	Role	A party that consumes electricity.
Customer Energy Manager (CEM)	Role	The CEM is a logical function optimizing energy consumption and or production based on signals received from the grid, consumer"s settings and contracts, and devices minimum performance standards. The Customer Energy Manager collects messages sent to and received from connected devices; especially the in-home/building sector has to be mentioned. It can handle general or dedicated load and generation management commands and then forwards these to the connected devices. It provides vice versa information towards the "grid / market". Note that multiple loads/generation resources can be combined in the CEM to be mutually controlled. When the CEM is integrated with communication functionalities it is called a Customer Energy Management System or CEMS.
Customer Energy Management System	System	Energy management system for energy customers to optimize the utilization of energy according to supply contracts or other economical targets. Is responsible for gathering flexibilities within the customer premises and providing them to an aggregator, and therefore does not directly participate in flexibility markets
Customer Information System	System	System or application which maintains all needed information for energy customers. Typically associated with call center software to provide customer services like hot-line etc.
Customer Portal	Application	Web-server application which allows utility customers to register and login to retrieve information about their tariffs, consumption and other information.
Demand Response Management System	System	a system or an application which maintains the control of many load devices to curtail their energy consumption in response to energy shortages or high energy prices
Distribution Management System	System	a system which provides applications to monitor and control a distribution grid from a centralized location, typically the control center. A DMS typically has interfaces to other systems, like an GIS or an OMS
Distribution System Operator (DSO)	Role	a natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other systems and for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity. Moreover, the DSO is responsible for regional grid access and grid stability, integration of renewables at the distribution level and regional load balancing.
Energy Management Gateway	System	An access point (functional entity) sending and receiving smart grid related information and commands between actor A and the CEM, letting the CEM decide how to process the events. The communication is often achieved through an internet connection of through a wireless connection.
Grid	System	Bulk power systems including power generation, transmission, and MV distribution.
Grid Access Provider	Role	A party responsible for providing access to the grid through a local metering point and its use for energy consumption or production to the party connected to the grid.
Grid communications network providers	Role	Plan, build and maintain the communications systems that enable the data communication required to maintain grid stability, load balancing and fault

		protection systems by a TSO or DSO. This function is mostly executed by the TSO or the DSO, or may be performed by an independent actor but the overall responsibility and ownership of information remains with TSO and DSO.4 Grid communications network provider ensures compliance with the agreed service levels (Service Level Agreements including quality of service, data security and privacy) and compliance with any national and/or international regulations as necessary;
Grid Operator	Role	A party that operates one or more grids.
Head End System (HES)	System	Central Data System collecting data via the AMI of various meters in its service area. It communicates via a WAN directly to the meters and/or to the NNAP of LNAP.
LNAP	System	The Local Network Access Point is a functional entity that provides access to one or more metering end devices, displays and home automation end devices connected to the local network (LN). It may allow data exchange between different functional entities connected to the same LN.
Meter Data Collector , MDC	Role	A party responsible for meter reading and quality control of the reading.
Meter Data Management System, MDMS	System	System for validating, storing, processing and analyzing large quantities of meter data.
Producer	Role	A party that produces electricity
Simple external consumer display	System	Display providing accurate information on consumption, tariffs and so on in order to increase consumer awareness.
Smart appliance (white goods)		An example of a smart device is a smart white goods appliance which is an appliance that has the capability to act in response to a signal from the grid and thereby optimize its behaviour towards the energy supply network. The signal can be received from a utility or a third party energy service provider directly or via a home energy management system. The signal can be information like the cost of energy or the amount of available renewable energy, or it can be a Demand Respond signal (delay load signal or other related information) that the appliance must receive, interpret and react upon based on pre-set or active consumer input. The smart appliance is not guaranteed to respond, but will do so based on its status and user settings in order to ensure the expected performance. The consumer has the ultimate control of the appliance and can override any specific mode (e.g. override a delay to allow immediate operation, limit delays to no more than a certain number of hours, or maintain a set room temperature). Any appliance operation settings or modes shall be easy for an average, non-technical consumer to activate or implement.
Smart Meter (SM)	System	The metering end device
Smart Metering gateway (LNAP)		An access point (functional entity) that allows access to one or more metering end devices and, when equipped with an interface, to advanced display / home automation end devices connected to the local network. A LNAP also may allow data exchange between different functional entities connected to the same LN. The LNAP may act simply as a router transferring messages between the metering end device and/or display/home automation devices and the Neighbourhood network of wide area network. It may also provide services including protocol conversion, device management, security and service capabilities. Services may be provided as functions of the LNAP itself or provide proxy services on behalf of limited capability devices connected to the local network

A.2 Definition of meta-model terms

Term	Definition	Source
Party	Parties are legal entities, i.e. either natural persons (a person) or judicial persons (organizations). Parties can bundle different roles according to their business model. *Examples*: real organizations like Dong Energy, Liander, APX Group	[52]
Responsibility	Responsibilities define external behavior to be performed by parties. *Examples*: Nominate Energy, Operate a grid, Determine the market energy price after applying technical constraints	[52]
Role	A Role represents the intended external behavior (i.e. responsibility) of a party. Parties cannot share a role. Parties carry out their activities by assuming roles, e.g. system operator, trader. Roles describe external business interactions with other parties in relation to the goal of a given business transaction. *Examples*: Balance Responsible Party, Grid Operator, Market Operator.	[53]
Actor	An Actor represents a party that participates in a (business) transaction. Within a given business transaction an actor performs tasks in a specific role or a set of roles.	[53]

Roles should be generic and atomic, i.e. they cannot reasonably be further decomposed. 'DSO' and 'Energy Supplier' are prominent examples that can be considered bundles of roles in terms of the EU market model. Standards should be designed around the atomic roles rather than bundles to avoid incompatibility with the market models in the EU member states. But using also generic use cases by nature implies to use bundle roles. When coming across e.g. the terms such as 'DSO' or 'Energy Supplier' consider decomposing them as depicted in Figure 6 and Figure 7. In general one should aim for using roles which are as atomic / indivisible as possible, e.g. as provided by the HEM-RM [54].



[54]

A.3 SGAM Interoperability Layers

The following table gives a brief overview of the five different interoperability layers defined by the SG-CG [29].

Layer	Description
Business Layer	The business layer represents the information exchange in smart grids from the viewpoint of a business. SGAM can map economic structures, business models, products and services of different market parties. It further allows for representation of business processes and business cases.
Function Layer	The function layer describes functions and services. These may have relationships and are represented from an architectural viewpoint, independent from actors and physical implementations. They are extracted from use case functionality which is independent from actors.
Information Layer	The information layer describes the information that is being exchanged and used between functions and services and contains the underlying data models. These information objects represent the common semantics to allow interoperable information exchange.
Communication Layer	The communication layer describes the protocols and mechanisms for the interoperable exchange of information between components.
Component Layer	The component layer describes the physical participating components in the context of the smart grid. It includes system actors, applications, power system equipment, network infrastructure and any kind of computers.

A.4 SGAM Domains

The following table gives a description to the five different SGAM domains, extracted from the conceptual model, based on [29].

Domain	Description
Generation	The generation domain represents bulk generation of electrical energy such as fossil, nuclear or off-shore wind farms typically connected to the transmission system.
Transmission	Transmission represents the infrastructure and operations which transport electricity over long distances.
Distribution	Distribution represents the infrastructure and operations to distribute electricity to customers
DER	DER represents distributed energy resources that are directly connected to the distribution grid, applying small-scale power generation technologies. These may be directly controlled by the DSO.
Customer Premises	Customer Premises represents customers of energy that at the same time can be producers of electrical energy. It includes industrial as well as commercial and home facilities.

A.5 SGAM Zones

The following table gives an overview of the six different SGAM zones [58].

Zone	Description
Process	The process zone includes transformations of energy and the physical equipment directly involved. Examples are generators, transformers, cables, electrical loads or any kind of sensors directly connected to the process.
Field	The field zone includes equipment to control, protect and monitor the power system process. Examples are any kind of intelligent electronic devices which use process data from the power system, protection relays or bay controllers.
Station	The station zone represents the areal aggregation level for the field zone. Examples are data concentration, functional aggregation, plant

	supervision or substation automation.
Operation	The operation zone hosts power system control operations in its respective domain. Examples are Distribution Management System (DMS), EMS, VPP Management Systems or EV fleet charging systems.
Enterprise	The enterprise zone represents organizational and commercial processes, services and infrastructures on enterprise level (utilities, service providers …). Examples are asset management, logistics, staff training, customer relationship management or billing and procurement.
Market	The market zone reflects the market operations that are possible along the energy conversion chain. Examples are energy trading, mass market or retail market.

Annex B – Wolfhagen DSM Use Case

1 Description of the Use Case

1.1 Name of the Use Case

Use Case Identification		
ID	**Area / Domain(s)/ Zone(s)**	**Name of the Use Case**
SW-WH-1		Sending and receiving dynamic price information

1.2 Version Management

Version Management

1.3 Scope and Objectives of Use Case

Scope and Objectives of Use Case	
Scope	The scope of this use case is the communication between the CEM at a household and the actors sending data to it. The communication between in-house devices and the CEM is left out of scope. This use case only describes the exchange of dynamic prices as soon as they are available. It does not include the algorithm to create the tariff, nor how the information that the dynamic price depends on is received.
Objective(s)	The objective of this use case is to describe the information exchange of dynamic prices (tariffs) between several actors to the consumer to allow the consumer to adapt his energy consumption based on the dynamic prices.
Related business case(s)	

1.4 Narrative of Use Case

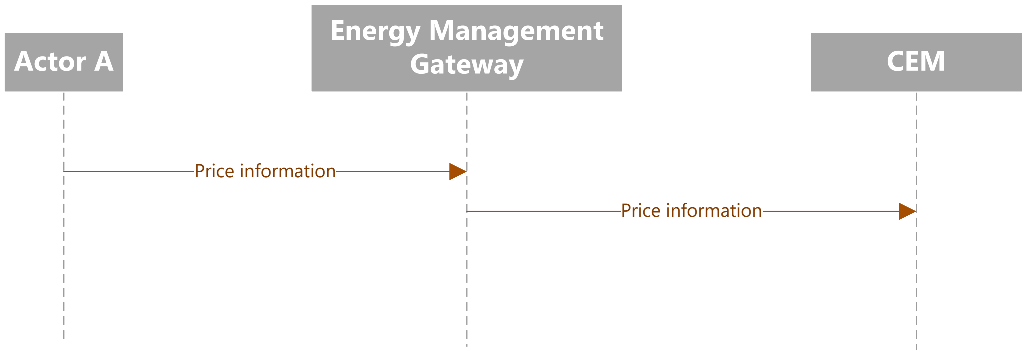
Narrative of Use Case
Short description
.This use case describes how information is sent from external actors towards the consumer's CEM.
Complete description
Actor A creates dynamic prices (tariffs) based on production and consumption forecasts. Actor A (BelVis-System) sends this price information to the Energy Management Gateway (FTP Server) every day at 9:00, from where it is available to the CEM (Wolfhagen Optimization Computer). The objective is to make the consumer aware of changing prices and help him change is consumption patterns to minimize his costs. The CEM, which is running on a Linux machine, is able to communicate with smart appliances in the household and can turn them on or off based on the consumers preferences and the dynamic prices. All price information is saved as a CSV file.

1.5 General Remarks

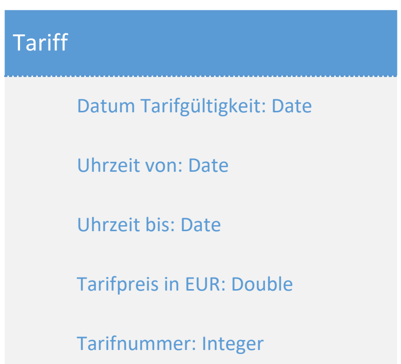
General Remarks
Technical Details

2 Diagrams of Use Case

Price Information exchange – Sequence diagram



Tariff Data Model



3 Technical Details

3.1 Actors

Actors			
Grouping		**Group Description**	
Actor Name	**Actor Type**	**Actor Description**	**Further information specific to this Use Case**
Actor A	External Actor	External actor (Smart Grid Market Role) interacting with the system functions and components in the home or home automation network through the energy management communication channel. Examples of such market roles are the Energy Provider, the Energy Services Provider, the aggregator, etc.	*Stadtwerke Wolfhagen (BelVis-System)*
Customer Energy Manager (CEM)	Role	The CEM is a logical function optimizing energy consumption and or production based on signals received from the grid, consumer"s settings and contracts, and devices minimum performance standards. The Customer Energy Manager collects messages sent to and received from connected devices; especially the in-home/building sector has to be mentioned. It can handle general or dedicated load and generation management commands and then forwards these to the connected devices. It provides vice versa information towards the "grid / market". Note that multiple loads/generation resources can be combined in the CEM to be mutually controlled. When the CEM is integrated with communication functionalities it is called a Customer Energy Management System or CEMS.	*This is in this case the same as a CEMS, see description*
Customer Energy Management System	System	Energy management system for energy customers to optimize the utilization of energy according to supply contracts or other economical targets. Is responsible for gathering flexibilities within the customer premises and providing them to an aggregator, and therefore does not directly participate in flexibility markets	*Optimierungsrechner (Optimization Computer)*
Energy Management Gateway	System	An access point (functional entity) sending and receiving smart grid related information and commands between actor A and the CEM, letting the CEM decide how to process the events. The communication is often achieved through an internet connection of through a wireless connection.	*FTP-Server*

LNAP	System	The Local Network Access Point is a functional entity that provides access to one or more metering end devices, displays and home automation end devices connected to the local network (LN). It may allow data exchange between different functional entities connected to the same LN.	*Optmierungsrechner*
Distribution Management System	System	a system which provides applications to monitor and control a distribution grid from a centralized location, typically the control center. A DMS typically has interfaces to other systems, like an GIS or an OMS	*BelVis-System*

3.2 Triggering Event, Preconditions, Assumptions

Use Case Conditions			
Actor/System/Information/Contract	**Triggering Event**	**Pre-conditions**	**Assumption**
Actor A	Every day at 9:00	Production forecast information has been received	All systems are running and connection to the Gateway has been established

3.4 Further Information to the Use Case for Classification / Mapping

Classification Information
Relation to Other Use Cases
Level of Depth
Primary use case
Priorisation
1
Generic, Regional or National Relation
Regional
Viewpoint
Technical
Further Keyword for Classification

4 Step by Step Analysis of Use Case

4.1 Overview of Scenarios

Scenario Conditions					
No.	**Scenario Name**	**Primary Actor**	**Triggering Event**	**Pre-Condition**	**Post-Condition**
1	Price information exchange	Actor A	Everyday at 9:00 o'clock CET	All systems are up and running and communication is established, Prices have been created	CEM has received price information

4.2 Steps - Scenarios

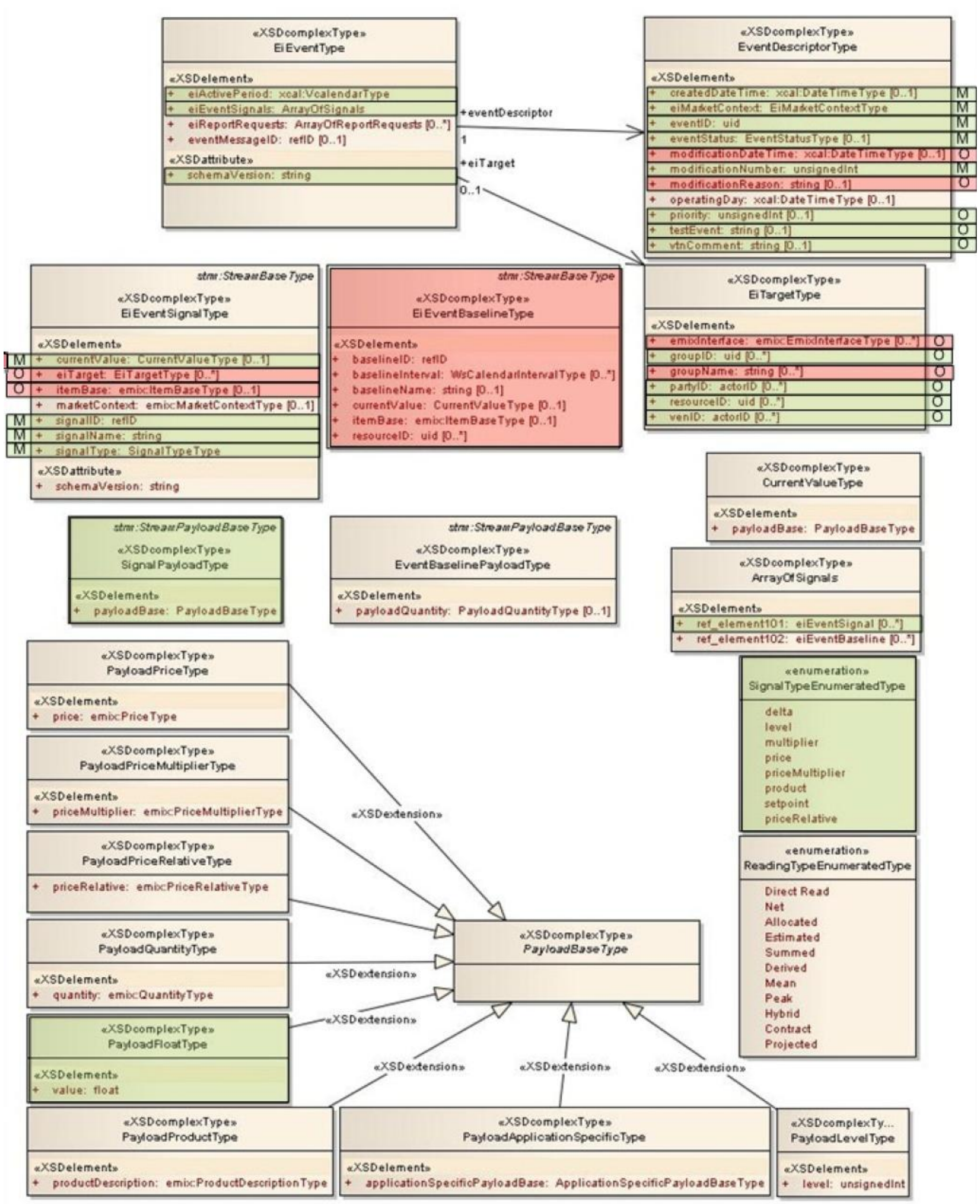
Scenario								
Scenario Name:		Price information exchange						
Step No.	**Event.**	**Name of Process/ Activity**	**Description of Process/ Activity.**	**Service**	**Information Producer (Actor)**	**Information Receiver (Actor)**	**Information Exchanged**	**Requirements, R-ID**
1	Everyday at 9:00 o'clock CET	Price creation	Prices are sent to Energy Management Gateway for further distribution		Actor A	Energy Management Gateway	Dynamic tariffs in CSV	
2	Everyday at 10:00 o'clock CET	Price download	Prices are downloaded by CEM		Energy Management Gateway	Customer Energy Manager	Dynamic tariffs in CSV	

5 Information Exchanged

Information Exchanged		
Name of Information (ID)	**Description of Information Exchanged**	**Requirements to information data**
Price information	CSV file which holds price information on an hourly basis for 48 hours. See the data model for the names of the fields.	Prices always start at 0:00 of day 1 and are stated for consecutive 48 hours

Annex C – OpenADR

1 Data Model



2 Dynamic Price example message

The following example shows a typical oadrDistributeEvent message with 3 dynamic prices from 0:00 to 08:00, 08:00 – 16:00 and 16:00 to 0:00, with electricity prices being 0,35€ kW/h, 0,50€ kW/h and 0,80€ kW/h respectively.


```xml
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 <oadr:oadrSignedObject>
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```

```
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