Integration of Residential Distributed Generators and Heat Pumps into the Low Voltage Grid from a Voltage Level Perspective

Von der Fakultät für Elektrotechnik und Informationstechnik

der Technischen Universität Dortmund

genehmigte

Dissertation

zur Erlangung des akademischen Grades

Doktor der Ingenieurwissenschaften (Dr.-Ing.)

von

Mark Philipp Arnold, M.Sc.

Referentin:	Prof. Dr.-Ing. Johanna Myrzik
Korreferent:	Prof. Dr.-Ing. Krzysztof Rudion
Tag der mündlichen Prüfung:	13.06.2016

Abstract

In context of combating climate change, carbon saving goals are defined on European level. One effect of this is the increased installation of photovoltaic, heat pump and combined heat and power systems on low voltage distribution grids. As the distribution grid was not designed to handle this quantity of distributed generators and large loads, there are undesirable influences. The voltage level is identified as the main issue in low voltage grids. From the point of view of a manufacturer of such devices the influence on possible connections to the low voltage grid and necessary measures are of interest. The characteristic voltage influence of combined-heat-and-power, heat pump and photovoltaic systems is evaluated. In order to quantify the influence, a 2020 penetration scenario of these devices is developed using market expectation data. It is shown that different grids show violations of the voltage limits according to EN 50160 and measures for voltage control are therefore necessary in order to integrate the anticipated number of appliances. A range of measures are evaluated regarding effectiveness, system operator and end-user economics, comfort and environmental influence. The measures are based on grid operator equipment or end-user appliances.

Battery storage based measures are identified as effective but very expensive compared to other solutions. The most cost efficient measure is the installation of on-load tap-changers at the low voltage transformers. Demand side management of heat pumps can be effective under certain circumstances but end-user comfort is endangered here. Considering the total economics, demand side management is more expensive than the use of on-load tap changers. From a manufacturer perspective there are no additional requirements for end-user appliances identified for voltage control on low voltage grids. Connection restrictions and the grid planning process have to be reviewed in order to enable cost efficient integration of the anticipated number of appliances in 2020. The results are validated for increased generator penetrations in a ’maximum PV’ scenario.

Acknowledgements

This work was developed during my time as PhD student at Bosch Thermotechnik GmbH in Wernau. The academic supervision was granted by the Department of Energy Efficiency and Renewable Energy Sources at the Institute of Energy Systems, Energy Efficiency and Energy Economics of TU Dortmund University.

I'd like to thank my academic supervisor at TU Dortmund University, Prof. Dr.-Ing. Johanna Myrzik, for her patience and support during the last years. Special thanks goes to my industrial supervisor at Bosch Thermotechnology, Dr. Wolfgang Friede, for the endless hours of support and motivation. Furthermore, I thank my second examiner Prof. Dr.-Ing. Krzysztof Rudion from the University of Stuttgart for his time and efforts.

I'd like to thank my mentor at Bosch Dr. Jürgen Rapp and my line manager Dr. Uwe Limbeck for the support and insights. Additionally, I'd like to thank the many colleagues at Bosch and at TU Dortmund University, especially Tobias Raff, Lukas Spitalny and Denis Unger, for the kind and unbureaucratic support. Thanks to all the students I had the pleasure working with.

Last but not least, I thank my wife for the constant encouragement and support.

Gerlingen, June 2016 Mark Arnold

Contents

1 Introduction

Climate Change is one of the big challenges in the world today. Since several years a number of governments have advanced international efforts to fight climate change [1]. In Europe this is reflected in the 20-20-20 goals - 20% less carbon emissions compared to 1990 - 20% renewable energies - 20% improved energy efficiency till 2020 [2]. In Germany these goals are incorporated in the 'Energiewende' - energy transition. The reduction of the carbon footprint is realised by shifting the energy generation from conventional carbon based sources to renewable and highly efficient sources and by reducing the energy demand by usage of efficient appliances. Transportation, electricity and process heat are the main areas of energy demand in Germany and therefore the primary target for all measures. In the domestic area, this refers to personal transportation by car or public transport as well as allocation of electricity and heat for space heating and domestic hot water generation. In the future the existing links between those areas will get stronger as electric vehicles, distributed generation (DG) of electricity as well as heat generation by heat pumps (HP) and combined heat and power (CHP) devices are linked by the electricity grid. The political goal to reduce the carbon footprint in Europe is therefore reflected by major changes in the energy sector. In Germany this leads to a growth in renewable energies, combined heat and power as well as the use of efficient electric and heating appliances [3]. Traditionally the electric grid in Europe was designed to transport electric energy from large power stations, connected to the transmission system, by means of different voltage levels on the distribution system to the location of demand. Domestic users are connected to the low voltage distribution grid. The dimensioning of the grid equipment, like cables, transformers or circuit breakers, is calculated by experience values of house connection power and the number of connected estates. The connection of generators and powerful loads like heat pumps, however, was not incorporated in the design of the system and therefore influence the grid operation in an undesirables manner. To ensure safe and reliable operation, standards and guidelines on European and national level define the voltage and current quality that can be expected on public grids and the requirements generators and loads have to fulfil in order to connect to the grid.

In order to reach the political and market expectations for the connection of photovoltaic (PV), CHP and HP devices in 2020 it is necessary to implement measures that ensure safe grid operation despite the influences of these appliances. From the perspective of a manufacturer of heating appliances and photovoltaic inverters it is of special interest if the next generation of appliances in 2020 has to fulfil additional requirements in order to support the energy transition. As these appliances are mostly connected to the low voltage grid the focus is set on this voltage level. The technical background and challenge as well as the focus of this work are defined within the first chapter.

1.1 The Electric Energy System

The electric energy system can be structured into four parts. The generation of electric energy, the transfer of electric energy, the demand of electric energy and the market for electric energy [4]. Since the liberalisation of the energy market in Europe the electricity transfer has to be separated from electricity generation and market. The traditional utility companies that operated power plants as well as the electricity grids where forced to split their businesses [5]. From a technical point of view the energy market is not necessary to operate the electricity system. It is, however, necessary to operate the system economically.

The electricity transfer is structured according to the main purpose of the relevant electric grids into transmission and distribution systems. The transmission systems in Germany are part of the Continental Europe Synchronous Area which is operated by members of the European Network of Transmission System Operators of Electricity (ENTSO-E) [6]. In Germany four transmission system operators are responsible to balance electricity generation and demand. Therefore they are in charge to maintain a stable system frequency. On distribution level there are nearly 900 different grid operators [7]. The tasks of grid operators are stated in the German energy economy act (Energiewirtschaftsgesetz - EnWG). Principally grid operators are obliged to operate a secure, reliable and capable electricity grid [8]. Traditionally distribution system operators are responsible for the reliablilty of the distribution network and the voltage quality. But current and future challenges do also cover the integration of renewable and distributed electricity sources into the grid and allocation of system services towards the transmission system operators. Figure 1.1 shows an overview on the electricity system and the different voltage levels.

Technically the electric grids are structured into high, medium and low voltage grids. High voltage systems with 380 kV are solely used for transmission systems, whereas high voltage grids with 110 kV are used within both, transmission and distribution systems. Medium voltage grids with 20 and 10 kV and low voltage grids with 0.4 kV are only used

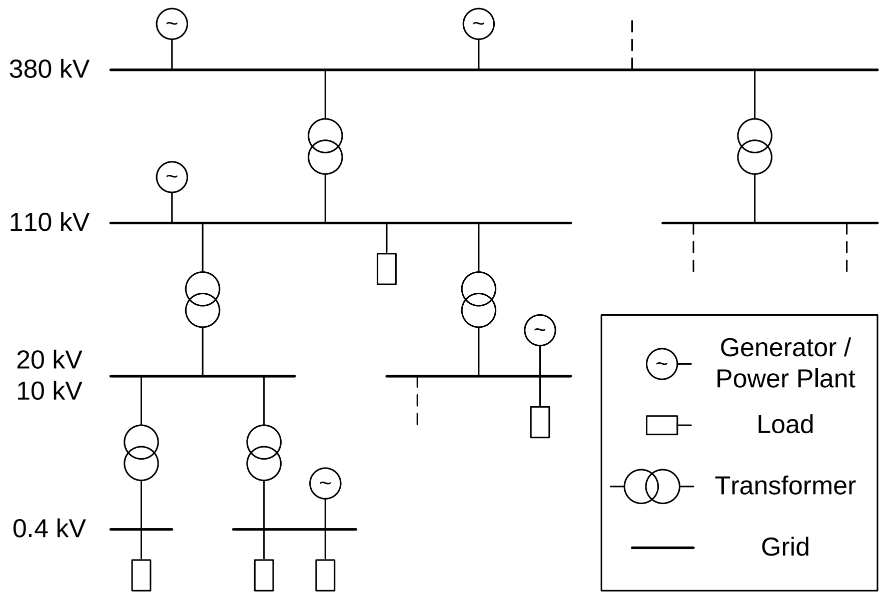


Figure 1.1: Overview on different grid voltage levels of the electricity system (Based on [4]).

in distribution systems. Additionally there are further voltage levels that are used in older parts of the system or to cater special needs of the demand facility. The use of different voltage levels arose historically from the economic optimisation of grids to the transferred power [9]. Distribution grids with 10 or 20 kV depending on the load density, distribute the electric power into rural or urban areas. Industrial plants and generators up to around 10 MW are connected here. The 0.4 kV grids distribute the power within villages and city quarters to the residential and commercial end-users. Besides one and three phase loads up to 300 kW also distributed generators like photovoltaic and combined heat and power devices are connected to this voltage level [4]. Traditionally the electricity grid was not smart. Smart in this context refers to the measurement and transmission of information about the grid status. Nowadays, the transmission grid and parts of the distribution grid on high and medium voltage level are already smart. The power flow through the lines can be altered by FACTS (Flexible AC Transmission System) equipment. The grid status and possible faults are visible and controllable from the central grid control rooms. When talking about the 'smart grid' that is yet to come it is always referred to the smart low and medium voltage grid. The distribution system didn't need to be smart, as there was a unidirectional power flow toward the loads. The dimensioning of the cables and the transformer could be based on empirical values [4].

The investment in grid extension is regulated by the German federal network agency (Bundesnetzagentur). A incentive regulation is set in place to support efficient grid enforcement. This incentive regulation rewards low yearly investments. Currently grid operators, therefore, enforce their networks in order to cope with the current situation only [10].

1.2 Regulatory Boundary Conditions

Legal and regulatory requirements define the boundary conditions for the operation of the electricity system. On one hand standards define what conditions can be expected on the grid and if or how devices are allowed to connect. On the other hand regulatory boundary conditions define the cost effectiveness of different energy solutions and therefore their market share and penetration on the grid. The same is valid for the cost effectiveness of possible grid services. The current regulatory boundary conditions are in a phase of adaptation to the changing conditions on the grid, especially to the integration of distributed generators. Therefore the current regulations, shown hereafter, do not yet support high penetrations of generators or heat pumps nor possible solutions as described in the following chapters.

1.2.1 Current Regulations

In principal there are three different types of regulations in the power systems context. Laws and directives on national and European level, Grid operators' requirements and standards. Figure 1.2 shows the relations between the different regulatory documents in Europe an Germany.

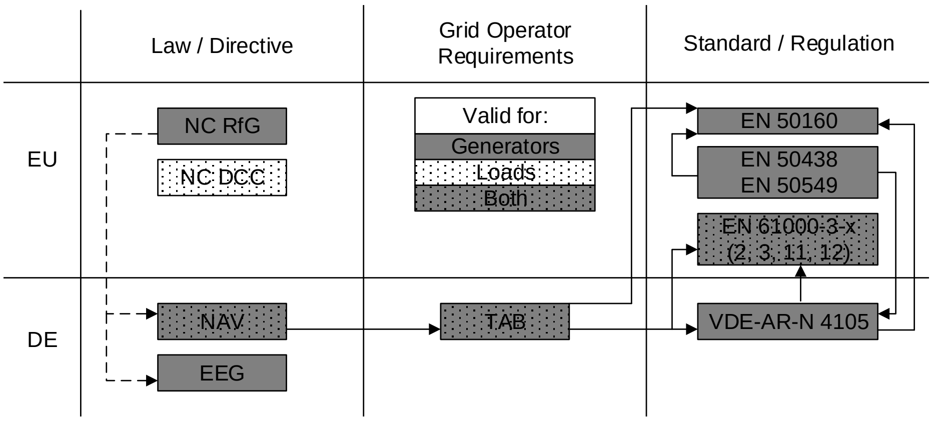


Figure 1.2: Relations between EU and German regulations

The Network Codes 'Requirements for Generators' (NC RfG) and 'Demand Connection Code' (NC DCC) are developed by ENTSO-E and then transferred into European legislation by the comitology process. The codes shall ensure a stable and reliable operation of the European electricity grids. The network code RfG states requirements for generators ($P_{max} \geq 0.8$ kW) regarding response to over- and under-frequency, frequency operation range and remote control capabilities. The codes refers to national regulations [11][12].

The German renewable energy act (Erneuerbare-Energien-Gesetz) is the main driver for the expansion of renewable energy generation in Germany. It contains regulations valid for renewable generators and efficient CHPs. It is the basis for the financial support of renewable generators and for their priority for grid connection. Remote control capabilities are requested for certain types of generators [13]. The German low voltage connection directive (Niederspannungsanschlussverordnung - NAV) regulates the terms on grid connection of demand facilities to the low voltage grid. The directive entitles grid operators to specify additional requirements for the grid connection within a technical connection requirements (Technische Anschlussbedingungen - TAB) document [14]. The TAB regulates the connection and operation of appliances on the low voltage grid. If required by the grid operator, heat pumps have to be remotely controllable and implement a limitation of hourly start-ups. Furthermore there are regulations for electromagnetic compatibility (EMC) and power quality (PQ) stated that refer to the European standard series EN 61000-3-2, -3, -11, -12 and EN 50160. For generators it is referred to the German regulation VDE-AR-N 4105 [15].

On European level the standards for grid connection of generators to the low voltage grid are structured by generator size. Generators with a current less or equal to 16 Ampere are element of the EN 50438 while generators with a current of more than 16 Ampere are subject to EN 50549-1. The regulations range from frequency and voltage response to operation ranges and protection settings. The connection of and requirements on generators on the low voltage grid in Germany is covered by the German regulation VDE-AR-N 4105. It contains requirements on frequency and voltage response, operation range, power quality and protection settings [16].

The Standards EN 61000-3-2 and -12 state limits for harmonic currents of electric appliances connected to the grid and their test procedures for appliances below 16 Ampere and between 16 and 75 Ampere respectively. Relative voltage change and flicker limits as well as the corresponding test procedures are defined by EN 61000-3-3 and -11 for appliances below 16 Ampere and between 16 and 75 Ampere respectively [17][18][19][20]. The voltage quality on European grids is defined by the EN 50160 standard. It states limits for certain phenomena that can be expected at the point of common coupling in public high-, medium- and low-voltage grids. Frequency, voltage altitude, waveform and balance values are given for normal operation [21][22]. Relevant requirements regarding power quality, connection and operation are stated in Table A.1 and Table A.2 respectively.

1.2.2 Future Developments

Looking back on the development in standards and legislation it can be anticipated that the requirements on participation of end user appliances in grid services will increase in the future. Regarding voltage control, for example, it is, to date, only required for generators to participate in reactive power response. Possible developments could include, however, that generators and large loads are requested to participate in both, reactive and active power response to voltage level violations. Active power response to frequency could also be requested from loads instead of generators only [23]. Similar to today's requirements for generators it is likely that future requirements for both, generators and loads, will be tailored to the size and location of the appliance. Regulations for appliances on the low voltage grid will be different from requirements on the medium voltage grid.

It can be expected that the feed-in compensation for renewables and CHP systems will be reduced. This increases the use of storage systems to increase the self consumption rate which, again, reduces the influence of the systems on the grid.

1.3 Challenges to the Future Grid

The future electric grid faces challenges due to changes in the amount, the size, the kind and the location of the connected appliances. The connection of large amounts of distributed generators to the medium and low voltage distribution grids, for example, lead to reverse power flows on the distribution grid and introduce voltage level violations and other issues. The intermittent operation of such generators, especially wind and solar, lead to frequency control issues. Wind generators are likely to introduce flicker to the network if no countermeasures are taken. A list with the network characteristics that are affected the most is shown below:

- Network frequency
- Transients
- Flicker
- Harmonics
- Unbalance
- Voltage
- Fault tolerance
- Short circuit power
- Network loading

The transmission and distribution networks are facing different challenges depending on the connected appliances and the main duty of the grid operator. In the context of the energy change PV generators and heat pumps get installed on low voltage distribution grids in high quantities. In a first step the technical challenges connected to this are approached by sharpened regulatory boundary conditions like shown in section 1.2. The political goal to increase the share of renewable energy and to reduce the country's carbon footprint by the use of highly efficient heating technologies like heat pumps and combined heat and power appliances make additional technical measures necessary. On low voltage distribution networks voltage control is the main challenge regarding the integration of distributed generators and powerful loads. Further challenges are unbalance and network equipment loading [24].

Voltage level

Along with the frequency, the voltage level is the main parameter that electric appliances rely on. In order to enable optimal operation the voltage level that can be expected on the electric grid is defined in EN 50160 [21]. Traditionally the voltage supplied by the low voltage transformer is nominal voltage or slightly higher in order to guarantee voltages within the boundaries at every location in the grid. The voltage level in the grid is influenced locally by loads and generators. Formula 1.1 shows the influence of active and reactive power flows on the systems voltage [25]. Generated power is counted positive. Reactive power Q is defined as inductive reactive power.

$$\Delta V = \frac{P \cdot R + Q \cdot X}{V} \tag{1.1}$$

It can be seen that the voltage level is influenced by active (P) and reactive (Q) power as well as the resistance (R) and the reactance (X) of the network. Increased generation (positive active power) increases the voltage level, while increased load (negative active power) decreases the voltage level. The increased connection of distributed generators and heat pumps therefore has an influence on the local voltage level in the distribution networks. Studies show that this can lead to violations of the upper [24] and lower [26] voltage level boundaries. As shown in Equation 1.1 reactive power can also be used to influence the voltage level. Reactive power voltage support is already compulsory for generators according to VDE-AR-N 4105. The X/R ratio of the distribution system defines the relative influence of active and reactive power on the system's voltage. For transmission systems applies $X/R >> 1$, therefore reactive power control is very efficient. On low voltage grids, however, the X/R ratio is around one or even lower. High reactive power flows are therefore necessary in order to influence the voltage of the system [27][28]. In order to control the voltage level on distribution and especially low voltage grids efficiently it is therefore necessary to adapt the control behaviour from a reactive power based to an active power based logic.

The violation of the voltage limits is seen as the main limitation for the connection of distributed generators to the low voltage grid [26][27][29]. In order to enable the anticipated number of PV, CHP and HP appliances on German grids until 2020 and beyond it is important to understand the concrete limitations and possible measures for voltage regulation. This is especially true from an end-users and manufacturers point of view as these groups are directly economically influenced if the connection is limited.

Network Loading

Distributed generation and loads like heat pumps increase the loading on German distribution grids [30][31]. The reason for the high impact of distributed generators is that especially solar power generators operate simultaneously and that the energy demand and energy generation profiles do not match [30]. A further increase in equipment loading is introduced by reactive power flows, used for example for voltage control [32]. Current flow through equipment like transformers and cables cause a temperature rise due to the internal resistance. The maximum load is defined by the thermal resilience. Equipment failure and power outages can be the result of overload. Even though loading over the rated power is possible for a limited period, it shortens the lifetime [33]. Within this work the loading of transformers and cables is taken into consideration as a boundary condition. The introduced measures are not optimised to reduce the equipment loading, but if equipment is overloaded the cost for replacement is incorporated in the economic evaluation.

Unbalance

In three phase systems the voltage amplitude is meant to be the same in all phases whereas the sine curves are shifted by 120° exactly. Unbalance is defined as deviation from that optimal condition. The cause of unbalance is mostly the single phase connection of loads and generators on the low voltage grid. The impact of small loads and generators is regularly compensated by other single phase devices connected to a different phase nearby. If, however, a range of devices, like PV systems, are connected to the same phase the influence adds up an can lead to significant impact. Negative impacts are documented for transformers, controls, distributed three phase generators and loads as well as power electronic devices [24]. Generators and loads with powers higher than 4.6 kVA are therefore required to be connected three phase in order to limit unbalance on the network [16]. Within this work, appliances with powers lower than 4.6 kVA are connected single phase, but arranged evenly to avoid unbalance on the network. Unbalance is therefore not taken into consideration within this work.

1.4 Current Status of Research

The transition of the electric energy system in Germany is in the focus of research. The main research areas relevant for the integration of CHP, HP and PV systems on the distribution grid are shown below.

Distributed generators and heat pumps

The main focus regarding the research on the German distribution systems is on PV integration. In Germany but also internationally the integration of PV is analysed regarding voltage level violations and equipment loading like shown in [34][33]. CHP systems are often analysed regarding their load shift behaviour for load reduction, like shown in [35][36]. The influence of heat pumps and other large loads on the voltage level is shown in [37], whereas demand side management of heat pumps is evaluated in [26]. Positive influences of CHP and HP on the influence of fluctuating generation is evaluated in [38].

In order to evaluate the influence of PV, CHP and HP appliances it is important to evaluate grids with all three kinds of appliances present. Currently research focuses on one or two different kind of appliances within one study.

Voltage control measures - DSO based

Two extensive studies evaluate the necessity of grid extension and possible measures for cost reductions for high, medium and low voltage grids in Germany [39][10]. [10] states the need for the construction of 57,000 km cables and the installation of 34,000 MVA additional transformer power until 2030 in the low voltage grids alone in order to enable the anticipated growth in renewable energies. The costs necessary to enable the transition of the energy system is quantified with 27.5 to 42.5 billion Euro between 2013 and 2030 [10] and 36 billion Euro between 2013 and 2032 respectively [39]. The necessary invest in the low voltage grid, however, is only 13 % of the total costs [10]. The highest invest is necessary in the medium voltage grid. The necessity of investment is highly variable between the different grids [39]. The use of innovative equipment can reduce the overall costs by up to 50 % [10] and is even able to avoid the necessity of new cables in the low voltage grids [39]. The evaluated measures for voltage stability in these and other studies range from Distribution System Operator (DSO) based grid extension [10], on-load tap-changers [40][41], autotransformers [42] and distribution grid FACTS [43] to end-user appliance based measures. Furthermore the voltage regulating influence of distributed and central storage facilities is evaluated [30].

On-load tap-changers (OLTC) are identified as a low cost alternative to cable based grid extension. Line drop compensation (LDC) can provide an optimised control of the OLTC. LDC allows to keep the voltage within a defined range at a specified location within the grid [44]. If different feeders have highly different penetrations with loads and generators, the OLTC technology is limited, as only the voltage in the whole grid can be changed and there is no possibility to adapt the voltages in different feeders differently [45][46]. Autotransformers can be used to influence the voltage in one or more specified feeders individually [47]. Electric storage is identified to reduce the necessary grid extension. The investment costs for the storage, however, are not considered [10]. FACTS are widely used for voltage control on the transmission system [48]. The use on distribution networks is discussed [49][50]. Two variations that can be used for voltage control on low voltage grids are the intelligent node and the distribution STATCOM (STATic synchronous COMpensator) with additional energy storage. The intelligent node connects two feeders that are regularly operated in radial configuration at their ends in order to shift power flow from one to the other feeder which reduces the voltage rise or drop. This end-to-end connection with the intelligent node does, however, not increase the short-circuit current of the system [51]. The intelligent node is of special interest if the two connected feeders have different power flow profiles. For example if one feeder has a high heat pump penetration, while the other feeder has a high PV penetration. In this case the intelligent node can optimise the utilisation of both feeders. The distribution STATCOM is a voltage source converter connected in parallel to the grid [49][50]. Additional energy storage enables active power control in grids with a low X/R ratio.

The dena (German Energy Agency) distribution grid study shows the necessity to expand the electricity grids in order to facilitate the energy change in Germany. One major recommendation is the adaptation of existing guidelines and anticipatory grid planning. Furthermore the necessity of further research especially on the economics of measures for voltage control is stressed [10]. As a first step, this work evaluates the technical and economic feasibility of different measures on the low voltage grid from different perspectives as shown in section 1.5.

Voltage control measures - appliance based

Appliance based measures for voltage control reach from active and reactive power control of generators [52][53] to demand side management of heat pumps [54][55]. Even though OLTCs are identified as the superior solution compared to reactive power control of PV systems [42], reactive power control has the potential to increase the penetration of PV [56]. Reactive power control on low voltage grids is discussed critically, especially as the additional reactive power flows add loading to the network. Alternatively active power voltage control is discussed. The reduction of generation peaks, mainly by PV, is identified as a potential for cost reductions. The evaluation is, however, mainly focused on large PV systems that are already remotely controllable by DSOs and do get financial compensation for power reductions [39][10]. The reduction in generated energy is, however, connected to economic losses for end-users [24]. Demand side management is not seen as major potential for the reduction of grid extension investments [39]. There is no negative influence on the end-user comfort detected, when operating heat pumps according to a time table as demand side management [26]. Demand side management of heat pumps for voltage control, however, can reduce the comfort of the end-user [46].

The current literature offers a wide selection of different voltage control measures that are evaluated individually or compared to each other. This work builds on this existing knowledge on possible voltage control measures.

Focus of the economic evaluation

Many studies, like the dena distribution grid study [10], focus on the costs for the DSO and evaluate the relative savings potential of alternatives to grid extension. Some studies do also take costs for generator management or losses for end-users into account [39][53]. Two different approaches can be found in literature. The bottom-up approach evaluates how much the penetration can be increased by different measures. Example is a study on the possible increase of PV systems depending on active and reactive power control and on-load tap-changers [53]. Alternatively the top-down approach is used, where the anticipated penetration in the future is used as the base case to predict the necessary measures for integration [39][10].

From a manufacturers point of view it is important to consider the costs for all parties. In order to evaluate the costs to integrate the anticipated number of appliances in 2020 a top-down approach should be used. Currently there is no work that combines the consideration of costs for all parties and the top-down approach.

Evaluation of the current status of the research

The current status of the research does not represent the manufacturer's point of view regarding the integration of CHP, HP and PV systems into the low voltage grid. The combined influence of CHP, HP and PV systems on the grids voltage and on each others operation has to be evaluated in order to predict the behaviour in real grids. The role of these appliances in a voltage control concept in 2020 and the economics for the system operator and the end-user have to be quantified. This is also necessary as input to the overall discussion like requested by [10]. Section 1.5 defines the focus of this work.

1.5 Focus Definition

Manufacturers point of view

As identified above, distributed generators and large loads are critical regarding grid connection. As more and more such appliances are connected to the grid and connection restrictions are introduced, appliance manufacturers are interested in the detailed mechanisms. Bosch is a manufacturer of heat pumps, combined heat and power appliances and photovoltaic inverters. Most of these appliances are connected to the low voltage grid. This work, therefore, focuses on the integration of these devices into the low voltage grids in Germany. In order to identify possible requirements for the next generation of the appliances, the focus is set on issues, restrictions and solutions in 2020. Electro mobility and the influence of automotive battery charging on the grid is therefore not evaluated. The goal is to define the role of end-user appliances for their integration into the low voltage grids in Germany.

Starting point is an analysis on possible penetration levels of those devices in 2020. All measures are evaluated according to their capability to integrate the anticipated penetrations. This top-down approach is chosen as it is the manufacturers interest to support the political and societal goal to transform the energy system by providing carbon saving technology. Connection restrictions due to technical issues are therefore a part of the problem and no part of the solution. The goal of the transition of the energy system is CO_2 reduction. Therefore the influence of different solutions on the CO_2 balance is evaluated. From a manufacturers point of view the research questions hence are:

- How can the anticipated numbers of CHP, HP and PV appliances in 2020 be integrated?
- Can the appliances support this process by their functionalities without compromising the end-user satisfaction?

Technical point of view

The connection of distributed generation, of which a major part renewables, now introduces two challenges to the grid. These two have to be strictly separated. First these new generation technologies are often fluctuating in power output (e.g. wind, photovoltaic) and are situated in rural and remote areas. This means that the power has to be transferred to the location of demand and the matching of generation and demand gets more complicated. The frequency control is the responsibility to the transmission system operator and therefore not discussed within this work.

Secondly many of these new generators are now connected to grids in the low and medium voltage level that were never meant to connect generators. The feed in of power into these grids that were not designed, not in dimensioning nor in operation, to handle generators, leads to local problems. On the low voltage grid the voltage level and the equipment loading are identified as the main issues (see section 1.3). These local issues cannot be solved in the transmission system, but have to be solved locally. A range of measures that allow for the integration of the anticipated number of HP, CHP and PV devices are evaluated in this work. The measures are partly implemented by the distribution system operator and partly implemented in smart devices at end-user level. Chapter 4 gives a detailed overview on the compared measures. Technically the measures are evaluated according to their capability to ensure voltage levels within the EN 50160 boundaries and their capability to ensure equipment loading within the operational limits. The grid's frequency is not considered as this is the responsibility of the transmission system operator, like discussed above. The technical point of view thus raises following research question:

- How can the different measures ensure the compliance of the voltage level to EN 50160 boundaries?

End-Users' point of view

From an end-user's point of view the security of supply, the costs and the comfort level are important for the evaluation of the technical measures for voltage control. The security of supply is considered mandatory and not discussed further. The economic evaluation of the different measures is based on the total costs. Depending on the measure there are invest and operation costs for the end-user, the DSO or both. In order to reach the installation goals in 2020 it is not only important that it is technically feasible, but also that it is economically feasible. The technical feasibility can be assured by a range of measures. The economic feasibility is influenced by costs for the DSO that have to be covered by all grid users and increase the electricity costs. Furthermore it is influenced by the costs for end-users that directly influence the invest into carbon saving technologies. Additionally it is important that the end-user comfort is not reduced significantly by the implementation of measures in order to reach the installation goals in 2020. The influence of the measures on the heating capability of CHP and HP devices is therefore evaluated. The end-users' point of view introduces the following research questions:

- What are the most economical measures to integrate the anticipated number of CHP, HP and PV appliances?
- How can comfort reductions be reduced to a minimum?

As shown above, the energy transition in Germany and other carbon saving activities in Europe have a major influence on way the electricity system is planned, operated and regulated. In order to enable the European and German goals it is of special interest to evaluate how CHP, HP and PV appliances can be integrated into the low voltage grid most economically. Technically the voltage level compliance is identified as the biggest hurdle to the grid integration. In order to answer the research questions raised above, this work is based on a grid simulation model that is used for the evaluation of the different measures, which is discussed in chapter 2. Chapter 3 quantifies the voltage level violations in 2020 whereas chapter 4 defines the considered measures that are based on grid equipment or end-user appliances. The evaluation of the measures according to effectiveness, system operator and end-user economics, comfort and environmental influence is shown in chapter 5. Chapter 6 summarises the results, evaluates necessary changes in grid planning and connection requirements in order to enable the most cost efficient approach and gives an outlook on further work.

2 Models

In order to evaluate the voltage behaviour as well as the equipment loading of grids with high penetrations of generators and high power loads the simulation tool DIgSILENT PowerFactory is used. PowerFactory offers two programming environments, one can be used for control of the simulation environment (Digsilent Programming Language - DPL) and the other for dynamic modelling (Digsilent Simulation Language - DSL). Figure 2.1 shows the simplified structure of the modelling concept. Within PowerFactory a physical grid model is combined with an power based component model. The grid model is build on two dimensional topology data as well as equipment specifications. The interface between the grid model and the component model is at the point of common coupling (PCC) of the houses. In every simulation step the two models exchange information on energy and grid status. The power based model of the house includes models of the heating system, PV generator, battery and a energy management system. The tool BTSL (Building Technology Simulation Library) is used to create heat demand profiles for space heating and domestic hot water (DHW) demand. The BTSL is a Matlab/Simulink library created by Bosch which contains verified component and house models. It can be used for extensive thermal and electric building simulations. The thermal simulations within the BTSL are based on TRNSYS. The same tool is used to extract the underlying weather data and synthetic electric load profiles. The profiles are described in section 2.1. In order to speed up the simulation process the individual load profiles for every house are created in advance and read by the interface during the simulation.

2.1 Load Profiles

To simulate the grid behaviour with connected CHP, HP and PV appliances it is important to provide the appliance models with correct boundary conditions in order to simulate correct behaviour. The heat appliances depend on a realistic heat demand that depends on user behaviour, environment temperature, irradiation and house insulation level. The PV model depends on realistic irradiation and temperature data and on information about the module's alignment. To reproduce realistic power flows it is additionally necessary to provide

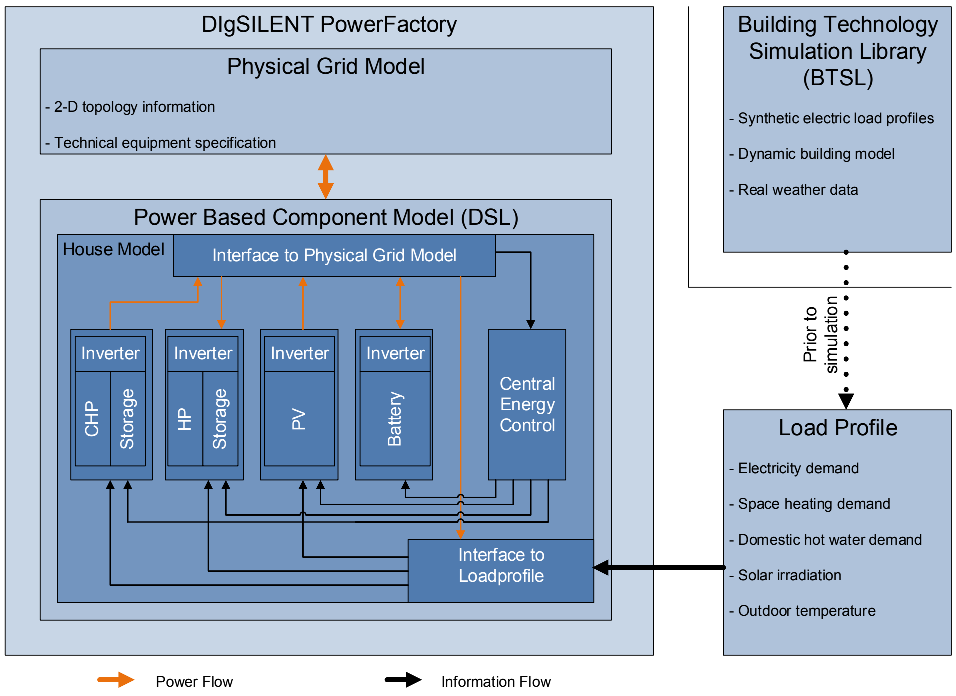


Figure 2.1: Modelling concept

an electric load profile for every house. In order to ensure realistic behaviour, correlating thermal and electric profiles as well as weather data have to be used. The VDI 4655 electric load profile [57][58], self created artificial profiles [59][60][61] or exemplary measured profiles [62] are used in literature.

Artificial electric load profiles could be generated within PowerFactory using behaviour profiles and appliance power demands. This would, however, increase the simulation time without having an additional positive influence on the simulation results. It is therefore chosen to import electric load profiles generated outside the PowerFactory environment. The thermal load profile consists of a thermal load for heating and a load for domestic hot water. For the DHW profile it is, as for the electric profile, possible but not sensible to be created within PowerFactory. The heating demand could be calculated using weather data like environment temperature and irradiation and an adequate model of the houses thermal properties. Henkel[1] developed a thermal house model within the PowerFactory environment but proofed simple models to be insufficient. It is therefore chosen to import an adequate heating demand profiles created outside PowerFactory.

[1]Bachelor Thesis (see page 160)

2.1.1 Types of Load Profiles

Principally it can be distinguished between measured load profiles and synthetic generated load profiles. Measured load profiles can not be generalised without knowing the exact composition of the loads, as scaling leads to higher peak demands which are not realistic. Furthermore those profiles can not be adapted to different boundary conditions if the exact boundary conditions of the measurement are not known. This is especially true for thermal load profiles, as they depend on the type of building as well as on user behaviour. The electric load profile is a combination of user independent loads, like the heating system, and user specific loads like computers or lights. Therefore a scaling between households with a different number of people is not possible. Measured profiles do, of course, represent a real household and can satisfy the need for correlating thermal and electric profiles. When using appropriate equipment, even the need for appliance exact profiles can be satisfied. Such a measured profile, however, does represent one specific behaviour only and is not suitable for generalisation.

Synthetic profiles are not identical to one real exemplary user profile but are synthetically created to be representative for a user type. The generation can be based on simulations, statistic behaviour patterns or by recreating exemplary user behaviour. The main advantage of synthetic load profile generation is the possibility to create a range of profiles for different user behaviour. As the boundary conditions for the profiles are known the profiles can easily be adapted to other house types or more people. Synthetic profiles therefore do not have to be scaled to be adapted to higher energy consumptions. The disadvantage of synthetic profiles is that they are not realistic on their own terms, but have to be validated against real measured profiles.

The standard VDI 4655 provides a combined synthetic and measured profile. The profile was created from measured data, which where compared to a mean value to choose the closest profile. There are however some drawbacks to that profile. The electric load, the hot water demand and the heating demand are given as percentage of the annual demand. As the electricity profile is generated of measured data it is not easily scaled to other types of households. The standard gives a normalised profile which is multiplied by the total electricity demand. This way the peaks of the profile get higher too. This, however, does not reflect the real behaviour where the total demand rises but the magnitude of the peaks does not at the same rate, as the peak loads stay the same (e.g. electric oven). Furthermore the stated electricity demand of 5250 kWh for a 3 person household is quite high. In contrast to the electricity and hot water demand, the annual heating demand is not given in the standard. Therefore the heating demand of the considered house has to be assumed or extracted from other sources [63].

To simulate the urban (324 households) and suburban (166 households) grids it is necessary to use a sufficient number of non-identical load profiles. As pointed out above it is furthermore necessary to use coherent thermal and electric profiles. As measured profiles that would fulfil this requirements are not available for this work, synthetic profiles are used.

2.1.2 Load Profile Generation

The synthetic load profiles for the use within this work are created in two steps. First user behaviour profiles for a number of different household types are created. These user behaviour profiles contain information about heating temperature settings, frequency and duration of hot water tapping as well as usage of electric appliances. Secondly the heating and DHW behaviour profiles are used to simulate the corresponding heat demand. The BTSL is used for this purpose. Within this tool a number of house types are available to generate realistic thermal load profiles from the consumer behaviour profile. The heat demand for hot water is generated by the user's hot water demand profile. The weather data used for the BTSL simulation is identical to the weather data used within this work. The electric profile is automatically created by linking the electric user behaviour to the corresponding power demand of the appliances. By the joint generation of thermal and electric load profiles it is secured that they match. All profiles below are created using the location setting Stuttgart, Germany. Section B.1 shows an overview of the generated load profiles.

To justify the usage of the generated profiles they have to be compared to other profiles. Figure 2.2 shows the validation exemplary for one day. The measured profile is based on measurements in a Bosch test house, the VDI 4655 standard profile on a three people household and the generated profile on the 'Standard 2' three person household. It can be seen that the profiles are consistent in having rather short and high power peaks distributed over the day. The measured and the generated profile show similar behaviour regarding the height and duration of the peaks, whereas the semi-artificial VDI profile shows higher base load and lower power peaks. In this context it has to be noted that the VDI 4655 profile is defined as the 'reference load profile of single-family houses for the use of CHP systems' [63] where high base loads are advantageous.

The gained load profiles are distributed over the grid. As there are more houses/flats than load profiles, the load profiles are shifted to earlier and later times, so every profile in the grid is different. The yearly energy consumption is 538 MWh for the suburban and 885 MWh for the urban grid whereas the maximum power demand is 390 kW for the suburban and 538 kW for the urban grid. For the household loads a cos(φ) of 0.95 (inductive) is assumed [48], so the maximum transformer loading is 411 and 566 kVA respectively. This

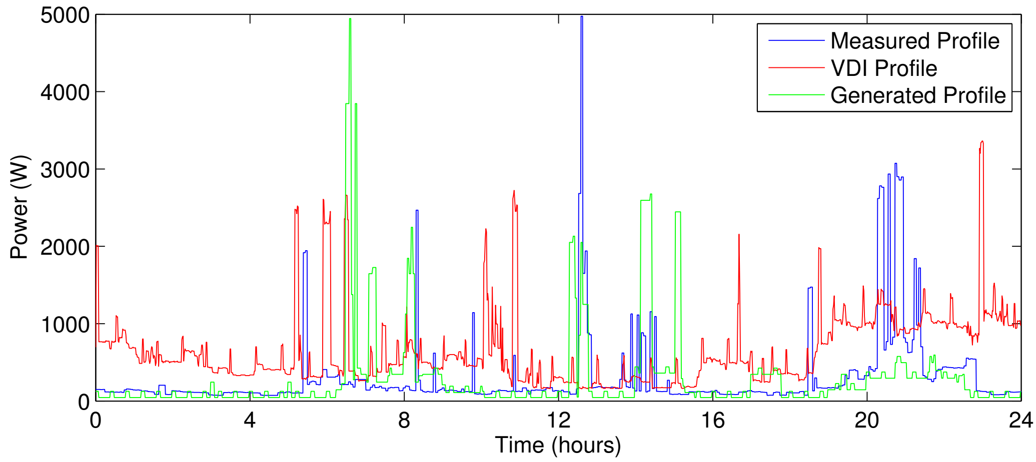


Figure 2.2: Examplary day profile of VDI 4655, Measured and Generated Profile

results in an per household load of 2.5 kVA for the suburban and 1.8 kVA for the urban grids. DSOs typically use maximal values of 3.5 kVA for single family houses and 1.5 kVA for multi family houses for the dimensioning of transformers.[2] Compared to the H0 profile the grid profiles show higher peaks but the same shape (see Figure B.1 and Figure B.2). The higher variability is due to the small number of houses within the grids. Overall the created individual load profiles as well as the consequent grid profiles show realistic behaviour.

The yearly heat demand of the generated profiles varies with the different house types. Table B.2 shows an overview. The average relative heat demand per square metre living area is shown in table Table B.3. It can be seen that it is classified as low for the new buildings, medium for the refurbished detached and the old multi family house and high for the old detached house according to the German heating index [64]. Consequently the heat demand profiles can be assumed to show realistic behaviour.

2.1.3 Weather Data

Weather data are important for the generation of the heating profile as heat gains and losses depend on solar irradiation and environmental temperature respectively. The models for CHP and HP systems are therefore indirectly influenced by that data. Photovoltaic systems are directly influenced by irradiation as well as temperature data. Within this work weather data is used in the IWEC (International Weather for Energy Calculations) format as this is also the basis for the Bosch internal BTSL calculations. This format is defined by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) and merges real monthly weather data to a typical year. The U.S. department of energy provides this IWEC data for over 1000 locations in over 100 countries [65]. Out of many

[2] RWE Westnetz GmbH transformer dimensioning (correspondence with Ü. Sezeneler)

available parameters for the different locations the air temperature and the solar irradiation are used to create the weather profile.

2.2 Component Models

As shown in Figure 2.1 the energy based house model is divided into a subset of modular component models. The models of the appliances consist of six different sub-models which are described below. Some models (e.g. Inverter model) are reused several times. The appliance models represent the appliances within the households that are not already included in the load profiles. The six sub-components are inverter, combined-heat-and-power system, heat pump, heat storage, photovoltaic module and battery. Additionally there is a model for the central energy control. Within this controller the voltage control measures are situated. The functionality depending on the used measure is described within chapter 4.

2.2.1 Inverter

The inverter model is used for all inverters and parametrised to the different application. The model acts as the interface between the appliances, like PV, CHP and HP and the electric grid. Figure 2.3 shows a block diagram of the inverter model. On the left side P_{in} represents the information on the active power flow between appliance and inverter. On the right side P_{out} and Q_{out} represent the information on the active and reactive power at the grid interface. All other in- and outputs are used to control the active and reactive power flows by the control algorithms shown in chapter 4. The value P_{aim} is defined as the aimed power of CHP or HP at the grid interface. The power signal to the appliance ($P_{aim\ app}$) therefore has to be adapted by the inverter losses. For the control of PV systems a limitation to P_{max} is used. The aimed reactive power (Q_{aim}) is not adapted and therefore forced at the grid interface. The output power is limited to ensure that the nominal apparent power (S_{nom}) of the inverter is not exceeded. Necessary input signal is the current power of the connected device. Output values are the active and reactive power at grid side. All other values can be used optionally. In regular operation the power factor is one and the output power is a function of input power and losses. The losses are calculated according to Equation 2.1 [66].

$$P_{losses} = S_{nom} \cdot \left(p_{self} + p_{voltage} \cdot \frac{S}{S_{nom}} + p_{resistance} \cdot \left(\frac{S}{S_{nom}} \right)^2 \right) \tag{2.1}$$

The power losses are dependent on the nominal apparent power of the inverter, the current apparent power and reactive power and on three constant parameters that represent

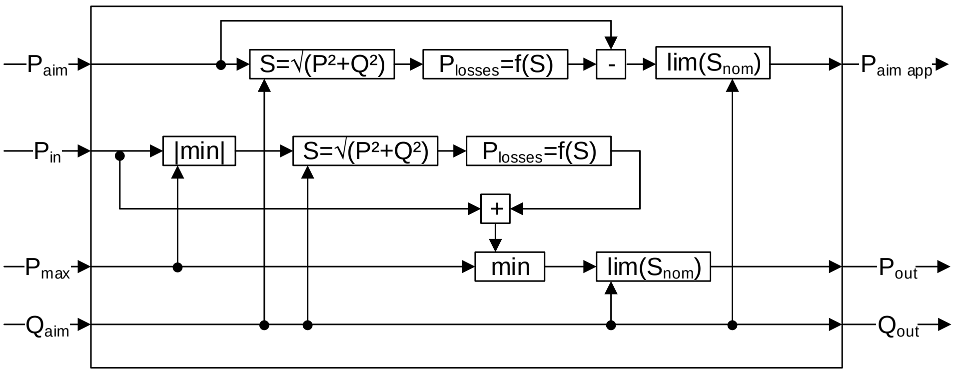


Figure 2.3: Block diagram of inverter model

the standby losses (p_{self}), the voltage dependent losses ($p_{voltage}$) and the current dependent losses ($p_{resistance}$). The nominal apparent power is given by the model parametrisation and characteristic for the inverter. The current apparent power is calculated from the current active and reactive power flows. The standby losses are not dependent on the power flow. The voltage dependent losses are losses at diodes and transistors and are proportional to the power flow. The current dependent losses are losses at impedances and rise proportional to the square of the power flow. The parameters are shown in Table 2.1 and the efficiency dependent on the standardised power in Figure 2.4.

Table 2.1: Parameters of inverter efficiency [66]

Parameter	Value
p_{self}	0.00724 kW/kWp
$p_{voltage}$	0.0181
$p_{resistance}$	0.028 kWp/kW

Within this work one inverter model is used for all appliance types. In reality the power electronics and efficiencies are different in different applications. As it is not the goal to represent on special appliance but rather the characteristic system behaviour within this work these differences are seen negligible. As shown in Figure 2.4 the principle characteristics like high losses at low powers and the highest efficiencies at 30% to 50% of nominal power are reflected by the used model.

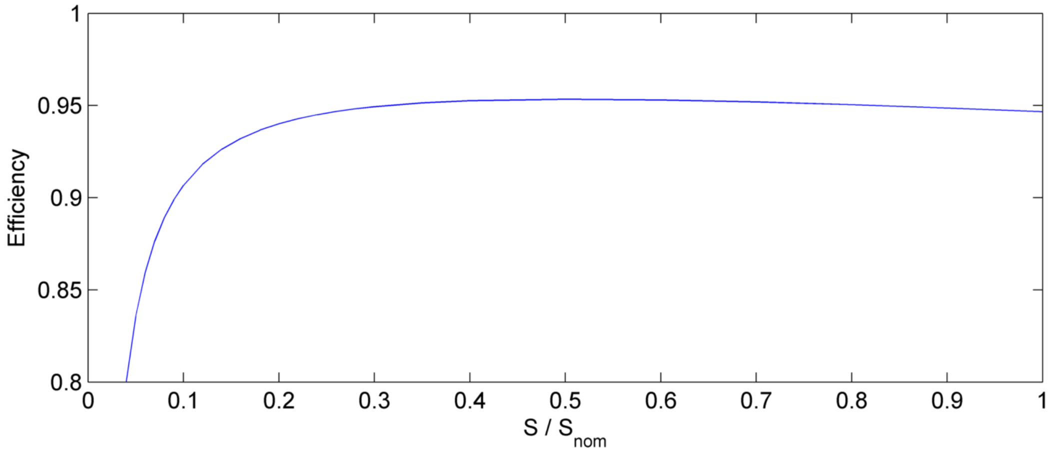


Figure 2.4: Efficiency characteristic of the inverter model

2.2.2 Combined Heat and Power System

Modelling

Three different types of micro CHP are modelled within this work as they represent the currently available technologies: Stirling engine; internal combustion engine (ICE) and exemplary for the fuel cell technology, solid oxide fuel cell (SOFC). The micro CHP is modelled by a electric and thermal efficiency. The efficiencies are used to calculate the thermal power output dependent on the electric power that is set by a proportional controller dependent on the heat storage temperature. The electric and thermal efficiencies of the different technologies are shown in Figure 2.5 and Figure B.3. Table 2.2 shows the maximum efficiencies.

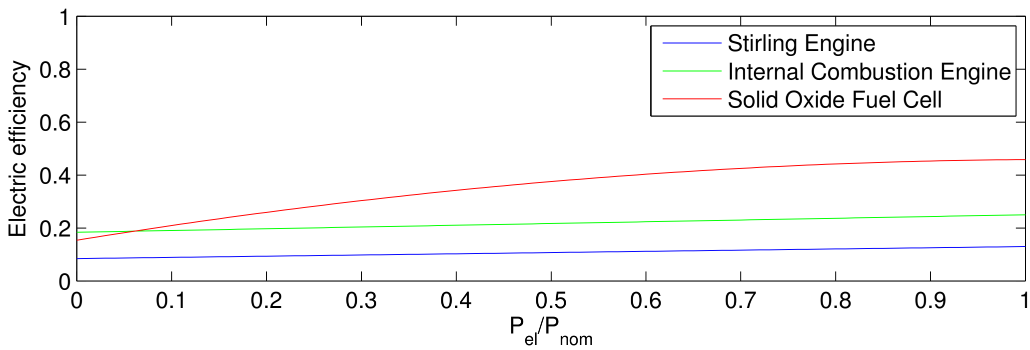


Figure 2.5: CHP electric efficiency

Two different controllers are implemented. One for the solid oxide fuel cell (SOFC) and one for internal combustion engine (ICE) and Stirling engine CHP systems. Figure 2.6 and Figure 2.7 show the different hysteresis of the SOFC and ICE / Stirling engine CHP models. The SOFC is operating on maximum power in space heating (SH) mode and reduces the power if the hot water (HW) storage reaches a limit temperature. As the SOFC shut down

Table 2.2: Maximum efficiencies and nominal electric power of CHP technologies

	Stirling Engine	Internal Combustion Engine	Solid Oxide Fuel Cell
η_{th_max}	0.85	0.70	0.48
η_{el_max}	0.13	0.25	0.46

is not dependent on the tank temperature but on other internal parameters, a shut down is not implemented but the SOFC can operate at minimum power level even if the heat storage is fully charged. This is an appropriate simplification, as the SOFC shuts down only a few times a year. The other CHP technologies are modelled by a hysteresis that shuts down the system at maximum tank temperature. Depending on the temperatures of the space heating and the HW buffer tanks it is decided which one is charged. Regularly the CHP systems are operated heat controlled. Additionally it is possible to activate a power controlled mode. This mode deactivates the proportional controller and only verifies if the aimed power can be generated depending on the storage temperatures. If this is possible the aimed power is set as electric power output. As micro-CHP systems are always installed with a peak boiler they can be power controlled independent of the tank temperatures. However, if the maximum tank temperature is reached the CHP systems have to reduce to minimum power (SOFC) or shut down (ICE / Stirling). The proportional controller is used to calculate the electric power output. The maximum electric power of the CHP system can be parametrised individually.

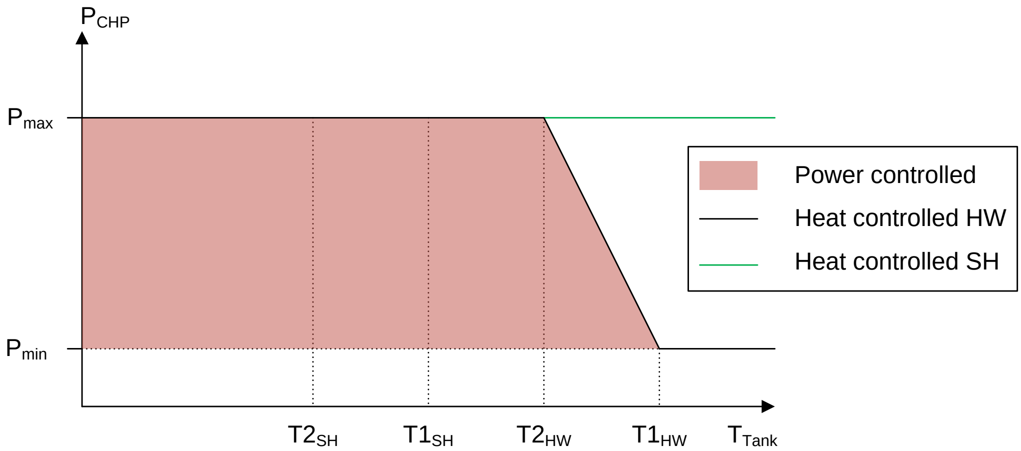


Figure 2.6: SOFC CHP controller

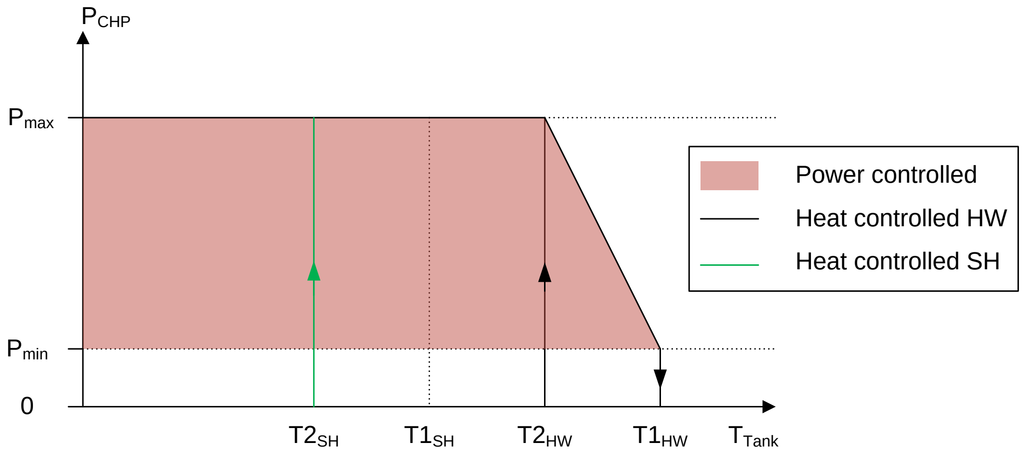


Figure 2.7: ICE and Stirling engine CHP hysteresis

Validation

All appliance models that are used for the grid simulation are not specified to represent one specific type, but rather to represent the general kind of application. This is as in real grids many different types are installed and to reproduce the grid's behaviour it is only necessary to represent the general behaviour. Therefore the models are validated using verified simulations and / or measurements of similar appliances to verify the principal behaviour. The SOFC model on PowerFactory is compared to the verified SOFC model in the BTSL. Both models operate on maximum power during the complete heating period and on variable powers during the summer. Using the same nominal power and heat load profile the PowerFactory model generates 97% of the electric energy per year that is generated by the BTSL model. This shows that the PowerFactory model represents the general type of SOFC CHP.

ICE and Stirling engine CHP system do not operate constantly during the heating period. Therefore a separate validation of the model is necessary. As no validated simulation model is available the PowerFactory model is compared to a measurement of a 4.7 kW ICE CHP installed in a Bosch test house (single family house). As the thermal load profiles do not match for the simulation and the measurement, relative values are compared. Using the same nominal power, the average electric power generation during times of operation differs by 1.8% between the model and the measurement. The average thermal efficiency differs by 1.4%. The model and the measurement show an average of 3.5 starts per day. This confirms the ability of the PowerFactory model to represent the general type ICE / Stirling CHP.

2.2.3 Heat Pump System

Modelling

The heat pump is modelled by a function of electric power and the coefficient of performance (COP) depending on environmental conditions. The HP model can be parametrised as a air/water or brine/water heat pump. The performance is dependent on the supply temperature of the heating system and on the ambient air or brine temperature depending on the type of heat pump as well as on the nominal heat power. The ambient air temperature is given by the weather data and the supply temperature is provided by the heat storage model. The brine temperature is assumed to be a constant value (3.38°C) which is the average brine temperature during the heating period according to [67]. Figure 2.8 shows the COP exemplary for a 6kW$_{th}$ air-water and brine-water heat pump depending on the outside air temperature.

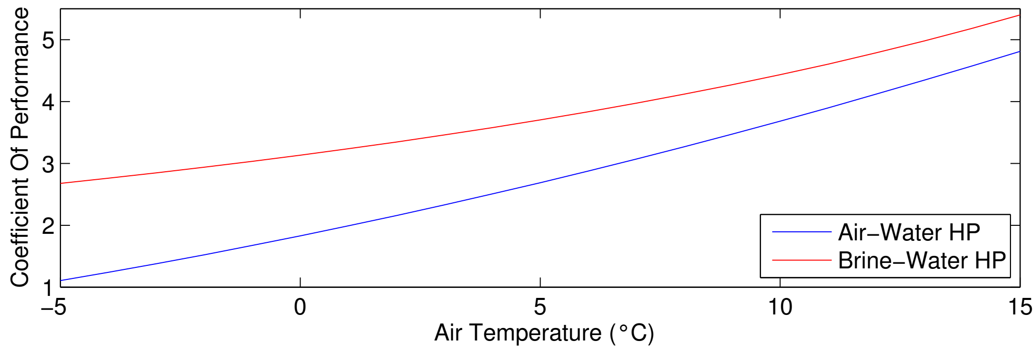


Figure 2.8: COP of 6kW$_{th}$ air-water and brine-water HP

A proportional hysteresis controller is used to control the heat pumps electric power. The electric power of the heat pump is a function of the tank temperature. The hysteresis can be seen in Figure 2.9. In a first step a decision is taken which tank is relevant for the heat pump hysteresis controller. The hot water tank has priority and a second hysteresis controller is set up to switch between the two tanks depending on their temperatures. The hysteresis shown in Figure 2.9 is valid for both storages but the temperature levels T1, T2 and T3 are parametrised differently. The operating point and efficiency model calculates the current possible electric power and the thermal efficiency from the ambient and supply temperature. The maximum heat power of the heat pump is a parameter, defined individually for each house depending on the heat demand. If the temperature in one storage falls below the level of T3, an ancillary heater is switched on. Additionally a power controlled mode can be used. In this mode the heat supply for the house is not considered but the heat pump operates on the given aimed power. Two constrains are considered in the power controlled mode: The minimum power (0.5 P_{max}) must not be undercut and the maximum tank temperatures must not be exceeded.

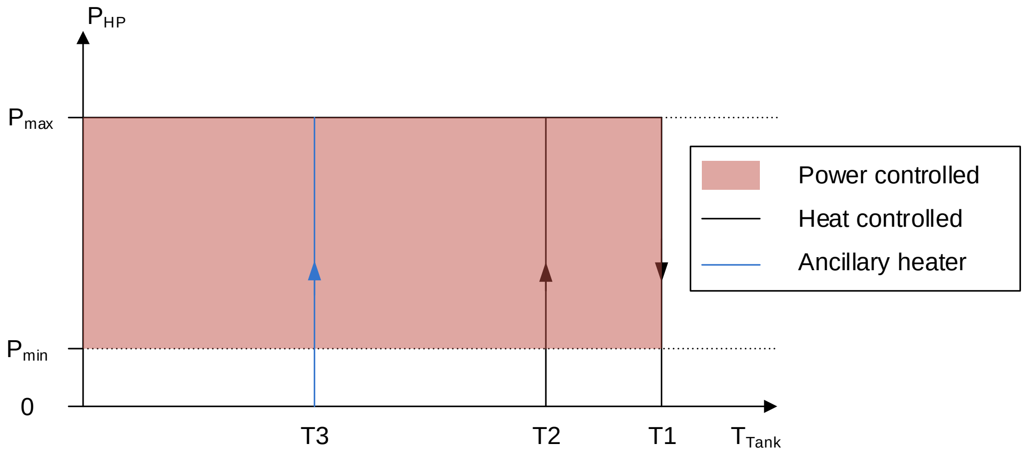


Figure 2.9: HP hysteresis

Validation

Simulating the same building type and user behaviour, the comparison of the PowerFactory heat pump model and the BTSL model shows a difference in generated heat energy of 2.7% per year. This difference is partly due to differences in heat losses between the detailed building simulation in the BTSL and the simplified model in PowerFactory. The PowerFactory model uses the electric heater for 5.3 % of the yearly heat generation. The standard dimensioning rule is 5 % of the yearly heat production. The number of yearly startups differ between the BTSL model, the PowerFactory model and the measurement from the Bosch test house. The used model, however, is situated exactly in the middle between the other two regarding the number of yearly startups. The PowerFactory heat pump model is therefore seen as a good representation of the principle operation pattern of heat pumps.

2.2.4 Heat Storage

The hot water storage tank model is used for CHP as well as HP applications. The heat storage tanks are modelled by a zero dimensional heat capacity model. To model limitations in the storage capacity due to changing supply and return temperatures the model is temperature based. The temperature change is defined by Equation 2.2. The heat power of the heat source ($\dot{Q}_{heatsource}$) is calculated by the CHP or HP model, the heat load ($\dot{Q}_{load}$) is defined by the load profile. The specific losses ($\dot{Q}_{losses}$) assumed for the DHW and buffer tanks are shown in Equation 2.3 and Equation 2.4.[3] The losses consist of a volume independent part and a part that is dependent on the tank volume in litre. The heat capacity of

[3] Losses according to Buderus Logalux data sheet (2012)

the storage is defined by the product of water volume (V_{tank}), the density of water (ρ_{water}) and the specific heat capacity of water (c_{water}).

$$\dot{T} = \frac{\dot{Q}_{heatsource} - \dot{Q}_{load} - \dot{Q}_{losses}}{V_{tank} \cdot \rho_{water} \cdot c_{water}} \tag{2.2}$$

$$\dot{Q}_{loss\ DHW} = 34.6\ W + 0.228\ \frac{W}{l} \cdot V_{DHWtank} \tag{2.3}$$

$$\dot{Q}_{loss\ buffer} = 28.3\ W + 0.224\ \frac{W}{l} \cdot V_{buffertank} \tag{2.4}$$

The state of charge (SOC) is defined by the current temperature as well as the minimum and maximum temperature. The minimum and maximum temperature of the tank is the supply temperature and return temperature respectively. The CHP system deviates from this setting as the heating buffer tank is allowed to be charged to the hot water supply temperature level. This enables a larger storage capacity without compromising the efficiency. The HP systems efficiency decreases with increasing supply temperatures, therefore the hot water temperature level is lower too. The supply temperature (ST) and return temperature (RT) are determined via a heating characteristic shown in Figure 2.10. The maximum values for ST and RT depend on the house and heating system and can be found in Table B.4. The buffer tank size varies in single family houses between 490 and 550 litres and in multi family houses between 2800 and 3200 litres. Similar the domestic hot water storage has 250 to 300 litres in single family houses and 950 to 1100 litres in multi family houses. These high values for the storage volumes are chosen to compensate the non existence of the heating circuits' and the house's heat capacity within the PowerFactory model.

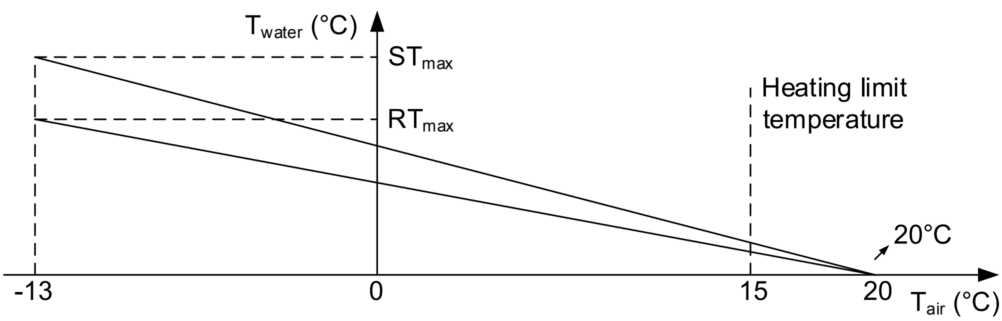


Figure 2.10: Heating characteristic to determine supply and return temperature

2.2.5 Photovoltaic System

Modelling

The PV model consists of three sub models. First the sun position is calculated depending on the time and the geographic position. Secondly the tilted irradiation on the PV panels is calculated using measured direct and global irradiation data, the sun position and the parameters for direction and tilt of the module. Thirdly the DC output power of the PV module is calculated using a efficiency function depending on the outside temperature and the tilted irradiation. The irradiation on the tilted panel is calculated according to [68]. Equation 2.5 to 2.8 show the basic correlations.

$$E_{global,tilted} = E_{direct,tilted} + E_{reflected,tilted} + E_{diffuse,tilted} \tag{2.5}$$

$$E_{direct,tilted} = f(E_{direct,horizontal}, \Theta_{tilted}, \gamma_{sun}) \tag{2.6}$$

$$E_{reflected,tilted} = f(E_{global,horizontal}, A_{foreground}, \gamma_{module}) \tag{2.7}$$

$$E_{diffuse,tilted} = f(E_{global,horizontal}, E_{direct,horizontal}, \gamma_{module}) \tag{2.8}$$

Where E is the $global$, $direct$, $reflected$ or $diffuse$ irrediance either on a $horizontal$ or $tilted$ surface. Θ_{tilted} is the angle between the sun direct irradiation (E_{direct}) and the normal vector on the tilted surface. γ_{sun} is the angle between the horizontal surface and the direct irradiation while γ_{module} is the angle between the horizontal and the tilted surface. $A_{foreground}$ is the foreground's albedo. Figure 2.11 shows the overview for the calculation of the direct irradiation on a tilted surface. For the detailed model it is referred to [68].

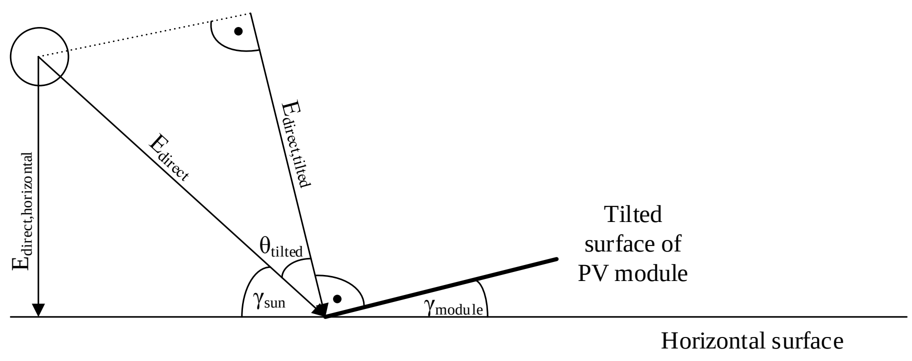


Figure 2.11: Overview of the geometric data for the calculation of the direct irradiation on a tilted surface

The efficiency model is based on [69] and [70]. The empiric model by [69] can be seen in Equation 2.9 and the used parameters a_1 to a_3 and α by [70] in Table 2.3. T_{amb} is the ambient temperature of the PV panels.

$$\eta_{PV} = (a_1 + a_2 \cdot E_{global,tilted} + a_3 \cdot ln\,(E_{global,tilted})) \cdot (1 + \alpha \cdot (T_{amb} - 25°C)) \qquad (2.9)$$

Table 2.3: Parameters of PV efficiency model

Parameter	Value
a_1	0.039329
a_2	-0.000013
a_3	0.012056
α	-0.003910

Validation

The PowerFactory PV model generates 958 kWh/kW$_{peak}$ per year in a reference system with 10.8 kW$_{peak}$ directed to south with an roof angle of 30°. This is realistic behaviour according to [71], even though new PV systems reach higher efficiencies. The PV model is therefore seen as a good representation of general PV generators.

2.2.6 Battery System

The model of a lithium ion battery is based on the SAFT Intensium Flex - Energy Module. Figure 2.12 shows the principle structure of the model.

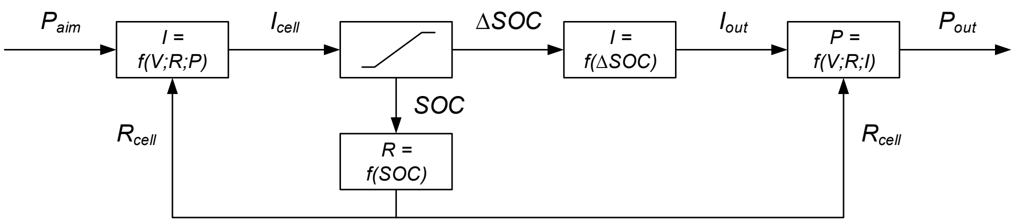


Figure 2.12: Battery model overview

The cell power (P_{aim}) is calculated using input power and number of cells. The aimed total input power is given by the central energy manager. The resulting cell current is calculated from Equation 2.10 and Equation 2.11 as a battery can be seen as voltage source. The cell voltage can therefore be calculated as the sum of the open circuit voltage V_{OCV} and the voltage drop or rise by the current flow over the internal battery resistance. R_{cell} is calculated depending on the current state of charge (SOC) according to Equation 2.12.

The function of the cell resistance was fitted to data sheet values of the SAFT Intensium Flex - Energy Module.[4] The fitting factors A_R to D_R are shown in Table 2.4.

$$P_{cell} = V_{cell} \cdot I_{cell} = (V_{OCV} + R_{cell} \cdot I_{cell}) \cdot I_{cell} \tag{2.10}$$

$$I_{cell} = -\frac{V_{OCV}}{2R_{cell}} + \sqrt{\left(\frac{V_{OCV}}{2R_{cell}}\right)^2 + \frac{P_{cell}}{R_{cell}}} \tag{2.11}$$

$$R_{cell} = A_R + B_R \cdot SOC + C_R \cdot SOC^2 + D_R \cdot SOC^3 \tag{2.12}$$

Table 2.4: Parameters of battery cell resistance

Parameter	Value
A_R	0.113
B_R	-0.00231
C_R	0.0000283
D_R	-0.0000001

The change in SOC is calculated by the cell current and the cell capacity which is 45 Ah. During SOC calculation the SOC is limited between minimum and maximum value, this ensures that there is no current flowing if the battery is already full or empty. The new SOC is used to calculate the cell resistance. Using the cell capacity and the calculated change in SOC the real cell current (I_{out}) can be calculated which is used to calculate the real cell power (P_{out}) using the cell resistance (R_{cell}).

2.3 Grid Topology

To obtain realistic behaviour, real grids are chosen for the simulation. An urban housing estate and a suburban detached houses estate grid, examined and evaluated by Scheffler [72], are implemented in PowerFactory. These grids represent existing old grids. Despite ambiguity regarding the meaning of the terms urban and especially suburban, these grid topologies are referred to as urban and suburban hereafter [73]. In order to evaluate the behaviour of new grids with the same topology, artificial grids are created by changing cables and transformer of the real grids.

[4] Internal Bosch Study by K. Büdenbender and M. Braun; Fraunhofer IWES 2010

2.3.1 Urban Grid

The urban grid is situated in a 36 houses inner city community. The buildings with nine flats each were build between 1910 and 1915. The grid is a meshed grid fed by several transformers which is operated as a star grid due to open circuit breakers. The grid examined by Scheffler is partly refurbished. This leads to different cable types being used [72]. To create an old grid the original cables are used in all feeders. The new grid is equipped with state of the art cables and transformer.[5] Figure 2.13 shows the grid topology, Table 2.5 the cable and transformer types. The exact cable and transformer specifications can be found in section B.3 and section B.4 respectively. Both urban grids are characterised by the maximum load of 597 kVA according to the load profile mix described in section 2.1.

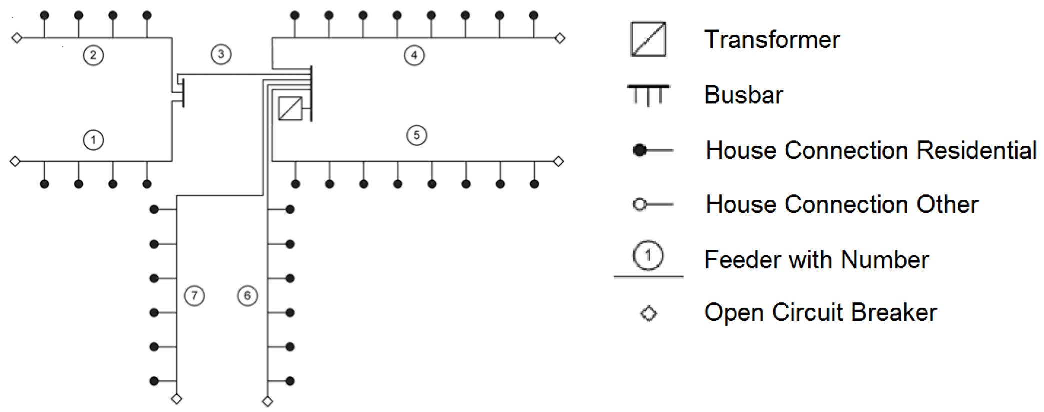


Figure 2.13: Grid topology of German urban low voltage grid [72]

Table 2.5: Cable and transformer types of urban grids

Grid	Urban Old	Urban New
Number of Houses	36	36
Transformer Power (kVA)	630	630
Main Cable Type	NAYY 4x70	NAYY 4x150
House Connection Cable Type	NAYY 4x25	NAYY 4x35
Longest Feeder (m)	235	235
Number of Houses in Feeder	8	8

[5] RWE Westnetz GmbH standard equipment 2013 (correspondence with J. Jendernalik)

2.3.2 Suburban Grid

The old suburban grid is a 166 detached houses community evaluated by Scheffler. It was build in the 1930s. The grid has a meshed topology but is operated as as a star grid with six feeders. The mesh is open at the circuit breakers between cables 1, 2 and 9 and between the cables 4, 5 and 7. The grid is realised with overhead cables of the Type NFA2X [72]. Figure 2.14 shows the grid topology, Table 2.6 the cable and transformer types. section B.3 includes the cable and section B.4 the transformer parameters.

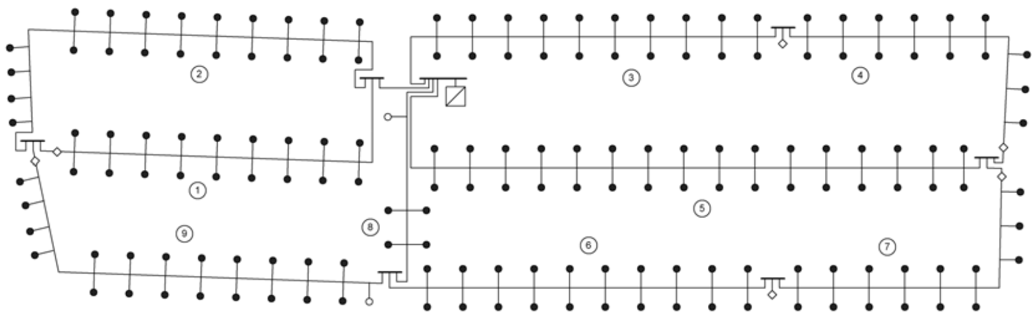


Figure 2.14: Grid topology of German suburban low voltage grid [72]

A new suburban grid is created by changing cables and transformer but using the same topology. Typical transformer and cable types in new grids were supplied by RWE Westnetz GmbH. The new equipment type can be found in Table 2.6. Section B.3 and section B.4 include the detailed cable and transformer parameters.

Both suburban grids are characterised by the maximum load of 433 kVA according to the load profile mix described in section 2.1.

Table 2.6: Cable and transformer types of suburban grids

Grid	Suburban Old	Suburban New
Number of Houses	166	166
Transformer Power (kVA)	400	630
Main Cable Type	NFA2X 4x95	NAYY 4x150
House Connection Cable Type	NFA2X 4x25	NAYY 4x35
Longest Feeder (m)	484	484
Number of Houses in Feeder	39	39

2.3.3 Topology Verification

The simulation of these exemplary grids generates exemplary results. In order to evaluate the results it is important to classify the grids regarding their representation of typical grids. Bodach [30] classified typical grids and their operating equipment like transformer and cables into eight groups that are shown in Table B.7. The grid suburban old described above is comparable to group D1 that represents old single family housing estates. A typical feeder length for this type of estate is less than 400 m. The longest feeder in the suburban old grid is 484 m long. It is, however, the only feeder above 400 m and the average feeder length is 322 m. The cable type used in the exemplary grid is stated as one typical cable type. The used transformer power is also stated as typical. As the transformer power as well as the cable size are on the higher edge of the stated values, the behaviour of the grid can be categorised as typical. The group D2 represents new single family housing estates like the suburban new grid. The stated feeder length and transformer power are similar to the group D1. The cable type used in the suburban new grid is stated as typical. The transformer power used is higher than the stated power. The used power is however used in new grids of RWE Westnetz and can therefore be considered as typical. The suburban new grid can therefore be categorised as typical. For urban multi family building estates it is not distinguished between new and old estates, so the urban old as well as the urban new grid are compared to group B which represents living areas with block buildings with six to twelve apartments per house connection. Both urban grids by Scheffler [72] have 9 apartments per house and a transformer power considered as typical by Bodach [30]. The maximum typical feeder length is defined as 300 m, while the two used grids have a maximum feeder length of 235 m. The cable type used in the urban new grid is stated, whereas the cable type used in the urban old grid is thinner than the stated cables. The urban new grid therefore can be categorised as typical, while the urban old grid is a weak grid which has to be considered for the evaluation of the voltage deviation results.

Other works use similar grids for their evaluations. Bodach [30] for example uses grids examined by Scheffler, while Kruschel [74] uses a simple artificial star grid with feeder length from 400 to 900 m. Huang [75] uses a small low voltage grid with only one main feeder with 315 m and 120 mm^2 cables. Kerber [76] uses transformer powers and cables similar to the suburban grid used within this work but states no feeder length. Gwisdorf [77] uses a simple one-feeder grid with transformer power and cable types similar to the suburban grids, but does vary the feeder length from 200 m to 2.2 km. Marra [78] simulates an urban grid with 271 households, compared to 324 in the urban grids used in this work. The used transformer power is similar to the grid used in this work, but the feeder length and cable data are not stated.

The suburban as well as the urban grid topologies used within this work do represent a fairly typical layout. This can be seen in comparison to the characterisation by Bodach [30] as well as grids used in other works.

2.3.4 Medium Voltage Grid

The medium voltage (MV) and high voltage (HV) grids are modelled as passive grids. No other loads or generators than the considered low voltage grid are connected. The voltage on the MV grid, however, is considered to fluctuate within the limits of $\pm$4% of nominal voltage [45]. In order to modulate the voltage variation that impacts the low voltage (LV) grid the voltage level of the MV grid is influenced locally at the MV to LV transformer. A PV generator and a load with H0 load profile (electric standard household load profile of the German Association of Energy and Water Industries - Bundesverband der Energie- und Wasserwirtschaft - BDEW) are connected directly to the MV busbar of the transformer. They are dimensioned in order to create a $\pm$4% voltage variation in the unloaded low voltage grid. If voltage fluctuations are considered in the simulations below, this equipment is activated in order to modulate the voltage variations of the MV grid. Contrary to the limitation of the LV voltage band to $\pm$6% nominal voltage, this considers differences between the load profile in the specific low voltage grid and the medium voltage grid.

2.4 Physical Model

As explained above, the physical grid simulation is based on PowerFactory algorithms. In this section the basic principles are briefly summarised. The voltage in an electric network is defined by the voltage source and the voltage drop or rise due to current flow through resistances. In an AC network the voltage is additionally influenced by the reactance. Figure 2.15 shows the equivalent circuit of a simple electric grid with a voltage source (e.g. transformer) represented by the voltage $\underline{V}_0$ and its internal impedance $\underline{Z}_0$. The electric generator is represented as the current source $\underline{I}_1$ and its internal impedance $\underline{Z}_1$ because most generators on the LV grid are connected via an inverter (i.e. PV). The load is represented simplified as the impedance $\underline{Z}_2$, while the cables are represented by the impedances $\underline{Z}_{L1}$ to $\underline{Z}_{L4}$.

According to the Kirchhoff law three equations (Equation 2.13 to 2.15) can be defined and used to calculate the voltage amplitude at the load $\underline{V}_2$ (Equation 2.16).

$$\underline{V}_0 - \underline{V}_{0R} - \underline{V}_{L1} - \underline{V}_1 - \underline{V}_{L2} = 0 \tag{2.13}$$

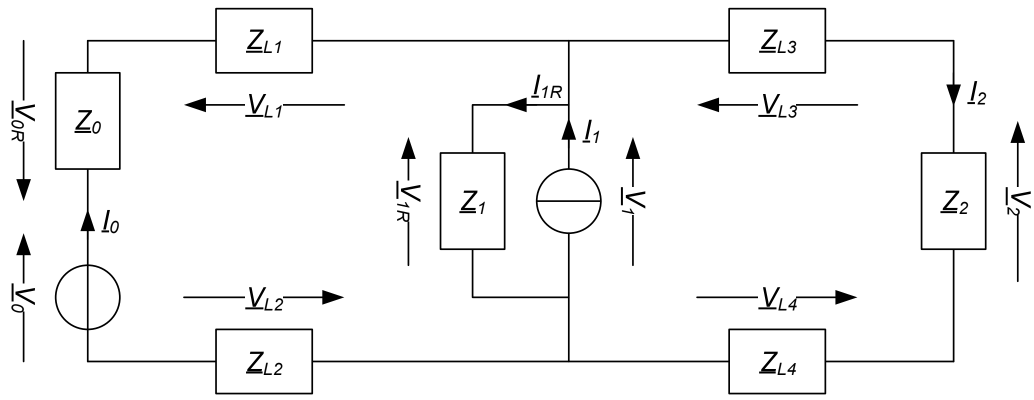


Figure 2.15: Equivalent circuit diagram of low voltage grid with generator and load

$$\underline{V}_1 - \underline{V}_{L3} - \underline{V}_2 - \underline{V}_{L4} = 0 \tag{2.14}$$

$$\underline{I}_0 + \underline{I}_1 - \underline{I}_{1R} - \underline{I}_2 = 0 \tag{2.15}$$

$$\underline{V}_2 = \frac{\underline{V}_0 + (\underline{I}_1 - \underline{I}_{1R}) \cdot (\underline{Z}_0 + \underline{Z}_{L1} + \underline{Z}_{L2})}{1 + \left(\dfrac{\underline{Z}_0 + \underline{Z}_{L1} + \underline{Z}_{L2} + \underline{Z}_{L3} + \underline{Z}_{L4}}{\underline{Z}_2} \right)} \tag{2.16}$$

Using substitutions for the loop impedance of the generator $\underline{Z}_{loop,gen} = \underline{Z}_0 + \underline{Z}_{L1} + \underline{Z}_{L2}$ and the load $\underline{Z}_{loop,load} = \underline{Z}_0 + \underline{Z}_{L1} + \underline{Z}_{L2} + \underline{Z}_{L3} + \underline{Z}_{L4}$ as well as the assumption that $\underline{I}_1 \gg \underline{I}_{1R}$ this simplifies to:

$$\underline{V}_2 = \frac{\underline{V}_0 + \underline{I}_1 \cdot \underline{Z}_{loop,gen}}{1 + \dfrac{\underline{Z}_{loop,load}}{\underline{Z}_2}} \tag{2.17}$$

This formula can now be used to calculate the voltage at the position of the load in this simplified example. The same principle is, however, also used to calculate complex electric grid systems with several hundred loads and generators as shown in chapter 3.

Chapter 2 describes the simulation setup. The simulation model is based on a physical grid model and power based components models. The calculation principles of the grid model is shown and the component models are described and validated. The electric and thermal load profile generation is explained and validated. The sourcing of the real weather data is described.

3 Influence on Voltage Level

In this chapter the influence of CHP, HP and PV appliances on the voltage level in low voltage grids as well as the corresponding transformer loading is examined is evaluated. Section 3.1 examines the characteristic influence of the different appliances and combinations on the voltage level and the transformer loading. Within section 3.2 scenarios for 2020 penetration levels are developed and the subsequent influence on the voltage level and transformer loading evaluated.

3.1 Characteristic Voltage Influence

3.1.1 Simulation Set-Up

The influence of CHP, HP and PV systems on the grid voltage and the transformer loading depends on the grid layout, the connection points of the devices and the equipment properties. The characteristic of the voltage or loading influence of the different devices, however, does not depend on these factors. The individual characteristics shown in subsection 3.1.2 and subsection 3.1.3 are therefore shown based on one exemplary grid layout. The Suburban Old grid consisting of 166 detached houses, described in detail in section 2.3, is used for that purpose. The topology is shown in Figure 2.14 whereas the properties are stated in Table 2.6. The voltage is measured at the end of feeder no. 7 as this location is furthest from the transformer.

Every house is represented by an individually parametrised house model as described in chapter 2 and shown in Figure 2.1. As a basic load profile for all houses a three person household 'Standard' is used. To avoid concurrency of load peaks and to supply every house with a unique profile every load profile is shifted by one minute compared to the other. The load profiles are then distributed across the grid randomly. The exact penetrations and settings for the CHP, HP and PV systems are shown along with the results of the simulations in subsection 3.1.2 and 3.1.3. Within this sections the characteristic influences of different appliances on the voltage level and the loading of the transformer are examined. The simulation period is a week in February for all simulations. This week is chosen to enable all different appliances to operate as PV is provided with solar irradiation and due to the low outdoor temperatures the heating equipment is operating.

3.1.2 Characteristics of Appliances

To enable comparability between CHP, HP and PV installations the simulations below assume a comparable installed power for the different appliances.

Combined heat and power

For the CHP systems a uniform distribution between an 0.7 kW SOFC, a 1 kW Stirling Engine and 5 kW ICE is assumed. For the 136 units that are distributed homogeneous over the grid this results in a total installed electric power of 303 kW. The voltage characteristic at the end of the longest feeder over one week is shown in Figure 3.1. The blue line shows the voltage level in per unit (pu) without any installed CHP systems but with the regular household load profiles. The red line shows the same week with 136 installed CHP systems. It can be seen that during the day the two profiles are very similar but shifted to higher voltages by the installed CHP systems. During the night the different working times of the different systems cause additional fluctuations. The maximum overall influence is low at only 3 percent.

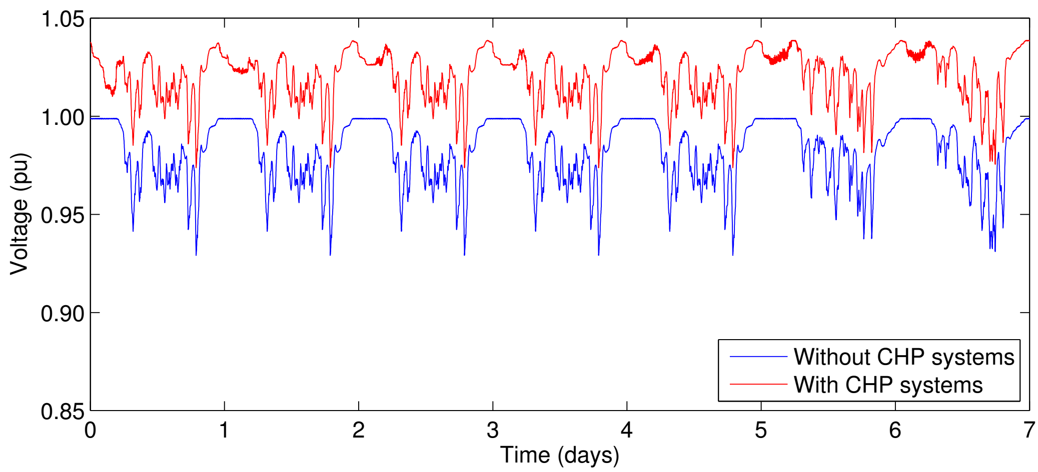


Figure 3.1: Voltage characteristic of CHP systems at end of feeder 7 (suburban old grid)

The transformer loading of the same configurations is shown in Figure C.1. It can be seen that the maximum loading without CHP systems is slightly higher but also that the loading with CHP systems virtually never drops below 20 percent. The loading of the two lines is countercyclical, as in times of high loading due to the households the CHP can reduce the transformer loading, but in times of low loading of the households, the transformer has to feed back the CHP power and is therefore higher loaded. In both cases the loading level of the transformer is uncritical.

Heat pumps

Due to the high heat demand of the old detached houses, big air/water heat pumps with a nominal heating power of 12 kW are used. Depending on the boundary conditions like air and heating water temperature this results in an electric power demand of about 4 kW with an additional 4 kW heating rod installed. This results in 272 kW total installed electric power for 34 heat pumps with 8 kW each. The voltage profile at the end of the longest feeder shown in Figure 3.2 illustrates the characteristic with and without heat pumps. It can be seen that the heat pump systems cause substantial voltage reduction, especially in the morning and in the evening. Similar to CHP systems the HP systems cause voltage fluctuations during the night. The depth of the voltage decrease is caused by the constant power behaviour of the heat pumps. This is valid for HPs that are connected by power electronics until they reach their maximum current limitation. To keep the power constant, in case of a voltage reduction, the current is increased. As the voltage decrease is defined by the current flowing through the resistance of the cables, an increased current reduces the voltage further. This leads in this case to voltage levels below EN 50160 levels [21].

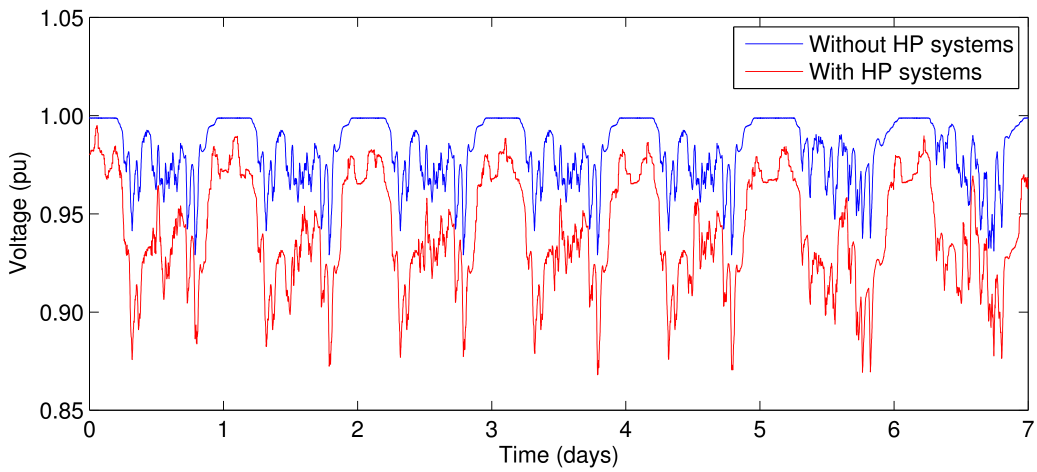


Figure 3.2: Voltage characteristic of HP systems at end of feeder 7 (suburban old grid)

This phenomenon can also be seen with the transformer loading shown in Figure C.2. As the transformer loading is directly related to the current flow, the loading increases over-proportionally compared to the power flow. While the loading peaks at around 70 percent for the regularly loaded grid, it exceeds 120 percent for the grid with installed HP systems. The connection of this amount of heat pumps would not be allowed by the grid operator.

Photovoltaic

For the PV simulations a uniform distribution and size of the systems is assumed. The 54 PV systems have a peak power of 5 kW. This leads to an overall installed PV power of 285 kW. Figure 3.3 shows the voltage profile at the end of the longest feeder over the specified week with and without PV systems. It can be seen that obviously the PV systems do not have an impact on the voltage level at night and during the morning and evening. During the day it is clearly visible that the PV power increases until noon to decrease afterwards. The exact PV power, however, is dependent on the irradiation and therefore not constant from day to day. In this context it has to be noted that this simulation is based on a week in February and therefore does not tab the full potential of the PV systems. This leads to an lower maximum influence on the voltage level compared to CHP systems with a comparable amount of installed power.

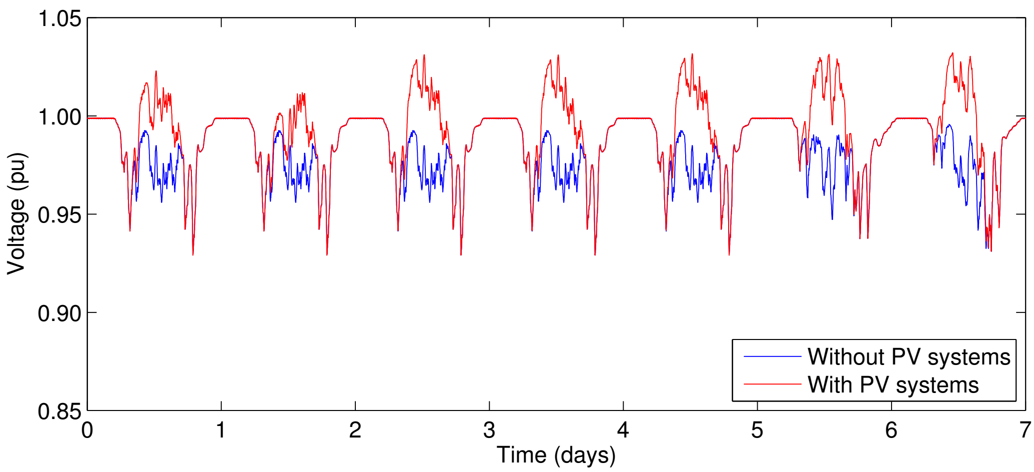


Figure 3.3: Voltage characteristic of PV systems at end of feeder 7 (suburban old grid)

Figure C.3 shows the transformer loading with and without PV installations. As with the voltage profile it can be seen that the PV systems have no influence in the nights, mornings and evenings. During the day the PV systems reduce the transformer loading as a part of the PV feed in is consumed by the grids power demand.

3.1.3 Characteristics of Combinations

To understand the behaviour in real grids it is essential to understand the behaviour of combinations of CHP, HP and PV appliances, as they are very likely to coexist on many grids. For the combination simulations below the same quantity and power assumptions as for the characteristic simulations above apply.

CHP and HP

Figure 3.4 shows the voltage behaviour at the end of the longest feeder with HP systems and with CHP systems as seen in Figure 3.2 and 3.1. Additionally the profile for a grid with both, HP and CHP, systems installed can be seen. The heating systems are distributed uniformly over the grid without having two appliances in the same house. The positive influence is remarkable, even though the systems do not communicate or try to reduce the influence otherwise. The maximum voltage is about as high as with only CHP systems, but the minimum voltage is noticeably increased compared to only HP systems on the grid. This effect is due to the similar operating behaviour but opposite influence of CHP and HP systems. Both are heat led, operating depending on the individual heat demand of the houses. As the heat demand depends on the outside air temperature that is similar for all houses the operating profiles fit well. The power needed by the heat pumps is delivered by the CHP systems. This leads to a voltage profile similar to the one without any appliances, even though more fluctuating.

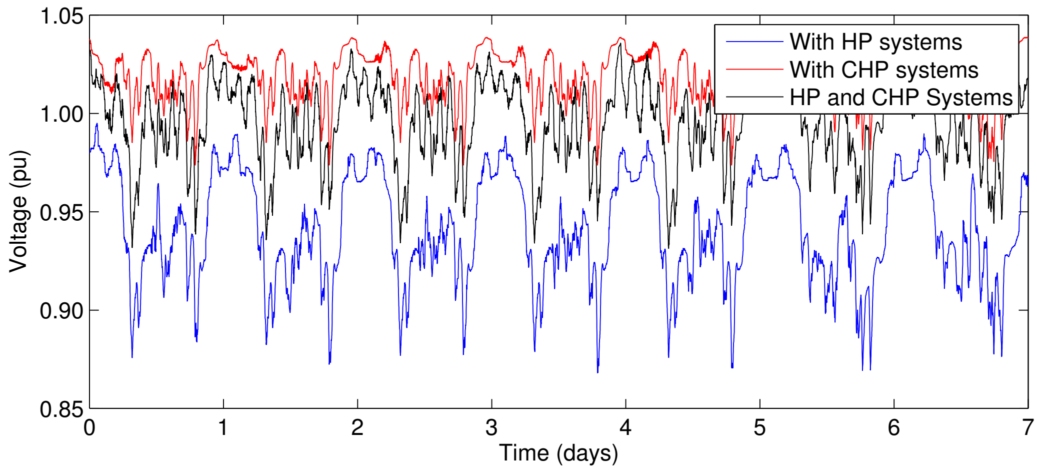


Figure 3.4: Voltage characteristic of combined CHP and HP systems at end of feeder 7 (suburban old grid)

As for the voltage profile, Figure C.4 shows a substantial reduction in transformer loading for the combination of CHP and HP systems compared to the grid with only HPs installed. The peak demand of the heat pumps in the morning and the evening is still represented in the combined profile, but reduced to around 60 percent transformer loading.

PV and HP

For the combination of PV and HP the distribution is also uniform over the grid, but in some houses both systems are installed. The voltage characteristics at the end of the longest feeder of PV, HP and the grid with both appliances is shown in Figure 3.5. As the PV systems only operate during the day, the voltage profile of the grid with both appliances is similar to the one with only heat pumps for the other times. During the day the voltage level is between the grid with HP or PV respectively. This means that the installation of HPs into a grid with PV can reduce the maximum voltage due to PV, but the minimum voltage due to HP can not be increased by the installation of PV systems. Furthermore it has to be noted that HP operate mostly in winter and PV mostly in summer. The simulated week was deliberately chosen to be cold and sunny, so all appliances are operating.

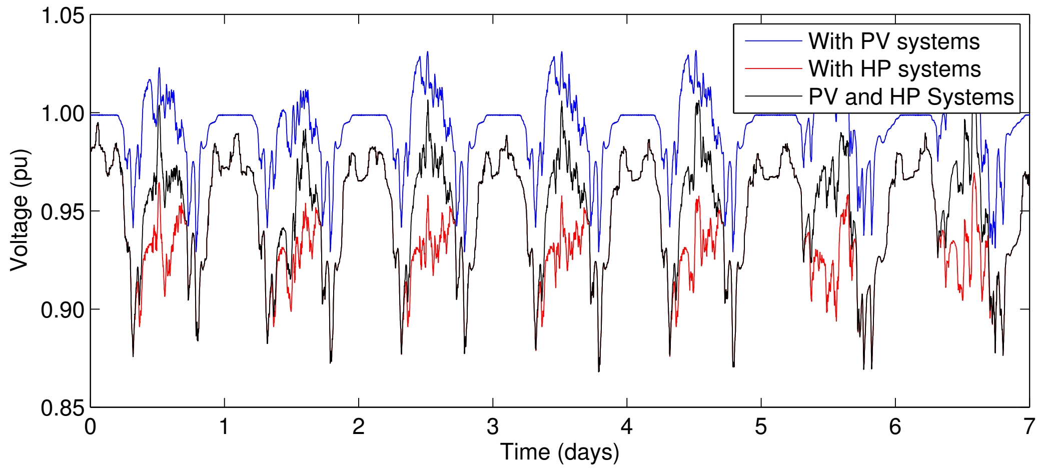


Figure 3.5: Voltage characteristic of combined PV and HP systems at end of feeder 7 (suburban old grid)

The findings from above are confirmed by Figure C.5 which shows the transformer loading. During the non-sunshine periods the transformer loading of the grid with both systems is identical to the loading with only heat pumps and only reduced during the day by the heat pumps power demand supplied by the PV systems.

3.2 Scenarios

To evaluate the influence of CHP, HP and PV on the electricity distribution grid in 2020 four scenarios are developed. Four exemplary German low voltage distribution grids are chosen representatively as discussed in section 2.3. These four grids do not represent extreme cases. The grids represent typical cases of new and old suburban (see Figure 2.14) and new and old urban (see Figure 2.13) distribution grids in Germany. As every grid is different, defined by length and kind of cables and other equipment as well as by the penetration of loads and generators and their behaviour, it is not sensible to evaluate the behaviour by parameter variation in order to obtain the behaviour of every single possible grid. It is, therefore, chosen to evaluate typical behaviour rather than full mapping of every possibility. The results shown below do not represent evidence that similar issues will arise in a majority of German low voltage grids, but show that issues will arise in some grids. The exemplary results are used to illustrate the efficiency and effectiveness of different measures shown in chapter 4.

3.2.1 Appliance Penetrations

A 2020 Scenario of CHP, HP and PV penetrations for each considered grid is developed hereafter. A literature research leads to a common understanding on how many CHP and HP appliances and how much PV power will be installed in 2020. Related to the number of houses existing in 2020 and the distribution between old and new houses four average scenarios for suburban old/new and urban old/new are defined. The definition of a conglomeration factor (CF) leads to four typical scenarios for highly penetrated low voltage distribution grids.

Literature Research

A range of literature sources that are considered for the development of the 2020 scenarios can be found in section D.1. The 19 sources are structured according to their publisher type and marked if CHP, HP and/or PV installation numbers are stated. Below the development of the appliance scenarios structured by appliance type is explained in detail.

Appliance Scenarios

The installed PV power in 2020 is estimated in various studies shown in Table D.1. The estimations reach from around 12 to around 54 GW installed PV power 2020 in Germany. There is a clear trend that older studies state lower estimations than newer studies. The average installed power of all studies does, therefore, not appreciate the change in the boundary conditions and is not suitable to represent a realistic 2020 scenario. For this reason the average of all 2012 and 2013 studies is chosen to represent the installed 2020 PV power hereafter. Table 3.1 shows an overview of all considered scenarios. The installed power refers to all PV systems but only small rooftop systems shall be considered in this work. The German Solar Industry Association (Bundesverband Solarwirtschaft - BSW) classifies systems into three groups. Powers less than 10 kW are defined as residential rooftop systems, powers between 10 and 1000 kW as large industrial rooftop systems and powers higher than 1000 kW as ground mounted systems. Currently 37.4 GW PV power is installed (Oct 2014) of which around 5 GW are systems below 10 kW. In 2014 20% of the new installed power was based on systems with less than 10 kW [79]. The number of current installed PV systems with less than 10kW, the anticipated total power in 2020 and the assumption that 20% of additionally installed PV power is based on systems below

10 kW are used to calculate the anticipated installed power on residential buildings. The installed residential PV power in Germany 2020 is therefore assumed to be 7.65 GW.

Table 3.1: Literature scenarios for 2020 PV penetrations

Year	Study		P_{PV} (GW)	
2012	Verteilnetzstudie dena	Min	48.0	[10]
		Max	52.0	[10]
2012	Leitstudie 2011 BMU		53.5	[80]
2013	Netzentwicklungsplan BNA	Min	46.7	[81]
		Max	52.2	[81]
	Anticipated installed PV		50.5	

Estimations on installed numbers or power of micro CHP in 2020 can be found in a number of studies (see Table D.1). For the determination of the 2020 scenario for CHP only the three studies that state the number of installed appliances are used. To distinguish between micro CHP for single and two family houses and micro CHP for multi family houses in the studies of Delta EE and Bosch, distributions by Delta EE are used.[6] This way a 2020 scenario for multi-family houses (MFH) and single/two family houses (SFH/TFH) is achieved. Table 3.2 shows the results.

Table 3.2: Literature scenarios for 2020 CHP penetrations

			N_{CHP} (thousand)		
Year	Study		MFH	SFH/TFH	
2012	Delta EE Micro-CHP Market Statistics & Forecast		43	122	[82]
2012	Bosch[7]		36	102	
2013	Paper MICROGEN	Min	73		[83]
		Max	135		[83]
	Anticipated number of CHP		72	112	

A number of studies state an estimation on installed HP numbers or HP heat energy generation in 2020 (see Table D.1). Most studies state the number of installed units. To calculate the number of installed units from studies that state the output heat power of the installed HP, the study of the Federal Association of Heat Pumps (Bundesverband

[6] Delta EE: CHP pathway simulations for Bosch (correspondence with S. Dwyer)
[7] Internal Report Bosch Thermotechnik GmbH 2012

Wärmepumpe e.V.) is used to allocate a number of HPs to a specific heat output as both are stated here [84]. The study of Spitalny [83] states installation numbers from 2012 onwards. To calculate the number of units in 2020 the installation numbers in 2011 are added [85]. Furthermore the ratio between HPs in SFH/TFH and MFH from Spitalny [83] is used to gain the numbers of installations in MFH and SFH/TFH for all studies. The average over the reviewed studies leads to the 2020 scenario of installed heat pumps. Table 3.3 shows the results.

Table 3.3: Literature scenarios for 2020 HP penetrations

			N_{HP} (thousand)		
Year	Study		MFH	SFH/TFH	
2010	Leitstudie 2010 BMU		36	768	[86]
2011	Branchenprognose 2011 BWP	Min	52	1,098	[84]
		Max	69	1,431	[84]
2012	Leitstudie 2011 BMU		35	746	[80]
2012	Bundestag		50	1,050	[87]
2013	Paper MICROGEN	Min	32	998	[83]
		Max	89	1,358	[83]
	Anticipated number of HP		52	1,064	

Average Scenarios

To define the average scenario on how many appliances are installed per house in Germany, the number of houses in 2020 is approximated. It is distinguished between houses with one or two flats and houses with three or more flats. Single family houses and two family houses are assumed to have a similar penetration of the different appliances and are therefore treated as one group. The number of single / two and multi family houses in 2010 from Destatis [88] statistics are linear extrapolated to 2020 by the average growth between 2000 and 2010. To separate between new and old houses it is defined that houses build from 2000 to 2020 are new buildings, while older houses are old buildings. This boundary is chosen as from 2000 low energy buildings started to raise awareness which resulted in the EnEV building regulation in 2002 [89]. The same differentiation between old and new buildings is defined by Destatis [90]. Table 3.4 states the assumed number of houses in 2020.

Table 3.4: Number of Houses 2020

	Number of Houses (million)	
	New	Old
SFH	2.07	10.40
TFH	0.38	3.41
MFH	0.17	2.99

Above the appliance scenarios on how many CHPs/HPs and how much PV power will be installed in 2020 are defined. For CHP/HP it is also distinguished between SFH/TFH and MFH installations. To gain a similar separation for the installed PV power it is estimated that 95% of the power is installed in SFH or TFH, while only 5% are installed in MFH. This is under average for MFH, as 16% of all residential houses are MFH with only 5% of the PV power.

For heat pumps in SFH/TFH and MFH and CHP in MFH the distribution between old and new buildings is stated by Spitalny [83]. For CHP in SFH/TFH the distribution stated for CHP in MFH is used [83]. For PV in SFH/TFH it is defined that 25% of the PV power is installed in new houses which represent 15% of the total number of houses. In MFH it is defined that 20% of the installed PV power is allocated at new houses that represent 5% of the buildings. To gain the average 2020 scenarios the numbers of appliances are divided by the applicable number of houses. The average scenario assumes that the appliances are equally distributed across Germany. As the 'suburban' grids described in section 2.3 consist solely of detached single family houses, the scenarios found for SFH and TFH are considered as 'suburban' below. The 'urban' grids do only consist of multi family houses so the MFH scenarios are considered to be 'urban' hereafter. Table 3.5 shows the resulting average 2020 scenarios.

Weighted Scenarios

Above four average scenarios were defined. To gain knowledge about voltage issues that arise in future grids it is, however, not sensible to use average scenarios. For this reason a conglomeration factor (CF) is established. CF is defined as the factor by that the penetration in the considered grid is higher than average. Hereafter the CF is always bigger than one as only highly penetrated areas are examined. In an estate with high penetrations the penetrations are assumed to be twice the average (CF = 2). This is as there is a tendency that in suburban grids appliances are installed in well situated households that are conglomerated in confined areas. In urban grids the installation is subject to renova-

Table 3.5: Average Appliance Scenarios 2020

	Suburban	
	New	Old
CHP (Number/House)	0.022	0.004
HP (Number/House)	0.305	0.023
PV (kW/House)	0.90	0.37
	Urban	
	New	Old
CHP (Number/House)	0.198	0.012
HP (Number/House)	0.229	0.004
PV (kW/House)	0.44	0.10

tions or building projects that are often carried out simultaneously in certain areas as the ownership structure is often bundled. Additionally PV systems in old and new buildings are conglomerated in certain areas as the local requirements for the installation (irradiation, direction of roof, etc.) have to be suitable.

The final 2020 scenarios on CHP and HP penetrations in the four examined grids are created using the average scenarios multiplied by the conglomeration factor. PV penetrations are additionally multiplied by a north-south ratio, as PV penetrations in southern Germany are higher than in the north. In Bavaria and Baden-Württemberg there is a 1.66 times higher penetration of PV systems than the average [79]. Table 3.6 shows the final penetrations for the grids.

Appliance Distribution

The distribution of the different appliances is not equally, but done without artificially creating issues regarding unbalance or conglomeration of one type in a specific feeder. It is ensured that no CHP and HP appliance are installed within the same premise. Appendix D.2 shows the distribution of the appliances for the four scenarios. The parametrisation of the different appliances depending on the building type is shown in Table D.6.

Table 3.6: Final Scenarios 2020

	Suburban	
Number/Grid	New	Old
Houses	166	166
CHP	7	1
HP	101	8
PV (Power)	123 (4 kW)	34 (6 kW)
	Urban	
Number/Grid	New	Old
Houses	36	36
CHP	14	1
HP	17	0
PV (Power)	9 (6 kW)	2 (6 kW)

3.3 Simulations

To evaluate the influence of the developed scenarios on the voltage level and equipment loading, four exemplary grids are simulated for a one year period. The four grids - a suburban and an urban grid in an old and new state each - are explained in detail in section 2.3. Figure 3.6 shows the principle structure of the simulation. Individual load profiles for all houses are used within the house and appliance models to calculate the power flows. These individual power flows are then used within the grid model to calculate the voltage and transformer loading of the grid. In the suburban grids there are 166 houses (n = 166) whereas in the urban grids there are 36 apartment houses with nine flats each (n = 36). During the scenario development connection restrictions like described in the German guideline VDE-AR-N 4105 were not considered as only market expectations and political goals were used to show a desirable state in 2020. Within the simulations, operation regulations like generator shut down at 1.1 pu are not implemented, as these already existing measures to prevent overvoltage are compared to other possibilities in chapter 4.

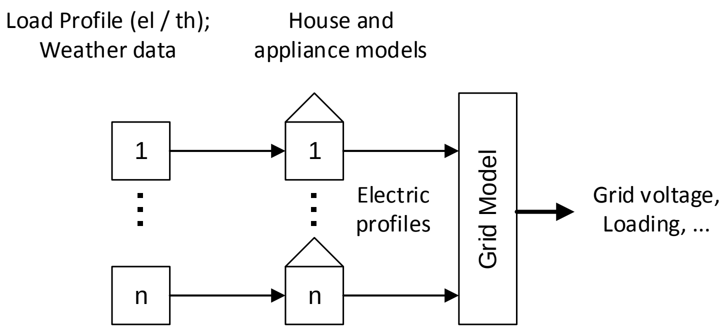


Figure 3.6: Simplified simulation overview

3.3.1 Suburban Grid New

In the suburban grids the location with the extreme voltages is the end of the longest feeder. For the used grid topology this position is the end of feeder 7. Figure 3.7 shows a detailed extract of the examined feeder (see also Figure 2.14). The models of the houses and appliances are not only situated in the examined feeder, but distributed over the whole grid.

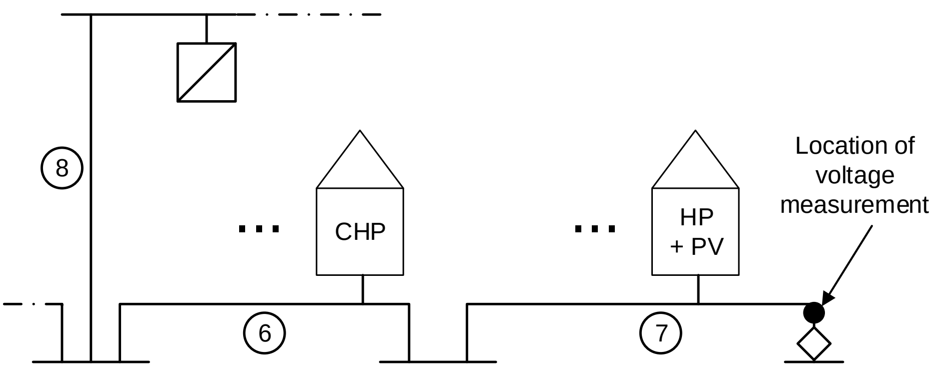


Figure 3.7: Extract of suburban grid topology

The voltage at the end of the feeder for the grid suburban new without CHP, HP or PV devices is shown in Figure 3.8. It can be seen that the voltage drops to around 0.93 pu on one day during the week. On weekends the voltage drops most as there are higher electric loads. No undervoltage is caused, however it has to be mentioned that there is no medium voltage grid voltage fluctuation considered here. Including variations on the medium voltage grid like described in subsection 2.3.4 the voltage drops to 0.90 pu (see Figure D.3). The voltage decrease by the MV grid fluctuations is not 4% as the load peaks of the grid and the H0 profile do not completely match as can be seen in Figure B.1. The voltage level never rises above 1 pu as there are no generators connected.

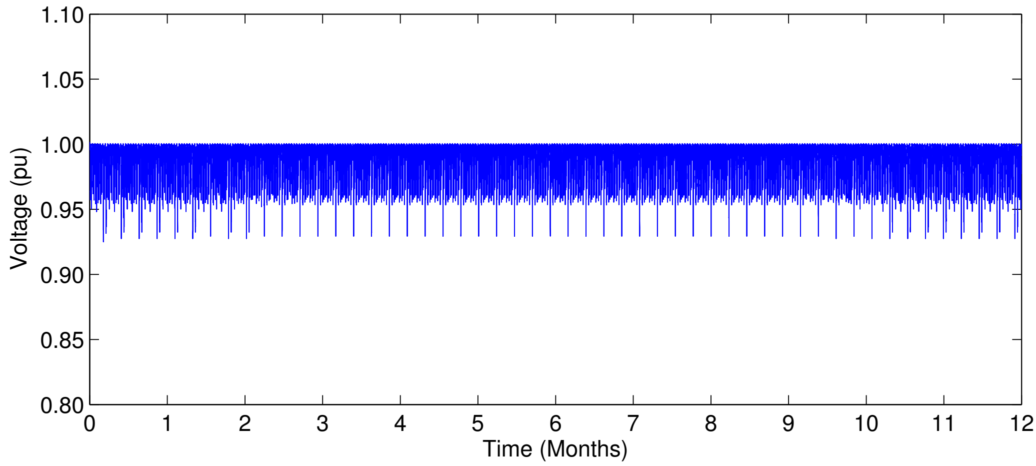


Figure 3.8: Voltage at the end of the longest feeder in suburban grid new w/o appliances

Figure 3.9 shows the the voltage for the same grid with CHP, HP and PV appliances according to the scenario suburban new (see Table 3.6). Undervoltage can be seen regularly during winter. There is, however, also a regular reduction in the voltage level during summer. The minimum voltage is 0.86 pu. The 0.90 pu limit is exceeded for 12 hours distributed on 36 days a year. This is due to the additional HP load for heating in winter and domestic hot water in summer. The installed PV and CHP systems cause no voltage rise above 1.10 pu. The maximum voltage is 1.06 pu.

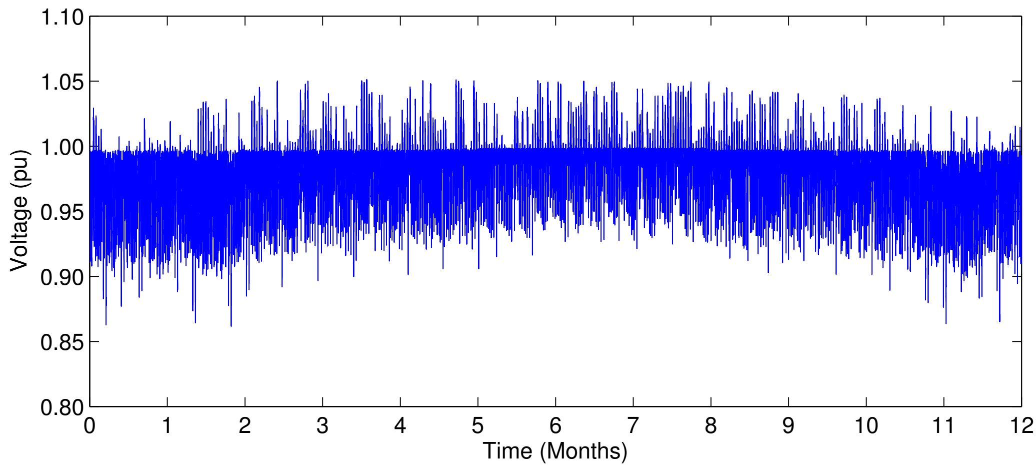


Figure 3.9: Voltage at the end of the longest feeder in suburban grid new w/ appliances

Even including voltage fluctuations of the medium voltage grid the voltage does not rise above 1.10 pu. Figure 3.10 shows the voltage characteristics during one year with CHP, HP and PV appliances according to the scenario suburban new and voltage variations according to subsection 2.3.4. The voltage drops, however, regularly below 0.90 pu. The minimum voltage is 0.83 pu which is outside of EN 50160 limits even if -15% of nominal voltage are considered (see Table A.1). The voltage drops below 0.90 pu for 288 h on 200 d per year.

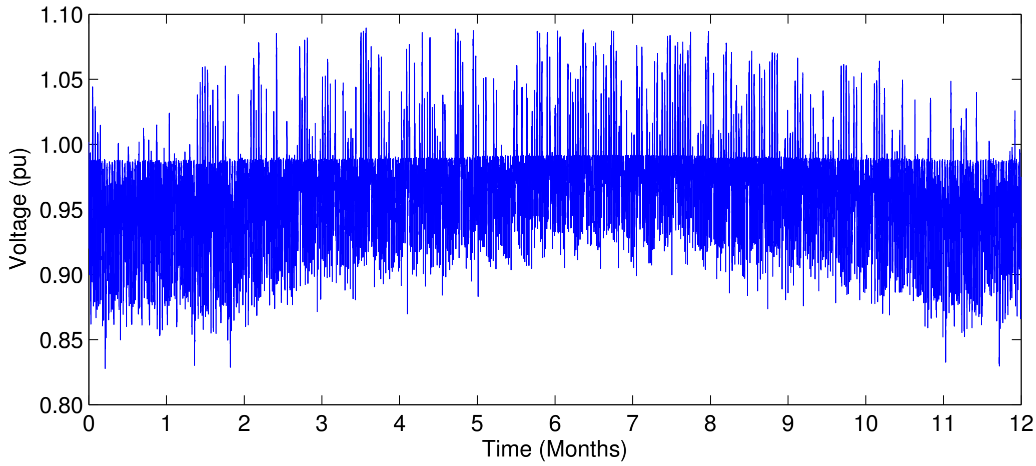


Figure 3.10: Voltage at the end of the longest feeder in suburban grid new w/ appliances and MV grid voltage fluctuations

Without installed appliances the transformer loading reaches a maximum of 72 percent of the rated power. With installed appliances and MV grid variations the loading reaches a maximum of 142%. It is, however, possible to operate transformers above 100% rated power for a limited time, so the transformer power is not solely used for the evaluation. The transformer is protected by fuses that prevent permanent damage. The fuses are tested according to EN 60269 [91]. A load of 1.3 times nominal current has to be withstand for 10 h without triggering. On the other hand the fuse has to trigger safely if is is loaded with 1.5 time nominal current for more than 2 h.[8] In the suburban new scenario the transformer fuse is not assumed to trigger as the maximum current does not exceed 1.3 time nominal current for more than 10 h and never exceeds 1.5 times nominal current as can be seen in Figure 3.11. During the complete year the current exceeds 1.3 times nominal current for a total of 0.1 h.

The loading of the cables is, similar to the transformer, evaluated according to the cable fuses. Exemplary the fuse with the highest loading is shown hereafter. The highest load can be seen at the beginning of feeder 8. Cable fuses have to withstand a load of 1.25 times rated current for at least 3 h while they have to safely trigger if the load exceeds 1.6 times rated current for more than 3 h. Figure 3.12 shows the considered current over one year. It can be seen that the current exceeds both thresholds for several times. The total time above 1.6 times nominal current during the year is, however, only 0.3 h, while

[8]RWE Westnetz GmbH transformer dimensioning (correspondence with Ü. Sezeneler)

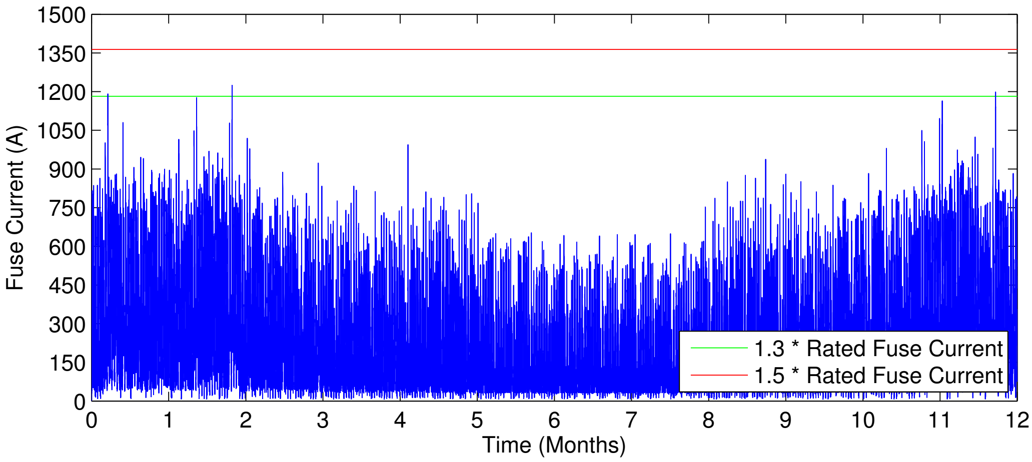


Figure 3.11: Current at transformer in suburban grid new w/ appliances and MV grid voltage fluctuations

the current is above 1.25 times nominal current for 1 hour per year. The fuse is therefore considered to not trigger.

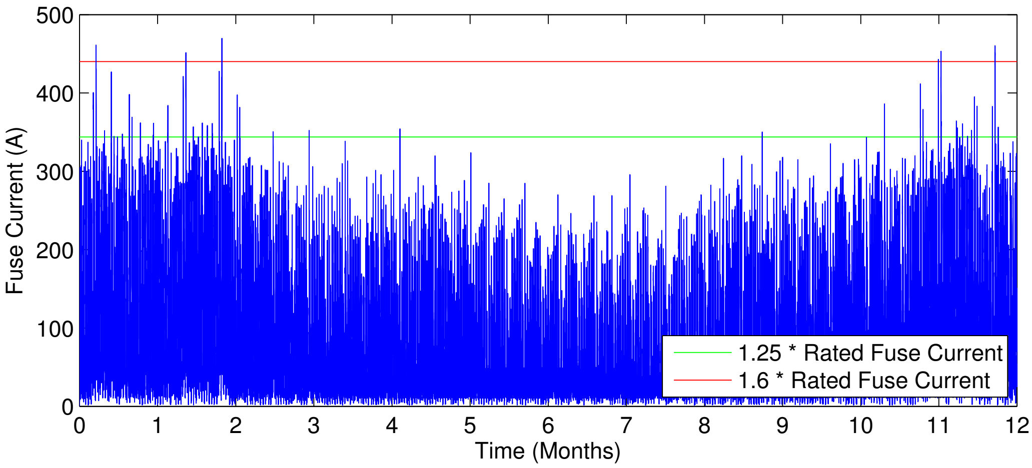


Figure 3.12: Current at beginning of considered feeder in suburban grid new w/ appliances and MV grid voltage fluctuations

It is shown that the introduction of CHP, HP and PV appliances to the grid has a radical influence on the voltage behaviour. The grid exceeds the lower EN 50160 voltage limit. The upper voltage limit and the operational loading of cables and transformer are, however, not exceeded. The installation, especially of heat pumps is therefore limited compared to the anticipated 2020 scenario if no additional measures are implemented. The NAV regulates that the installation of heat pumps has to be approved by the grid operator. It can be assumed that the DSO will only allow the connection without any grid enforcement if the minimum voltage including the heat pump does not decrease below 0.94 pu in order to guarantee EN 50160 limits even with MV grid fluctuations. Even though there is no overvoltage the installation of generators is limited by the VDE-AR-N 4105 connection restrictions that only allow a voltage rise of 3% caused by generators. According to these current regulations only 67% of the anticipated generator power and 12% of the heat pumps could be installed.

3.3.2 Suburban Grid Old

The suburban old grid has lower penetrations with CHP, HP and PV appliances. It is, however, equipped with thinner cables which increases the voltage influence. Even without any installed appliances the voltage drops below 0.90 pu if not below 0.85 pu for the grid with and without MV grid voltage variations. This is caused by the thin NFA2X 4x95 cables. The voltage rise is limited to the influence of the medium voltage grid as can be seen in Figure D.7 and Figure D.9. The voltage at the end of the longest feeder including appliances and MV grid voltage fluctuations is shown in Figure 3.13. It can be seen that the maximum voltage does not exceed 1.10 pu, while the minimum voltage exceeds 0.90 pu. The voltage does, however, not exceed 0.85 pu and is below 0.90 pu for only 0.7% of the year. It is therefore assumed that the grid does comply with EN 50160.

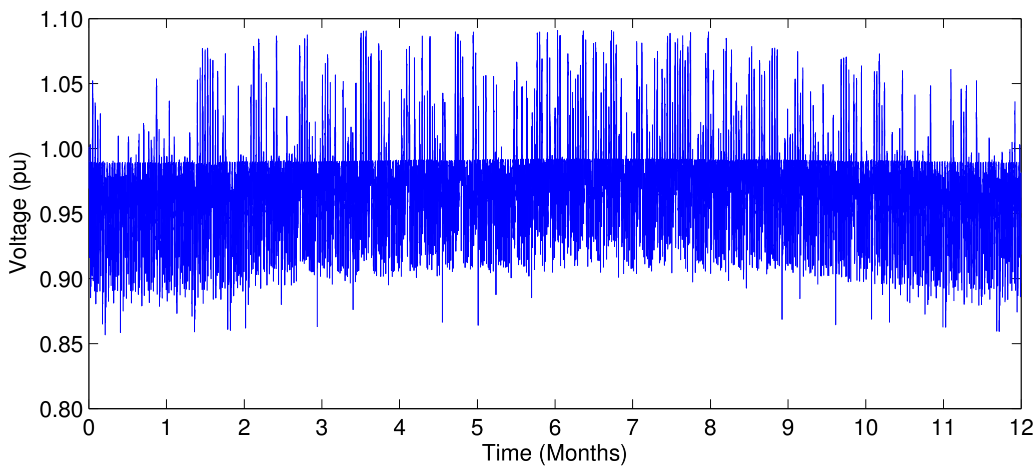


Figure 3.13: Voltage at the end of the longest feeder in suburban grid old w/ appliances and MV grid voltage fluctuations

The transformer loading reaches 117% nominal power without and 125% nominal power with installed appliances. The fuse current at the transformer, however, does not exceed operational limits as is shown in Figure 3.14. The lower load compared to the suburban new grid is due to similar transformer dimensioning with less installed appliances.

Similarly to the transformer, the cable fuses are not overloaded. Figure 3.15 shows the fuse current at the same position as in the suburban grid. It can be seen that the current

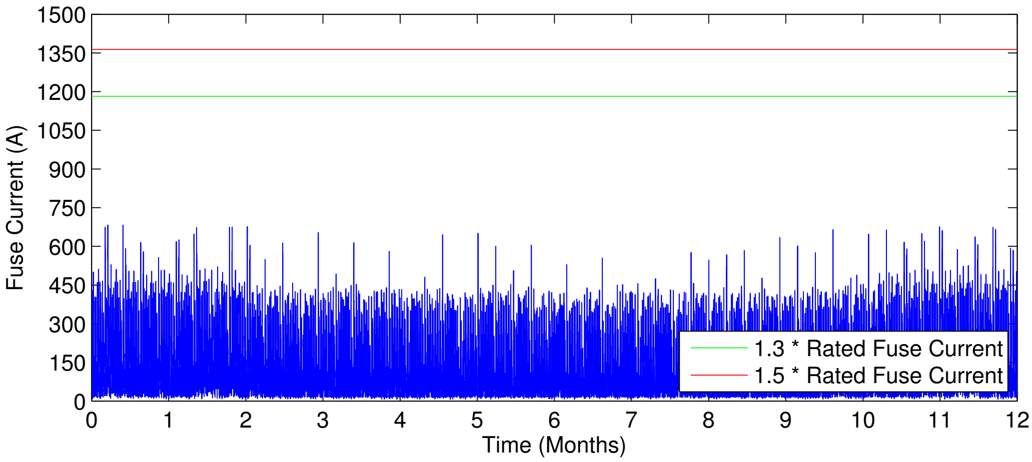


Figure 3.14: Current at transformer in suburban grid old w/ appliances and MV grid voltage fluctuations

does never exceed the two thresholds of 1.25 and 1.6 times rated current. Even though the cables in the suburban old grid are considerably thinner than in the new grid, the rated current is only minimally smaller as they are installed above ground as can be seen in section B.3.

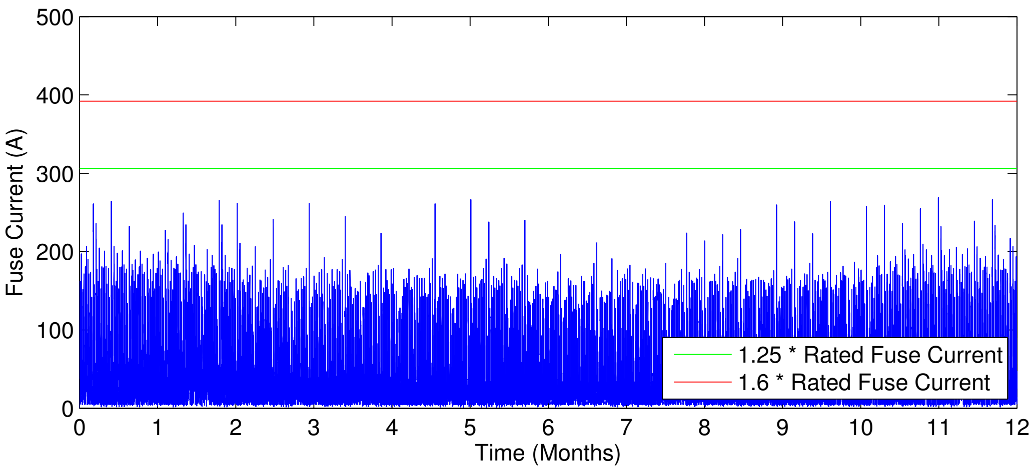


Figure 3.15: Current at beginning of considered feeder in suburban grid old w/ appliances and MV grid voltage fluctuations

Similar to the new suburban grid the old grid does not exceed the upper EN 50160 voltage limit, nor cable or transformer loading boundaries. The voltage drops below 0.90 pu, but if considering the -15% threshold according to Table A.1 the limits are not violated. The grid is, however, operated at the limits of feasibility. If additional appliances shall be installed beyond 2020, measures for voltage control have to be implemented. According to current regulations only 78% of the anticipated generator power and 38% of the heat pumps could be installed.

3.3.3 Urban Grid New

The urban grid topology has several feeders of the same length. Exemplary two feeder are examined. This is as the houses are not all directed into the same direction and therefore PV power generation differs between some feeders. Examined are the longest feeders in each direction which are feeder 5 and 7 according to Figure 2.13. Figure 3.16 shows an extract of the examined feeders and the location of voltage measurement.

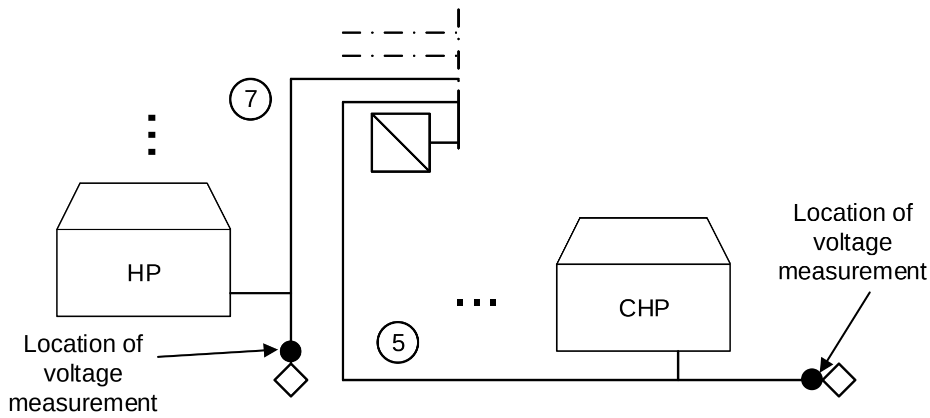


Figure 3.16: Extract of urban grid topology

The figures below show the voltage at the end of feeder 5. The voltage in the case without and with installed CHP, HP or PV systems and not considering MV grid voltage fluctuations is shown in Figure D.13 and Figure D.14 respectively. The voltage drops to 0.92 pu in both cases whereas the maximum voltage with appliances is 1.01 pu. The voltage influence is lower than for the suburban grids as the penetration is lower and the cables are shorter. If medium voltage grid fluctuations are considered the minimum voltage is 0.90 pu and the maximum voltage is 1.04 pu. The voltage profile without appliances is shown in Figure D.15 and the profile with appliances is shown in Figure 3.17.

The maximum transformer loading is 97% nominal power without and 106% nominal power with installed appliances. The current at the transformer fuse does not exceed the rated fuse current as can be seen in Figure 3.18.

The current at the cable fuse is shown in Figure 3.19. It can be seen that the rated current of 275 A is never exceeded and therefore the critical limits of 1.25 and 1.6 times rated current are never reached. The cable and transformer currents are lower than for the suburban new grid, as the penetration of appliances is lower in the urban new scenario.

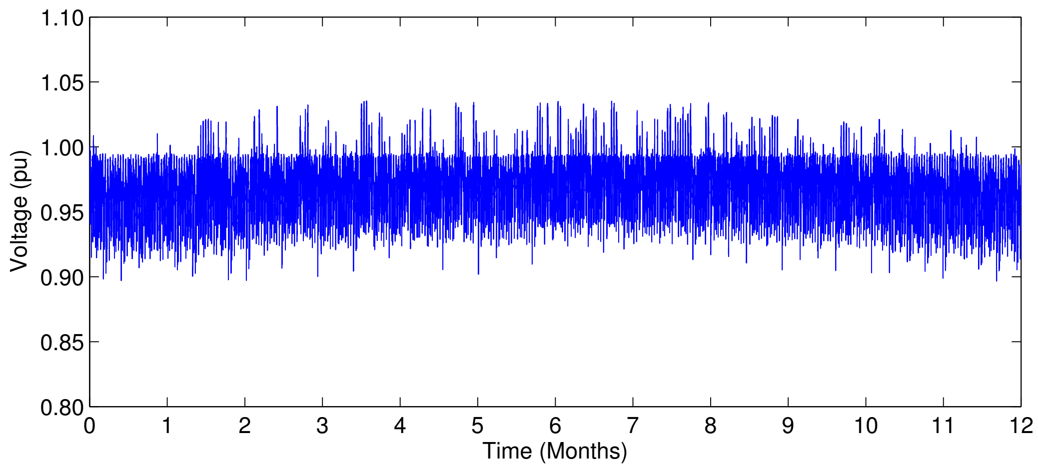


Figure 3.17: Voltage at the end of the longest feeder in urban grid new w/ appliances and MV grid voltage fluctuations

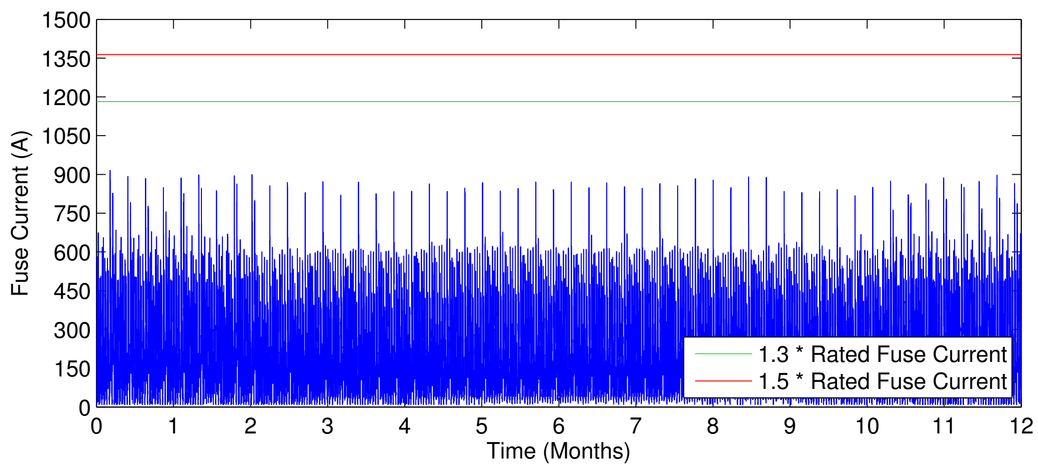


Figure 3.18: Current at transformer in urban grid new w/ appliances and MV grid voltage fluctuations

The urban new grid does not violate EN 50160 voltage boundaries nor maximum cable or transformer loading. The lower voltage boundary is however reached if MV grid voltage fluctuations are considered. The influence of the heat pumps is reduced by the installed CHP systems like shown in section 3.1.3. It is therefore not possible to install more heat pumps without implementing more CHP systems or voltage control measures. According to current regulations only 6% of the heat pumps could be installed as the voltage drop without installed CHP units is very high. The installed CHP units allow for a higher HP penetrations from a technical perspective as shown in section 3.1. There is no connection restriction for generators in this grid.

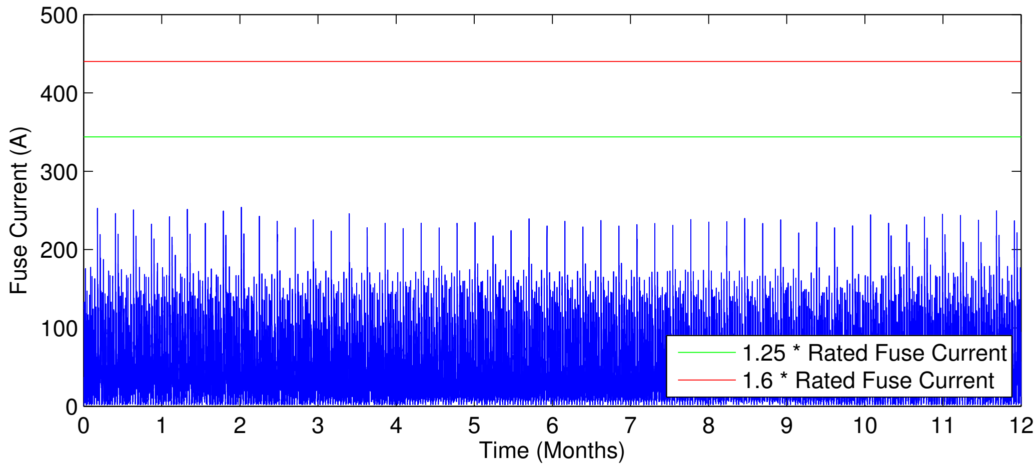


Figure 3.19: Current at beginning of considered feeder in urban grid new w/ appliances and MV grid voltage fluctuations

3.3.4 Urban Grid Old

The voltage in the old urban grid without and with installed appliances, not considering MV grid voltage fluctuations, is shown in Figure D.19 and Figure D.20 respectively. The two profiles are almost similar as the penetration of appliances is very low (see Table 3.6). The minimum voltage is 0.90 pu in both cases whereas the maximum voltage is 1.00 pu. There is no voltage rise above 1.00 pu as there is only one PV with 6 kW peak power installed in the considered feeder. The voltage drop is higher than for the urban new grid, as thinner cables are installed here. If medium voltage grid fluctuations are considered the minimum voltage is 0.88 pu and the maximum voltage is 1.04 pu. The voltage profile without appliances is shown in Figure D.21 and the profile with appliances is shown in Figure 3.20.

The maximum transformer loading is 99% nominal power without and 98% nominal power with installed appliances. The current at the transformer fuse does exceed the limit of 1.3 times rated fuse current for 0.32 h per year. The critical limit of 1.5 times rated current is never reached as can be seen in Figure 3.21. The transformer is therefore not overloaded.

The current at the cable fuse is shown in Figure 3.22. It can be seen that the rated current is exceeded and therefore but the critical limits of 1.25 and 1.6 times rated current are never reached. The cable and transformer currents are lower than for the urban new grid but closer to the critical limits as smaller dimensioned equipment is used in the old grid.

The old urban grid does violate the lower EN 50160 voltage boundary but not the maximum cable and transformer loading. The lower voltage boundary is only reached if MV grid

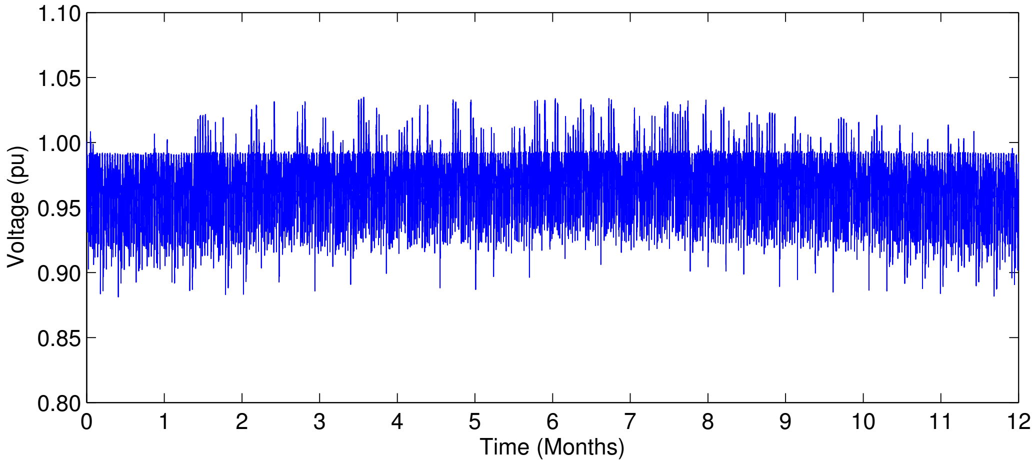


Figure 3.20: Voltage at the end of the longest feeder in urban grid old w/ appliances and MV grid voltage fluctuations

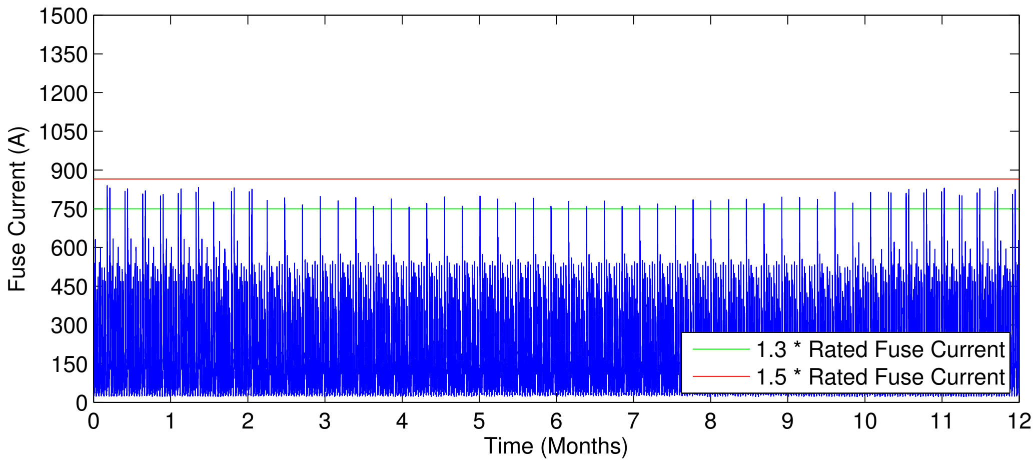


Figure 3.21: Current at transformer in urban grid old w/ appliances and MV grid voltage fluctuations

voltage fluctuations are considered. If, however, considering the -15% threshold according to Table A.1 the EN 50160 limits are not violated. Further installation of heat pumps and other loads on the grid without implementing voltage control measures is, however, not possible. According to current regulations all generators could be installed.

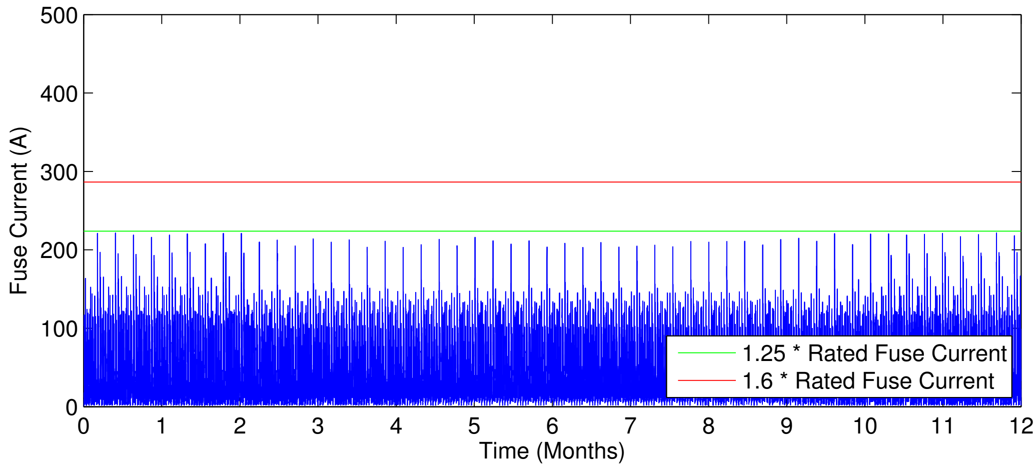


Figure 3.22: Current at beginning of considered feeder in urban grid old w/ appliances and MV grid voltage fluctuations

3.4 Reference Scenario

The analysis of the voltage characteristics of CHP, HP and PV systems shows that HP and CHP do complement each other nicely, while other combinations do not have special benefits regarding the voltage characteristics. In the installations scenario for 2020, however, CHP do only play a minor role in the suburban grids where the highest voltage fluctuations can be seen. This leads to a big influence of HP systems on the voltage behaviour. The evaluations above show that for the considered 2020 scenario undervoltage is the limiting factor. Even if the upper or lower voltage boundaries are not reached, current regulations prevent the installation of the anticipated number of appliances. In order to increase the number of possible installations measures for voltage control have to be implemented. The new suburban grid shows the strongest violation of the lower voltage barrier and the highest voltage of all grids. It is, therefore, chosen to evaluate different measures. The measures are simulated for the week that shows the highest voltage during the year and the week that shows the lowest voltage during the year. Based on these simulations the technical effectiveness, the economics, the end-user comfort as well as the impact on the CO_2 balance are evaluated.

4 Measures for Voltage Control

As shown in section 3.3 it is necessary to implement additional measures in order to integrate the anticipated amount of appliances in 2020. It is distinguished between measures that are implemented and operated by the grid operator and measures that are implemented in end-user appliances. All measures are based on one or more of the following four principles in order to influence the voltage level according to section 2.4:

- Reducing the system's loop impedance.
- Changing the voltage ratio between low and medium voltage grid.
- Influencing the system's active power flow.
- Influencing the system's reactive power flow.

The following sections describe the measures simulated and evaluated in this work as well as their parametrisation.

4.1 Grid Operator Based Measures

4.1.1 Grid Extension

Traditionally low voltage grids are enforced by splitting an existing feeder into two parts and installing an additional parallel cable to connect one part of the feeder to the transformer. Depending on the use case, either voltage or load reduction, this additional cable splits the existing feeder in the middle or at two third of the length [10]. Additionally a full change of all main connection cables is considered.

Additional parallel cable (Expansion)

In order to keep the voltage level within the boundaries within the considered feeder a parallel cable is connected between the transformer and feeder 7 The new parallel feeder has the same length as feeder 6 and 8. The connection between feeder 6 and 7 is split up.

Figure 4.1 shows the connection of the new cable and the necessary new circuit breaker to disconnect feeder 6 from feeder 7. The cable diameter is chosen in order to fulfil the voltage boundaries and is set to NAYY 4 x 300 mm^2. The detailed cable parameter can be found in section B.3.

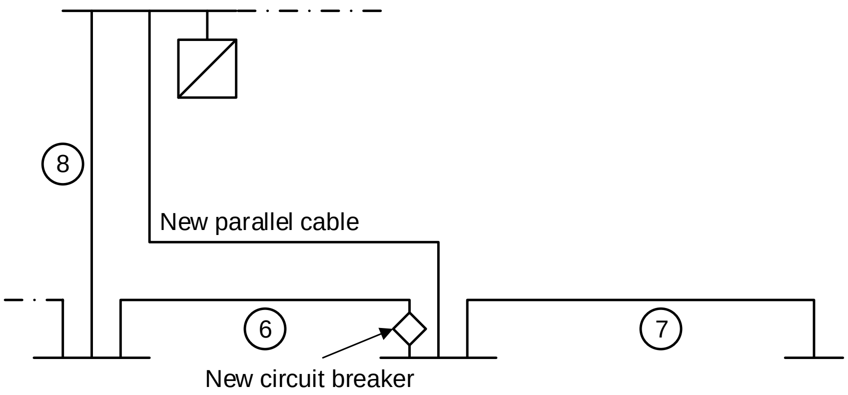


Figure 4.1: Connection schematic of additional parallel cable (Expansion)

Change of all cables (Cable)

Instead of installing an additional parallel cable all main connection cables in feeders 1 to 9 are changed. The house connection cables are not changed. The cables are sized in order to fulfil the voltage boundaries and set to NAYY 4 x 300 mm^2. The detailed cable parameter can be found in section B.3.

Change of cables in highly stressed feeder (Feeder 8)

As shown in Figure 2.14 feeder 8 connects the feeders 6 and 7 as well as feeder 9 to the transformer. Therefore the power flow through feeder 8 is considerably higher than in a regular feeder with the length of feeders 8, 6 and 7, which are the considered feeders for the evaluation. The cables in feeder 8 are therefore changed to NAYY 4 x 300 mm^2 when considering the measure 'Feeder 8'.

4.1.2 Transformer

Section 3.3 shows no transformer overload. Therefore an increased transformer power is not considered hereafter. It is however considered that the transformer is replaced by an modern transformer with integrated on-load tap-changer.

On-load Tap-changer (OLTC)

On-load tap-changers are able to change the voltage at the low voltage side of the transformer independent of the voltage level at the medium voltage side by changing the tap point on the inductor. As the name suggests this is possible during operation - on-load. Figure 4.2 shows the principle functionality. The functionality of OLTCs is limited by two means. First the voltage level can only be influenced in a limited range as the voltage at the transformer as well as in every other position of the grid has to fulfil the boundary conditions according to EN 50160. The theoretical maximum voltage difference between transformer and end of the feeder is therefore limited to 0.2 pu. Secondly OTLCs always influence the voltage in all feeders of a grid. In situations where not all feeders are affected similarly by voltage rise or drops the usage of OLTCs is therefore limited.

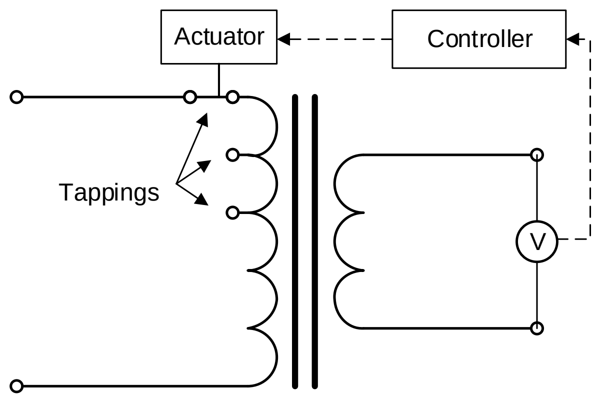


Figure 4.2: Schematic of OLTC principle

The OLTC used for the evaluation is designed to change the voltage by $\pm$ 6% nominal voltage in 2% steps. The detailed transformer parameters can be found in section B.4. The control is based on voltage measurements at the LV side of the transformer. The controller input is adapted by the current tap setting (see Equation 4.1). The used hysteresis controller and the used parameters can be seen in Figure 4.3 and Table 4.1 respectively. The tap changer is only able to switch one step at a time.

$$V_{\text{OLTCcontroller}} = V_{\text{LV}} - \text{tap} \cdot 2\% \tag{4.1}$$

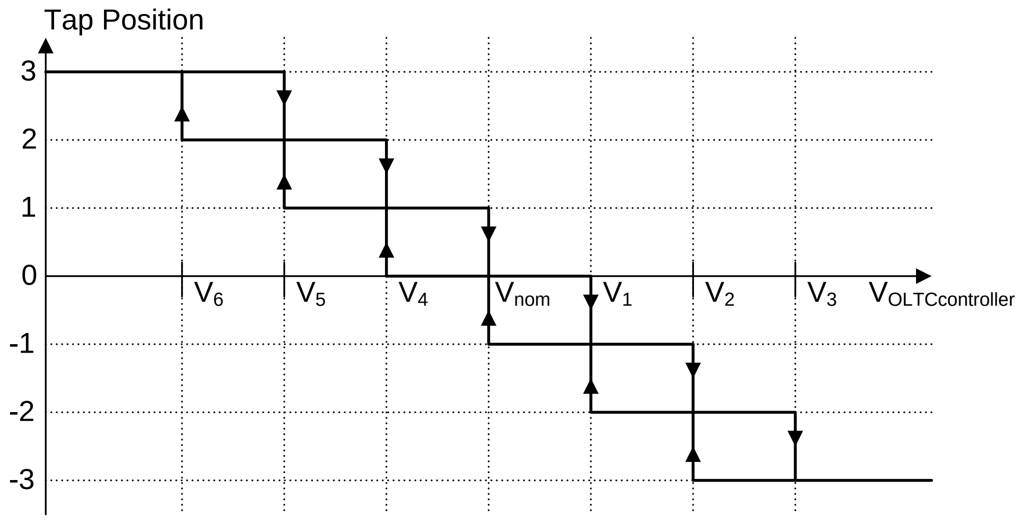


Figure 4.3: Hysteresis controller of OTLC

Table 4.1: Parameters of OLTC controller

Parameter	V_{nom}	V_1	V_2	V_3	V_4	V_5	V_6
Value (pu)	1.00	1.01	1.02	1.03	0.99	0.98	0.97

4.1.3 Distribution Grid - Flexible AC Transmission System (DG-FACTS)

As discussed in section 1.4 there are different types of DG-FACTS discussed for the use in low voltage grids. An intelligent node can not improve the voltage behaviour if the different feeders have a similar power flow, therefore this work evaluates an distribution STATCOM with stationary battery storage. The device is able to provide active and reactive power control according to a voltage controller. The controlled value is the measured voltage at PCC of the DG-FACTS device. The device is positioned at the end of the considered feeder and dimensioned in order to being able to ensure EN 50160 limits at this position. Figure 4.4 shows the installation location and the setup of the DG-FACTS measure.

The proportional voltage controller is shown in Figure 4.5. The parameters a - d can be individually parametrised for active and reactive power control. The heuristically determined parameters are stated in Table E.1. The dimensioning of the STATCOM and the battery storage is determined to fulfil the EN 50160 boundary conditions and defined in Table E.2.

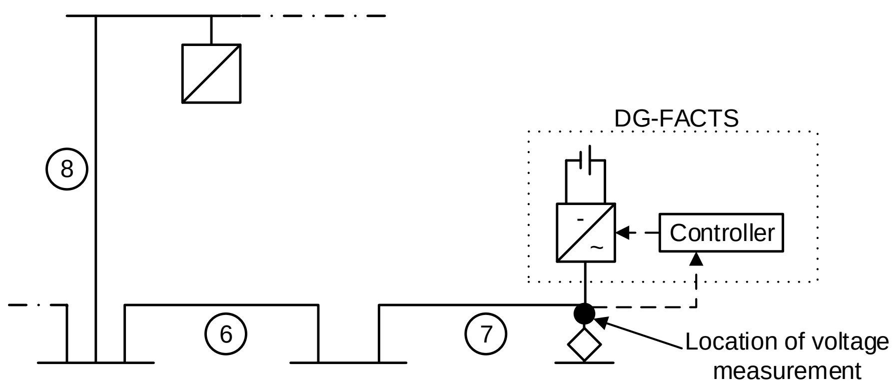


Figure 4.4: Schematic of DG-FACTS installation

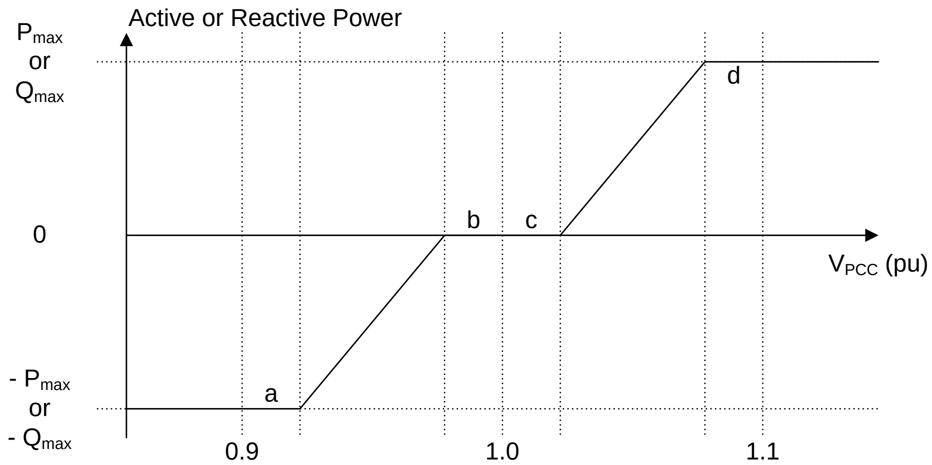


Figure 4.5: Proportional controller for active and reactive power of DG-FACTS device

4.2 End-User Appliance Based Measures

Voltage regulating measures that are situated at the end-users' appliances are only effective if the majority of appliances are equipped with the functionality. Hereafter it is assumed that all appliances in the grid, not only in the considered feeder, have the considered measure implemented. Figure 4.6 shows the principle structure of all appliance based measures. A voltage measurement at the point of common coupling is the control input for the voltage controller that controls the inverter. If necessary the inverter forwards a control signal to the appliance.

4.2.1 Generators

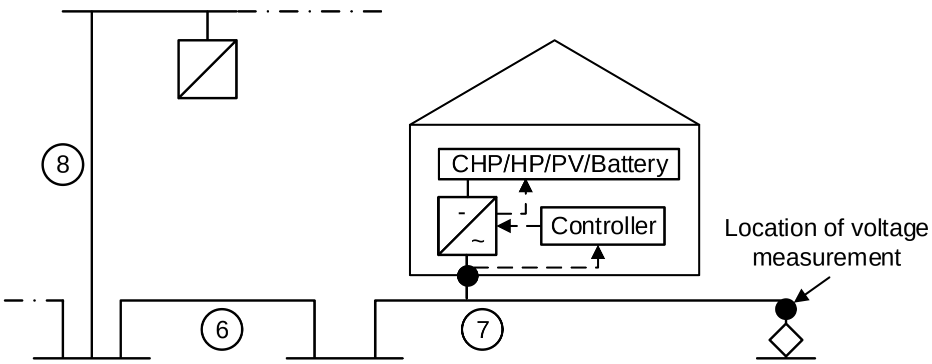


Figure 4.6: Schematic of end-user appliance based voltage control measures

Shutdown at overvoltage (VDE)

According to VDE-AR-N 4105 every generator connected to the public grid has to be equipped with an network and system protection (NS protection). The NS protection has to disconnect the system according to voltage and frequency boundary conditions [16]. In this work only the overvoltage protection U> is considered. A 10 minute moving average voltage measurement is the input to the controller. If the voltage is higher than 1.1 pu the system is disconnected from the grid. The frequency of averaging (1/(3 s)) as well as the disconnection time (<100 ms) required by VDE-AR-N 4105 are not considered, as the simulation time step is 60 s. The reconnection is dependent on the average voltage value to be within operational limits for 60 seconds. Afterwards the system is allowed to ramp up power with 10% P_{max} per minute.

Reduction of peak power (EEG)

Photovoltaic generators have to fulfil additional requirements according to the renewable energy act. Operators of systems with less than 30 kW peak power can choose if they enable remote control by the grid operator or if they limit the maximum feed-in power to 70% peak power [13]. Grid operators do not use the remote control for voltage control in low voltage grids but for voltage and load control on higher voltage levels. It is therefore defined that all systems reduce their maximum power output to 70% peak power if this measure is considered. According to the renewable energy act the reduction of the power is referenced to the point of common coupling. It is therefore possible to use the full power of the system for self consumption and only limit the system's power if the feed-in power reaches the limit. Hereafter the limitation is realised by the installation of an inverter with the maximum power of 70% PV peak power. This implies that the self consumption power is also limited. As less inverter power is installed this reduces the investment costs for the system operator.

Active power control (APC)

In order to guarantee the voltage level the power of the generator is reduced according to a voltage measurement at PCC. The power reduction is controlled by a proportional controller with dead band. At voltages lower than 1.09 pu the power is not limited. Between 1.09 and 1.10 pu the maximum power is limited proportionally between maximum power and zero. As the maximum power is limited the feed-in power is not necessarily reduced immediately, depending on the status of the generator. Figure 4.7 shows the proportional controller.

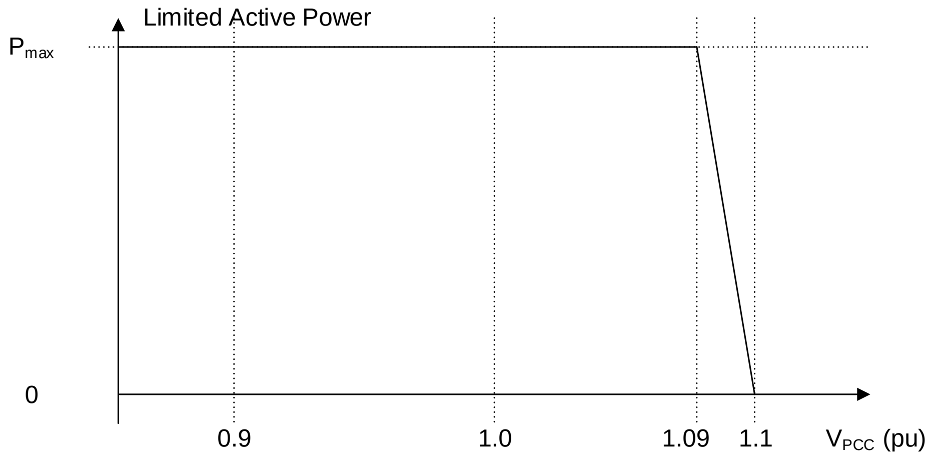


Figure 4.7: Proportional controller of measure active power control (APC)

A variant of this measure implements an additional use of the thermal storage of CHP systems (APCth). Regularly the full storage capacity of the thermal buffer tank is utilised for optimum energy and cost efficiency. Using this variant the buffer capacity is not used completely in order to have capacity available for charging to enable voltage control. Regularly generators are only able to shut down at overvoltage. APCth enables the CHP also to provide undervoltage protection as the additional thermal capacity can be charged if the voltage drops below a threshold. The additional power feed-in increases the voltage. In order to not interfere with end-users comfort the storage tank is designed larger when APCth is considered.

Reactive power control

As shown in section 2.4 the reactive power flow in an electricity system has an influence on the voltage. The influence is defined by the reactance of the system. In order to provide reactive power the inverter either has to reduce the maximum active power or the nominal apparent power of the inverter has to be increased. Hereafter the inverter size is increased so that maximum active power can be realised at minimum power factor. This increases losses and investment costs of the system.

According to VDE-AR-N 4105 generators with powers higher than 3.68 kW are required to implement reactive power control depending on the appliance power (cosP). The proportional controller is implemented according to the guideline with a dead band from zero to 50% P_{max} and a proportional decrease of the power factor from 1.0 to 0.95 between 50% and 100% P_{max}. The power factor refers to underexited operation.

Similar to cosP the measure cosV09 changes the power factor of the appliance in order to lower the voltage rise by the generator. In this case, however, the power factor is controlled by the voltage at PCC. The proportional controller with dead bands is shown in Figure 4.8. The minimum power factor is 0.90 or 0.95 in the variant cosV095. Table E.3 shows the parameters for the two variants.

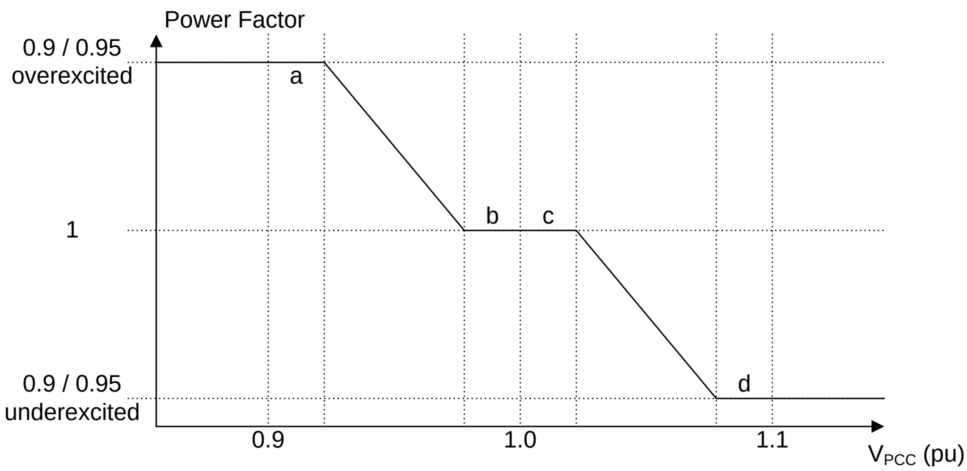


Figure 4.8: Proportional controller of measures cosV09 and cosV095

4.2.2 Demand Side

Contrary to generators demand side participation in voltage control is not required in current regulations. Similar to generators, changes in active as well as reactive power flow can be used to influence the voltage at PCC.

Demand side management

Within this work demand side management is only implemented for heat pumps. The measure DSM reduces the heat pump power according to a proportional controller with dead band. For voltages above 0.91 pu the heat pump power is not limited. Between 0.91

and 0.90 pu the maximum power is reduced linearly to zero. As the maximum power is reduced the actual power reduction is dependent on the current status of the heat pumps. The heat pump model is able to modulate between 50 and 100% maximum power. If the DSM controller requests powers below 50% maximum power the heat pump shuts down. Figure 4.9 shows the proportional controller of the measure DSM.

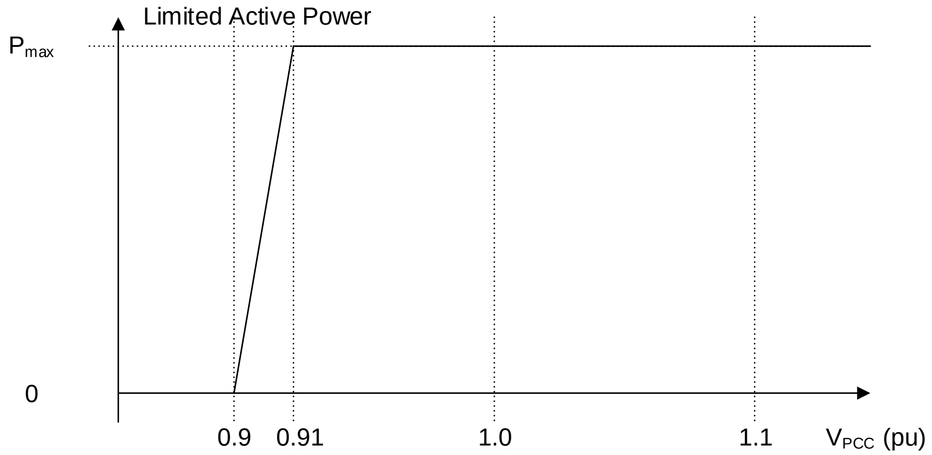


Figure 4.9: Proportional controller of measure demand side management (DSM)

Additionally the measure DSMth includes the thermal storage for voltage control. Similar to APCth thermal storage capacity is provided to be charged at overvoltage. Using this mechanism the heat pump can provide voltage support at overvoltages by drawing active power to charge the thermal buffer tank. In order to not interfere with end-users comfort the storage tank is designed larger when DSMth is considered.

Reactive power control

Inverters are able to provide reactive power control regardless of the direction of active power flow. In principle it is therefore possible to use heat pumps that are connected to the grid by power electronics to provide reactive power voltage support. In this work it is assumed that the heat pumps are connected to the grid by means of inverters that are able to provide reactive power. The inverters are dimensioned to be able to provide the maximum defined reactive power at maximum defined active power. This increases the losses of the inverter. Similar to reactive power control for generators it is possible to control the power factor by the appliance power or the voltage at PCC.

The measure cosP095HP refers to the power factor control according to the appliance active power draw. Similar to cosP the controller includes a dead band below 50% maximum power and reduces the power factor proportionally to 0.95 (overexcited) between 50 and 100% maximum power. The measure cosP09HP operates in a similar way but with a minimum power factor of 0.9 (overexcited). Contrary the measures cosV09HP and cosV095HP control the power factor by a voltage measurement at PCC. The proportional controller is shown in Figure 4.10. Table E.4 shows the parameters for the two measures.

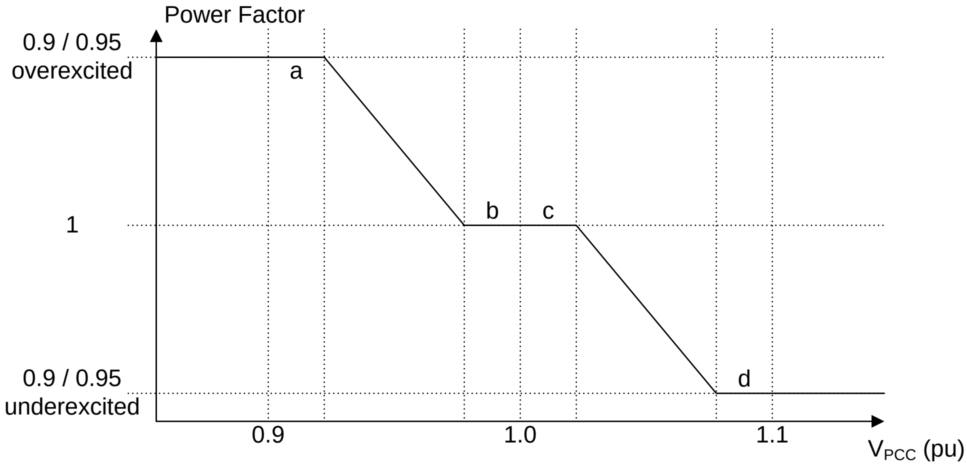


Figure 4.10: Proportional controller of measures cosV09HP and cosV095HP

4.2.3 Electric Storage

Unlike measures for generators or heat pumps, electric storage is not yet available in the considered grid. To evaluate electric storage all houses with a generator, either PV or CHP, are equipped with a AC coupled battery storage system, consisting of an inverter and a lithium-ion battery. The system is dimensioned according to the needs of the appropriate measure.

Self consumption optimisation (sco)

Self consumption optimisation (sco) with a battery storage is mainly for economic benefit of the end-user. Generated electricity that is not needed in the house is stored in the battery storage until the electricity consumption is higher than generation. The reduction of fed-in power of the generator has, however, an influence on the voltage level in the grid. If a PV generator and a heat pump are installed within the same premise this measure automatically transfers energy from times with high PV generation to times with high HP demand. The controls are, however, optimised to maximise the self consumption of generated energy, not to limit the grid demand of heat pumps.

The principle structure shown in Figure 4.6 is also applicable for battery systems. However, additionally to the voltage the power flow at PCC is measured. The sco controller controls the storage system in order to regulate the power at PCC to zero. The systems have different capacities for PV and CHP systems, but identical parameters otherwise. Table 4.2 shows the dimensioning of the storage systems.

Table 4.2: Dimensioning of battery systems for PV and CHP for self consumption optimisation

Inverter Power (kVA)	Battery Capacity PV (kWh)	Battery Capacity CHP (kWh)
4.6	6	4.5

Voltage Control (stoV)

In order to enable voltage control with distributed energy storages all battery systems are assigned with additional battery capacity for over- and undervoltage protection. The battery capacity that is available for sco is controlled with the same algorithm as shown above. Additionally there is a specific battery capacity allocated that is only allowed to be discharged if the voltage at PCC is below a certain threshold. Similarly there is capacity allocated for overvoltage situations. The battery capacity for voltage regulation is unblocked if the voltage is below 0.91 pu or above 1.09 pu respectively. The additional capacity is dimensioned in order to being able to keep the voltage within EN 50160 limits at all times. The detailed battery system dimensioning is shown in Table 4.3.

Table 4.3: Dimensioning of battery systems for PV and CHP for voltage control

	Inverter power (kVA)	Usable battery capacity (kWh)		
		sco	overvoltage control	undervoltage control
PV	9	6	0	36
CHP	9	4.5	0	36

The voltage control is based on active power control and the proportional controller is shown in figure 4.11. The parameters a - d are shown in Table E.5. The power is dependent on the voltage level at PCC, but limited to the power at PCC. No power is fed into the grid or drawn from the grid for voltage support. The system is able to reduce the house's influence to zero. In sco operation the maximum power of the system is limited in order to maximise the voltage support effect. The limited maximum power prolongs the period during the day in which the battery is able to store generated electricity as the capacity limit is reached later. During voltage support the full inverter power is available. The maximum power level during sco operation is stated in Table E.5. If the battery SOC is in the range that is reserved for voltage support, but the voltage level is above 0.95 pu, the battery is charged with 50% of the sco power stated in Table E.5. This charging process is also allowed to draw power from the grid. Without this charging control the battery would not be able to regain the necessary SOC for voltage control during winter days. Using this method a load shift is realised from times with low voltages to other times.

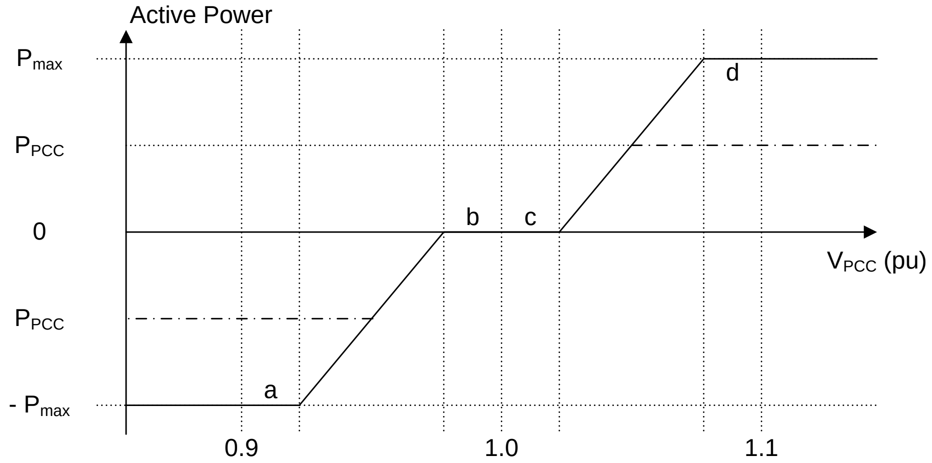


Figure 4.11: Proportional controller for active power of distributed storage for voltage control (stoV)

4.3 Combinations

All measures are simulated and evaluated independently. The only exception is that all measures are combined with the measure VDE to ensure overvoltage protection. Additionally to this individual evaluations there is a number of combinations of special interest described below.

4.3.1 State of the Art (SotA)

Three measures for voltage control are already compulsory for generators on German low voltage grids. The measure VDE as described above is the disconnection of generators at overvoltage. Additionally generators with powers higher than 3.68 kVA are required to provide reactive power control like described above for measure cosP. These two measures are stated in the connection guideline VDE-AR-N 4105 [16]. Furthermore PV generators with powers up to 30 kW are required to implement either a remote control for the grid operator or limit the maximum feed-in power to 70 % of the system's peak power. This measures is described under the name EEG above and is stated in the renewable energy act [13]. In order to evaluate the effectiveness of these compulsory measures the combination of these three measures is evaluated and named State of the Art (SotA).

4.3.2 State of the Art + X

In order to evaluate some promising measures under current legal boundary conditions they are evaluated with additional SotA measures implemented. Table 4.4 shows the list of evaluated combinations. The usage within a combination does not change the models or controls of the single measures.

Table 4.4: List of combination of measures

SotA		State of the art measures
	+ Expansion	Additional parallel cable
	+ Cable	Change of all main cables
	+ OLTC	On-load tap-changer
	+ DG-FACTS	Central DG-FACTS device
	+ DSM	Demand side management of heat pumps
	+ stoV	Voltage control by distributed battery storages

5 Evaluation of Measures

5.1 Evaluation Criteria

The different measures are evaluated according to their influence on the voltage level, the economics, the end-user comfort and the CO_2 balance. The measures are identified as effective, if they are capable to keep the voltage within EN 50160 limits of $\pm10\%$ at every position in the considered feeder. The relevant voltage is the 10 minute moving average value. EN 50160 does allow for undervoltage of -15% if the time below 0.90 pu does not exceed 5% of a week interval. This exception is not considered hereafter, as there should be some reserve for deviations from normal load profiles. This is as if a measure is not able to keep the voltage within the $\pm10\%$ range, it can not be guaranteed that the time below 0.9 pu is less than 5% under any circumstances. The economic analysis does consider operation and initial investment costs. Equipment replacement ahead of schedule due to loading or voltage influences is not considered. The end-user comfort is evaluated according to shut down times of the heat pumps and temperature reductions. The CO_2 balance is evaluated according to operation based changes in CO_2 emissions.

5.2 Calculation Basis

5.2.1 Economics

In order to evaluate the total costs per year a number of steps have to be taken. Figure 5.1 shows the principle process. The investment costs are calculated by the relative investment costs shown in Table 5.2 and the dimensioning of the equipment. Similarly the operation costs are calculated from the relative operation costs per kWh (Table 5.1) and the change in energy consumption or feed-in according to the simulation. Both costs are added and used as input for the annuity calculation.

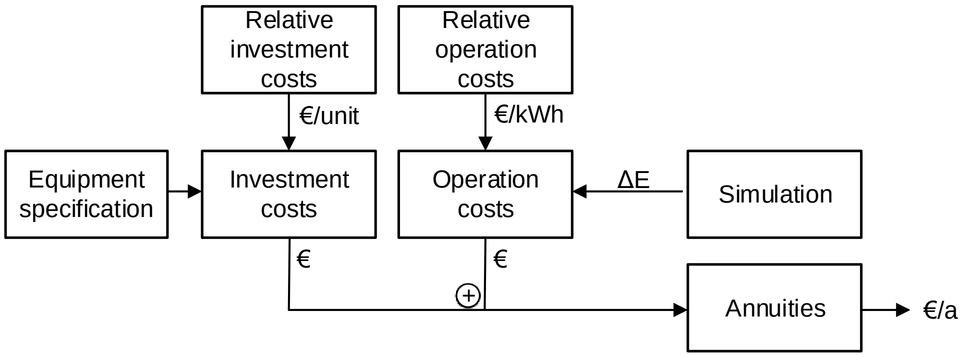


Figure 5.1: Schematic of cost calculation

Operation costs

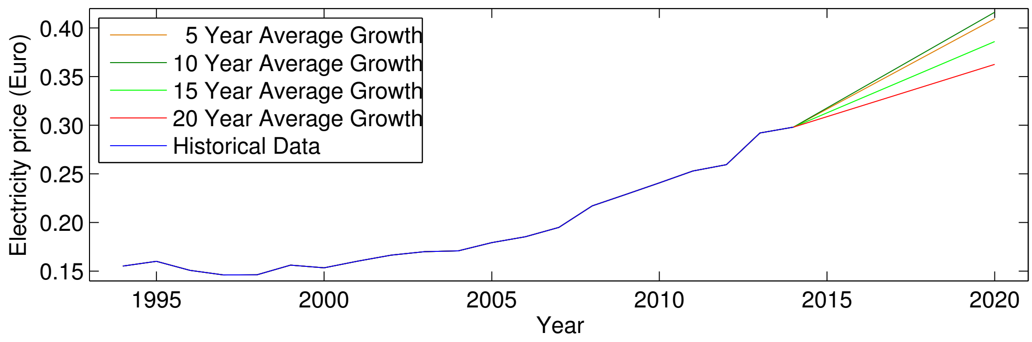
The operation costs are based on the prices shown in Table 5.1. The anticipated value is used for the economic evaluation, whereas the minimum and maximum values are used for parameter variations.

- For gas and electricity prices historic data from 1994 to 2014 are used to calculate four possible price scenarios for 2020 [92]. The price growth rate of the last five, ten, fifteen and twenty years is extrapolated to 2020 (see figures 5.2a and 5.2b). The maximum, minimum and the average of those values are used as maximum, minimum and anticipated gas and electricity prices in 2020.

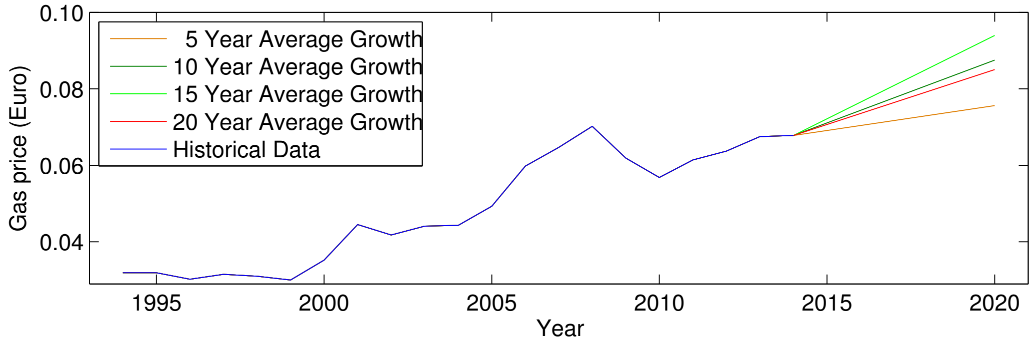
- The costs for grid losses as well as the CHP feed-in tariff are based on the CHP index of the European Energy Exchange. The CHP index shows quarterly average stock prices of electricity. The maximum, minimum and average of the historic values from 2000 to 2014 are used as maximum, minimum and anticipated prices.

- The PV feed-in tariff is calculated according to the renewable energy act [13]. The minimal value is based on the assumption that 52 GW PV peak power is installed till 2020. The maximum value is the maximum that could be reached if the installation number are below expectations until 2020 and the feed-in tariff would therefore increase compared to the current level. The anticipated value is based on the used 2020 scenario and its anticipated PV installation level of 50.47 GW installed PV peak power.

- The credit for CHP generation is based on [93], the CHP gas energy tax refund on [94] and the avoided grid fees for CHP operation is based on values of the grid operator Netze BW [95].



(a) Electricity price



(b) Gas price

Figure 5.2: Historical price development and future development according to average growth rates

As operation costs for the system operator the change in grid losses is considered. The costs for grid losses result from the change in grid losses multiplied by the price for grid losses stated above. The change of operation costs for the end-user can result from HP, CHP and PV operation, but also from changes in peak boiler usage and the use of grid electricity. Latter are calculated by the change in gas or electricity usage multiplied by the price for gas or electricity from the grid. Heat pump operation costs are not evaluated separately as changes in electricity demand are included in the calculations for grid electricity and PV feed-in. Following the current trend there is no heat pump electricity tariff considered. PV and CHP operation are evaluated using the change in fed in electricity multiplied by the relevant feed-in tariff. CHP operation costs are additionally influenced by the change in gas consumption and the change in CHP generation, valued by the gas price, the gas energy tax refund, the credit for avoided grid fees and CHP generation credit respectively. An overview on how the different costs are calculated is shown in Table F.3.

Table 5.1: Relative operation cost predictions for economic evaluation

		Minimum		Anticipated		Maximum	
C_{gas_grid}	(€/kWh)	0.076	[92]	0.086	[92]	0.094	[92]
$C_{electricity\_grid}$	(€/kWh)	0.363	[92]	0.394	[92]	0.416	[92]
C_{grid_losses}	(€/kWh)	0.017	[96]	0.043	[96]	0.073	[96]
$C_{PV\_feed-in}$	(€/kWh)	0	[13]	0.0949	[13]	0.1675	[13]
$C_{CHP\_feed-in}$	(€/kWh)	0.017	[96]	0.043	[96]	0.073	[96]
$C_{CHP\_generation}$	(€/kWh)			0.0541	[93]		
C_{grid_fees}	(€/kWh)			0.0037	[95]		
C_{gas_tax}	(€/kWh)			0.0055	[94]		

Investment costs

Similar to the operation costs, the minimum, maximum and anticipated prices for the investment cost calculations are shown in Table 5.2.

- The minimum inverter costs are based on the minimum prices for 2020 stated in [97], whereas the maximum price is based on an exemplary current market price for a battery inverter [98]. The anticipated value is calculated as the average of minimum and maximum values. Similarly the battery prices are calculated. The battery prices are stated for a cycle lifetime of 3000 cycles.

- The costs for a building to cover the DG-FACTS device are based on the price for a transformer building according to [10]. It is assumed that the costs for the building and the ancillaries are 50 % of the given value each.

- The prices for an 630 kVA transformer with OTLC range from the minimum stated in [53] to the maximum stated in [10]. The anticipated value is calculated as the average.

- The cable prices are defined for NAYY cables and include material and installation. For 150 mm^2 cables values are given in [53] and [10]. Other diameters are calculated by linear extrapolation of the material costs. The share of the material costs on the total costs is stated in [53]. The anticipated values are calculated as the average values.

End-user investment costs are based on changes in inverter power and battery capacity. The inverter power changes for HP, CHP, PV and Battery systems depending on the measure. The battery capacity changes only for measures that include battery systems. DSO investment costs are influenced by inverter and battery prices as well as the price for the

Table 5.2: Relative investment cost predictions for economic evaluation

		Minimum		Anticipated		Maximum	
$C_{inverter}$	(€/kVA)	130	[97]	305		480	[98]
$C_{battery}$	(€/kWh)	202	[99] [100] [101] [102]	378		554	[98]
$C_{building}$	(€)			10000	[10]		
C_{OLTC}	(€/630kVA)	11175	[53]	35588		60000	[10]
C_{cable_4x150}	(€/km)	43000	[53]	51500		60000	[10]
C_{cable_4x300}	(€/km)	61000		73100		85200	

building for DG-FACTS devices. Furthermore OLTC and cable investments are evaluated for the system operator.

Value added tax

The prices for operation or investment are partly with and partly without value added tax (VAT). Tables F.1 and F.2 show in the second column if the different prices contain VAT or not. The other columns show if VAT has to be considered for the investment or operation of a certain equipment. If the price does not contain VAT but it has to be considered for a certain cost, a VAT rate of 19 % is considered. The invest and operation of CHP systems is evaluated according to the small-business regulation (Kleinunternehmerregelung) whereas for PV systems a business registration is assumed.

Annuities

The economic calculations are based on annuities according to [103]. Annuity calculations enable the evaluation of yearly costs depending on investment costs, operation costs and gains as well as a certain interest rate. The annuity (A) can be calculated using Equation 5.1.

$$A = C \cdot \frac{r}{1-(1+r)^{-T}} \tag{5.1}$$

The costs (C) can be either operation or investment costs. Gains and savings have to be stated as negative values. The interest rate (r) and the observation period (T) define the annuity of the costs. For investment costs T is always defined as the equipment lifetime, no residual values or procured replacements are considered. The operation costs are calculated for the two simulated weeks. The observation period therefore is two weeks for the operation costs. The total annuity of a certain measure is calculated as the sum of all applicable investment and operation annuities as shown in Equation 5.2 and Equation 5.3. A definition of the different annuities can be found in Table F.3. There are not considered any price dynamics, the prices are given for 2020.

$$\begin{aligned} A_{DSO} = A_{cable\_invest} + A_{OLTC\_invest} + A_{DG-FACTS\_inverter\_invest} \\ +A_{DG-FACTS\_battery\_invest} + A_{DG-FACTS\_building\_invest} \\ +A_{DG-FACTS\_losses} + A_{grid\_losses} \end{aligned} \tag{5.2}$$

$$\begin{aligned} A_{end-user} = A_{HP\_invest} + A_{CHP\_invest} + A_{CHP\_operation} + A_{PV\_invest} \\ +A_{PV\_feed-in} + A_{storage\_inverter\_invest} + A_{storage\_battery\_invest} \\ +A_{electricity\_consumption} + A_{gas\_consumption} \end{aligned} \tag{5.3}$$

In the sections 5.3 and 5.4 the economic evaluation is shown as the annuities relative to the total end-user energy costs. DSO margins are not considered. The interest rates used for the calculation are shown in Table 5.3. The base rate of the European central bank is set as minimum interest rate. This scenario assumes political sponsorship. The maximum interest rate is the interest rate for DSO equity whereas the anticipated interest rate is the interest rate for DSO dept capital according to [10].

Table 5.3: Interest rates for annuity calculations

	Minimum		Anticipated		Maximum	
Interest rate (%)	0.05	[104]	3.80	[10]	9.05	[10]

5.2.2 End-User Comfort

The only measures that have an influence on the end-user's comfort are DSM and DSMth as they limit the available heat power of the heat pumps. The end-user comfort is evaluated by two means. First the shut down time with demand side management of heat pumps is compared to state of the art shut down times by DSO load management. Secondly the temperature reduction due to the reduction of power and shut down is compared to the temperature reduction due to the state of the art shut down time. The temperature decrease is calculated using a zero dimensional heat capacity model of the house. The usable heat capacity of the house is calculated according to DIN 18599 [105]. The calculated heat capacity for the new detached house that is used within the suburban new grids is 23732 kJ/K. The difference between the heat energy is delivered by the heat pump and the heat load of the house is used to calculate the temperature change in the house. The results are shown in subsection 5.3.3.

5.2.3 CO_2 Balance

The CO_2 balance is calculated relative to the maximum CO_2 savings without measures. The CO_2 emissions of the specified grid without any CHP, HP or PV appliances installed is defined as 0 % savings, whereas the emissions with the anticipated 2020 penetrations installed is defined as 100 % savings. The CO_2 balance with different measures is evaluated according to this scale. The change in CO_2 emissions for HP, PV, battery, DG-FACTS and system losses are calculated according to Equation 5.4.

$$\Delta CO_2 = \Delta E \cdot CO_{2\_electricity} \tag{5.4}$$

ΔE is the change in demand or generation of electricity or the losses respectively. Higher demand and less generation are stated positive whereas lower demand and more generation are stated negative. A positive change in CO_2 is therefore an increase in emissions. The value for $CO_{2\_electricity}$ can be found in Table 5.4. For CHP systems the calculation is more complicated, as the gas consumption of the CHP is reduced if the generation is limited, but the gas demand of the peak boiler increases at the same time. Furthermore the reduction in electricity production increases the demand of electricity from the public grid. Equation 5.5 shows these changes in CO_2.

$$\begin{aligned}\Delta CO_{2\_CHP} = \Delta E_{CHP\_generation} \cdot CO_{2\_electricity} - \frac{\Delta E_{CHP\_generation}}{\eta_{CHP\_el}} \cdot \frac{CO_{2\_heat}}{\eta_{peak\_boiler}} \\ + \Delta E_{heat\_boiler} \cdot CO_{2\_heat}\end{aligned} \tag{5.5}$$

The change in CO_2 emissions by CHP operation according to Equation 5.5 consists of three parts. First the influence of the generated electricity ($\Delta E_{CHP\_generation}$), secondly the change in gas demand by the CHP and thirdly the change is gas demand of the peak boiler. The change in gas demand is calculated by dividing the change in electric energy ($\Delta E_{CHP\_generation}$) by the electric efficiency of the CHP (η_{CHP_el}). The CO_2 impact of gas is calculated by dividing the CO_2 impact of gas heating (CO_{2_heat}) by the efficiency of a gas boiler (η_{peak_boiler}). The influence of changes in peak boiler operation is calculated using the value for change in peak boiler heat generation (ΔE_{heat_boiler}).The CO_2 impact of gas heating can be found in Table 5.4 and the efficiency values are shown in Table 5.5. There is no life cycle CO_2 analysis considered.

Table 5.4: CO_2 emission values

Germany mix 2020	CO_2 emission (kg/kWh)	
$CO_{2\_electricity}$	0.511	[106]
CO_{2_heat}	0.237	[107]

Table 5.5: Efficiency values for economic and CO_2 balance evaluation

	Efficiency (%)	Appliance	
Fuel Cell CHP electric (700 W)	45	Buderus Logapower FC10	[108]
Fuel Cell CHP thermal (700 W)	45	Buderus Logapower FC10	[108]
Peak boiler (14 kW)	98.2	Buderus Logamax plus GBH172	[109]

5.3 Simulation Results Reference Scenario

5.3.1 Voltage Level

As shown in subsection 3.3.1 the considered grid does not exceed the maximum voltage level according to EN 50160. The minimum value, however, is exceeded. If considering the 10 min average voltage value, rather than the absolute values the maximum voltage in the suburban new grid is 1.09 pu and the minimum voltage is 0.83 pu. Measures are therefore necessary in order to install the anticipated number of heat pumps in the grid. The expansion of the grid as well as the change of all cables is suitable to ensure the voltage boundary, whereas the change of feeder 8 is not sufficient. The installation of an OLTC or of DG-FACTS is sufficient. Selected results are shown in Table 5.6. An overview on all measure abbreviations can be found on page 142.

On the end-user side only distributed battery storage (stoV) is able to ensure the voltage limit. All generator based measures do not have any influence on the lower voltage level. Demand side based measures increase the minimum voltage but are not sufficient to ensure the 0.90 pu boundary. This is as the local voltage measurement of the devices does

Table 5.6: Selected voltage level and equipment loading results in reference scenario

Measure	V_{max}	V_{min}	Trafo load	Cable load
Reference	1.09	0.83	OK	OK
Expansion	1.05	0.92	OK	OK
Cable	1.07	0.90	OK	OK
OLTC	1.05	0.90	OK	OK
DG-FACTS	1.09	0.91	OK	OK
DSM	1.09	0.89	OK	OK
stoV	1.09	0.90	OK	OK
SotA	1.08	0.83	OK	OK
SotA + Expansion	1.05	0.92	OK	OK
SotA + Cable	1.05	0.90	OK	OK
SotA + OLTC	1.05	0.90	OK	OK
SotA + DG-FACTS	1.07	0.91	OK	OK
SotA + DSM	1.08	0.89	OK	OK
SotA + stoV	1.07	0.90	OK	OK

not show the minimum voltage in the grid and therefore not all HP shut down in times of undervoltage. The operating systems suppress the voltage at the end of the feeder below 0.90 pu. If DSM would shut down all HP in cases of undervoltage, the voltage level could be ensured, as the minimum voltage with voltage fluctuations and no appliances is 0.90 pu. One possibility to enable DSM to shut down all HP is communication between the systems. If systems connected close to the transformer get the information that the voltage at the end of the feeder exceeds the limit they can react on that information. If this smart grid approach is chosen, the minimum voltage with DSM is 0.90 pu and therefore within the EN 50160 limits. The voltage level influence does not differ between DSM and DSMth.

The combination of the SotA measures is not able to ensure undervoltage protection, as only generator based measures are included. The combination with measures that are able to prevent undervoltage is, however, effective. The combination of SotA and DSM is only effective if a smart grid approach, like discussed above, is implemented. An overview on all voltage level and loading results is shown in Table G.1. The transformer and the cables are not overloaded without or with any measures.

5.3.2 Economics

The economic evaluation of all measures is shown in Table G.2. The additional costs are presented relative to the end-users' energy costs. The costs are the sum of all operation and investment costs of all end-users connected to the relevant feeder or the DSO respectively. The reference energy costs of the end-users' are the costs for electricity and gas in case all appliances are installed without any measures. In the reference scenario this is 5232 € for 39 households in two weeks. As shown in subsection 5.3.1 not all measures are effective. The evaluation below considers only effective measures and is based on the boundary condition that no SotA measures are installed. The relative costs for end-users, DSO and the relative total costs of these six measures are shown in Figure 5.3. It can be seen that the electric storage based measures DG-FACTS and stoV are very expensive compared to the other measures. The installation of distributed electric storage for voltage control costs additional 32.3% of the end-users energy costs.

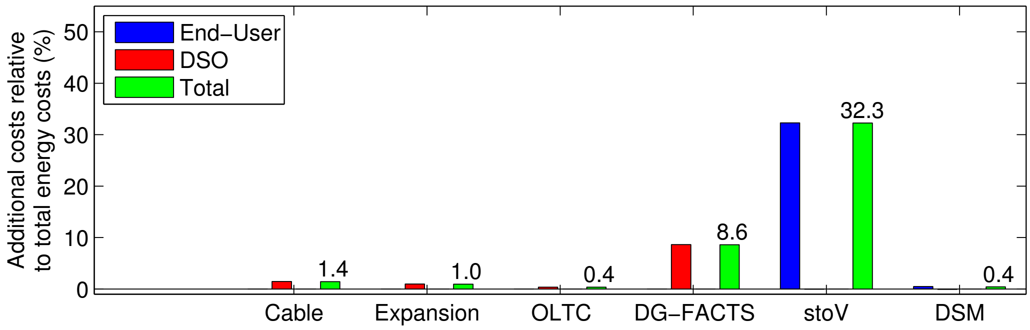


Figure 5.3: Economic evaluation without SotA 2020

Figure 5.4 shows the four economically feasible measures from Figure 5.3. It can be seen that the three DSO based measures do not introduce cost for the end-users whereas DSM does. The increased end-user costs for DSM are additional costs for heat pump operation, as the efficiency of the HP systems is reduced by the load shift. This is mainly due to increased operation of the electric heating rod. DSM reduces the costs for the DSO as losses in the grid are reduced by the reduced peak time loading. Overall the installation of an OLTC is the most economic measure to integrate the anticipated 2020 penetrations.

The evaluation above is based on the comparison of measures in an environment without SotA measures. If the evaluated measures are installed additionally to the SotA measures the economic evaluation is influenced. Figure 5.5 shows the economics including SotA measures in 2020. It can be seen that SotA introduces costs for the end-users without adding value to voltage control. As is shown in Table G.2 the main costs for SotA is introduced by reactive power control (cosP) as additional inverter power has to be provided. The reduction of the PV power to 70% peak power increases operation costs but the re-

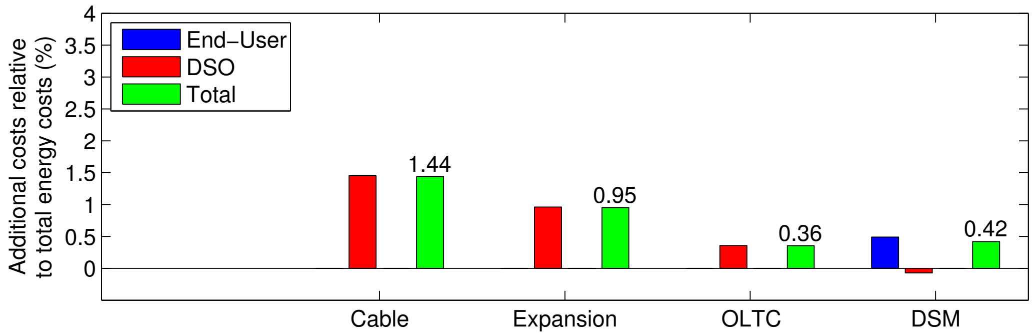


Figure 5.4: Economic evaluation without SotA 2020 (not considering battery based measures)

duction in investment costs for reduced necessary inverter power overcompensates this. The end-user costs for SotA increase the costs for all measures as they are independent of the other measures. Costs for DSM are increased by installing SotA as PV generation is reduced which increases shut-down times for the heat pumps. SotA itself is not able to guarantee EN 50160 voltage levels, so it has to be accompanied by another measure. The most cost efficient combination is SotA and OLTC. Concluding it can be seen that OLTC is the most cost efficient measure with and without state of the art measures. To maintain the legal need to install the SotA measures increases the costs. This is especially due to the costs for reactive power control (cosP) of generators. Battery based measures are very expensive due to the high investment costs. DSM is more expensive than OLTC even though no investment costs are taken into account. A sensitivity analysis of the economic evaluation regarding the anticipated prices is shown in Figure G.1

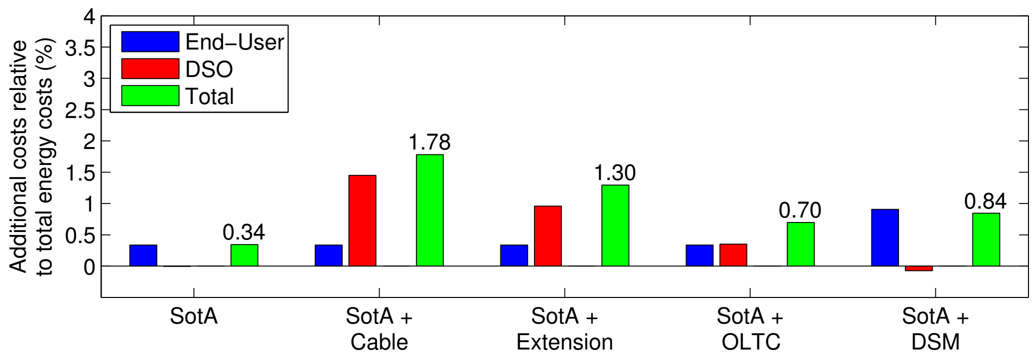


Figure 5.5: Economic evaluation with SotA 2020

5.3.3 End-User Comfort

The times of power reduction and shut down are shown in Table 5.7. The time of power reduction includes the shut down time. Grid operators are allowed to block heat pump operation for 120 minutes up to 3 times per day. Currently heat pumps are blocked for a maximum time span of 90 minutes by the grid operator Netze BW [110]. It can be seen that even if just considering the shut down time of DSM, this time span is exceeded.

Table 5.7: Power reduction and shut down times of DSM and DSMth

	DSM	DSMth	SotA + DSM
Reduction (min.)	144	262	257
Shut down (min.)	104	126	124

The temperature reduction of the house is shown in Figure 5.6 exemplary for SotA + DSM. It can be seen that the temperature reduction due to DSM is considerably more than due to the scheduled 90 minutes block by the DSO. The maximum temperature reduction is 1 K or 51% higher for DSM than for the 90 minutes block.

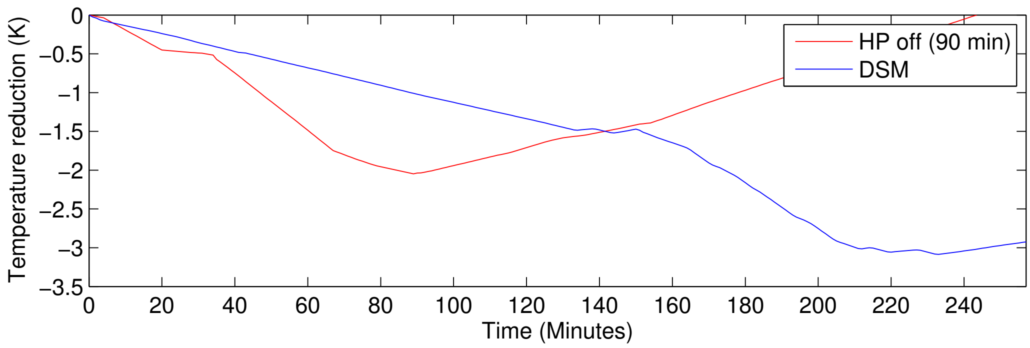


Figure 5.6: Temperature reduction due to SotA + DSM and HP shut down in reference scenario

The evaluation of the shut down time as well as the evaluation of the temperature reduction show that end-user comfort reductions have to be expected with DSM. This is not acceptable from a manufacturer's point of view.

5.3.4 CO_2 Balance

Figure 5.7 shows the CO_2 savings of the different measures. The reference scenario is defined as 100% CO_2 savings in subsection 5.2.3. If considering connection restrictions that apply today for generators and heat pumps, only 54% of the savings can be realised. This is mainly due to the limitation of generators by VDE 4105 and due to limited connection of heat pumps as the voltage boundary of EN 50160 is violated. According to current connection restrictions, the suburban new grid would be able to accommodate 67% of the anticipated PV penetration and 12% of the anticipated HP penetration. If measures are installed to accommodate the full 2020 penetrations, the changes in CO_2 savings are small compared to the case with connection restrictions. The change of all cables increases the savings by 5% if no SotA measures are considered, whereas DSM including SotA reduces the savings by 5%. The influence of the different measures on the CO_2 savings is negligible as long as there are measures installed. Important to reach the saving goals is that CHP, HP and PV appliances can be installed to the grid.

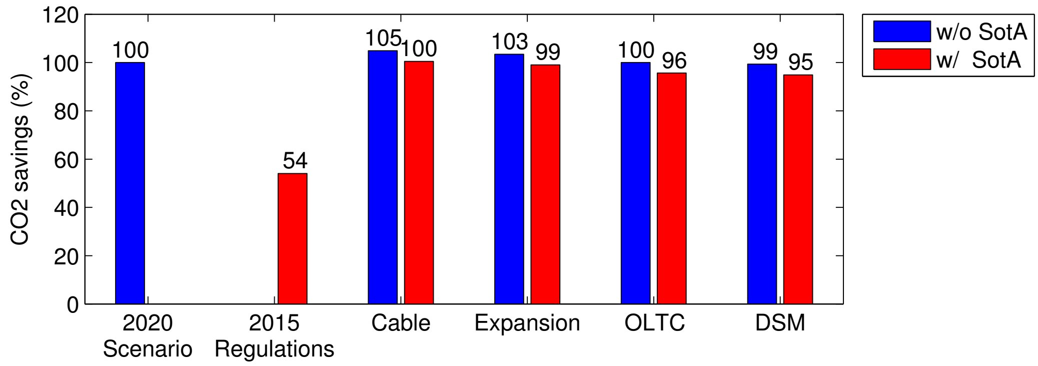


Figure 5.7: CO_2 balance of measures in the reference scenario

5.4 Simulation Results Maximum PV Scenario

5.4.1 Boundary Conditions

The reference scenario evaluated above shows undervoltage issues only. In order to evaluate the measures under overvoltage conditions an exemplary maximum PV scenario is introduced. In this scenario 99% of the houses are equipped with a PV generator. The higher penetration of generators has an influence on the technical and economic feasibility of the different measures. The penetration levels of CHP and HP systems are identical to the reference scenario, whereas the PV penetration is maximised. Table 5.8 shows the penetration levels for the 2020 and the maximum PV scenario of the new suburban grid.

The measures are principally the same, but are differently parametrised if necessary. Feeder 8 is overloaded in this scenario. Therefore it is changed to NAYY 4x300 cables additionally to all measures that are not cable based. The cable for the Expansion measure can be designed thinner and is set to NAYY 4x150. For DG-FACTS and stoV measures the battery capacity as well as the inverter power has to be adapted. These changes influence the technical and economic evaluation. The economic evaluation is based on the costs and prices determined for the reference scenario.

Table 5.8: Penetration levels of 2020 and maximum PV scenarios

	Suburban new	
Number/Grid	Reference	Maximum PV
CHP	7	7
HP	101	101
PV (Power)	123 (4 kW)	164 (7 kW)

5.4.2 Voltage Level

The increased PV penetration in the grid leads to overvoltage as can be seen for the reference in Table 5.9. The maximum voltage is 1.16pu. On the other hand, undervoltage is reduced by the generators. The minimum voltage, therefore, is only 0.84. Opposing to the reference scenario feeder 8 is now overloaded at times of high PV feed-in. The measures for overvoltage control are not able to prevent this overload, therefore the change of cables in feeder 8 is necessary additionally. It can be seen that all measures are able to prevent overvoltage. This is as VDE is effective and all measures are combined with VDE as described in section 4.3. Undervoltage can be prevented by the same measures as in the reference scenario. Additionally DSM is now able to keep the voltage within EN 50160 levels without communication, as the voltage drop by HP that are not shut down is reduced by the changed cables in feeder 8. The complete overview on voltage level and loading results for all measures is shown in Table G.3.

Table 5.9: Selected voltage level and equipment loading results of maximum PV scenario

Measure	V_{max}	V_{min}	Trafo load	Cable load
Reference	1.16	0.84	OK	overload
Expansion	1.10	0.90	OK	OK
Cable	1.10	0.90	OK	OK
OLTC	1.08	0.93	OK	OK
DG-FACTS	1.10	0.91	OK	OK
VDE	1.10	0.87	OK	OK
DSM	1.10	0.90	OK	OK
stoV	1.10	0.90	OK	OK
SotA	1.10	0.87	OK	OK
SotA + Expansion	1.08	0.90	OK	OK
SotA + Cable	1.07	0.90	OK	OK
SotA + OLTC	1.05	0.93	OK	OK
SotA + DG-FACTS	1.09	0.91	OK	OK
SotA + DSM	1.10	0.90	OK	OK
SotA + stoV	1.09	0.90	OK	OK

5.4.3 Economics

The reference energy costs of the end-users' in the maximum PV scenario are 4227 € for the 39 households in two weeks. The reduced costs are due to increased PV self consumption. The additional costs are shown relative to this value. Similar to the reference scenario, DG-FACTS and stoV measures are expensive and are not considered hereafter. Figure 5.8 shows the relative additional costs for the end-user, the DSO and the total costs in the maximum PV scenario. It can be seen that OLTC is the most economic measure. As the voltage is considerably higher than in the reference scenario some devices have to shut down at overvoltage when the expansion measure is installed. This leads to cost for the end-users. DSM is the most expensive measure as a lot of possible generation is prevented by overvoltage shut down.

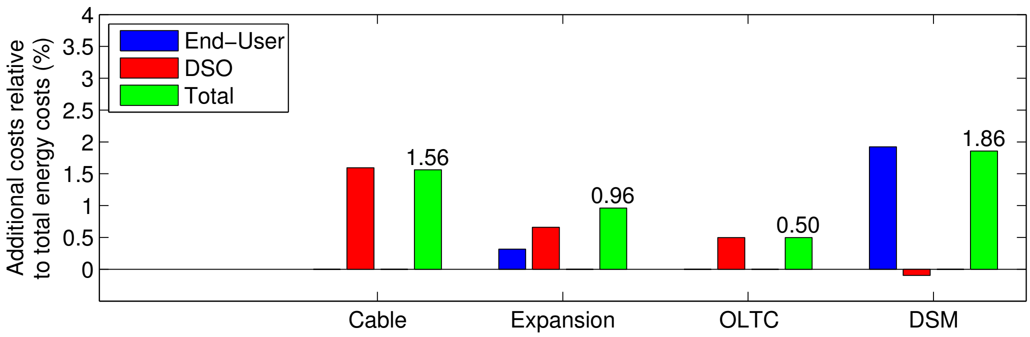


Figure 5.8: Economic evaluation without SotA in maximum PV scenario

Figure 5.9 shows the selected measures with activated SotA measures. It can be seen that the SotA measures, even though they are not sufficient, introduce costs for the end-user. This is as the power generation is restricted more often due to the higher PV penetration compared to the reference scenario. DSM is the most economic measure that is able to keep both, lower and higher voltage boundaries. OLTC and Expansion are similar whereas the change of all cables is the most expensive measure of this selection. It can be seen that the end-user costs are strongly influenced by the costs for the SotA measures. Furthermore it is shown that the increase in end-user costs due to SotA increases the overall costs of the DSO based measures significantly. The overall costs of DSM are decreased compared to Figure 5.8 as the reduction in PV feed-in is more expensive than limiting the power to 70 % according to the measure EEG as in this case less invest costs have to be accounted.

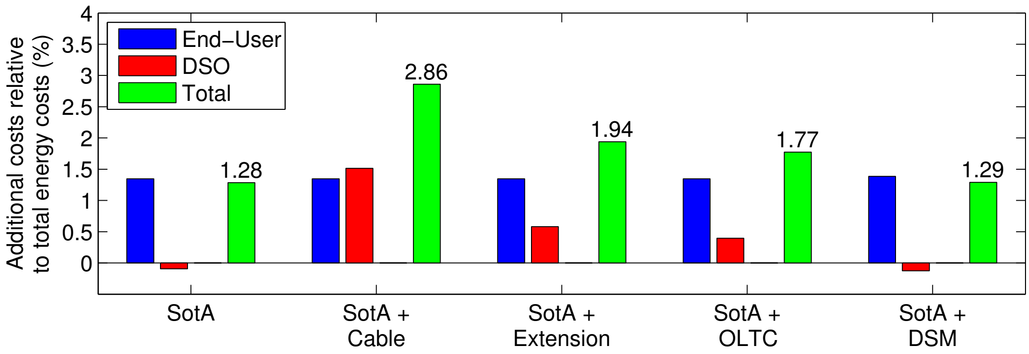


Figure 5.9: Economic evaluation with SotA in maximum PV scenario

5.4.4 End-User Comfort

DSM reduced the heat pump's power less often in the maximum PV scenario, as the increased PV installation leads to a higher voltage level. The maximum power reduction period is 125 minutes of which the heat pump is shut down for 37 minutes. No comfort reduction has to be assumed as the generated heat with DSM is higher than for the 90 minutes shut down. It is, however, a delicate equilibrium between PV and HP installations that enables this. An increase in HP, for example, leads to longer power reductions and therefore to comfort issues as shown in subsection 5.3.3.

5.4.5 CO_2 Balance

The CO_2 balance in the maximum PV scenario is calculated similar to the reference scenario. The CO_2 savings potential with all appliances according to the maximum PV scenario is defined as 100% savings. The grid without any installed CHP, HP or PV appliances is defined as zero percent savings. Figure 5.10 shows the CO_2 savings of the different measures and of the grid with only appliances installed that could be installed according to current regulations. In case of the maximum PV scenario current connection restrictions would allow 29% of the anticipated generators and 12% of the anticipated heat pumps.

It can be seen that the measures have a similar influence on the savings as in the reference scenario. Cables can increase the CO_2 savings by 5% and DSM decreases the savings by a maximum of 3%. According to current regulations, however, only 14% of the reference savings could be realised as the connection of the appliances is limited. The absolute savings for current regulations in Figure 5.10 and Figure 5.7 are the same, they only differ relative to the possible savings according to the different scenarios.

The evaluation of the reference scenario and the maximum PV scenario show that only a few measures are able to prevent undervoltage, whereas overvoltage protection is ensured

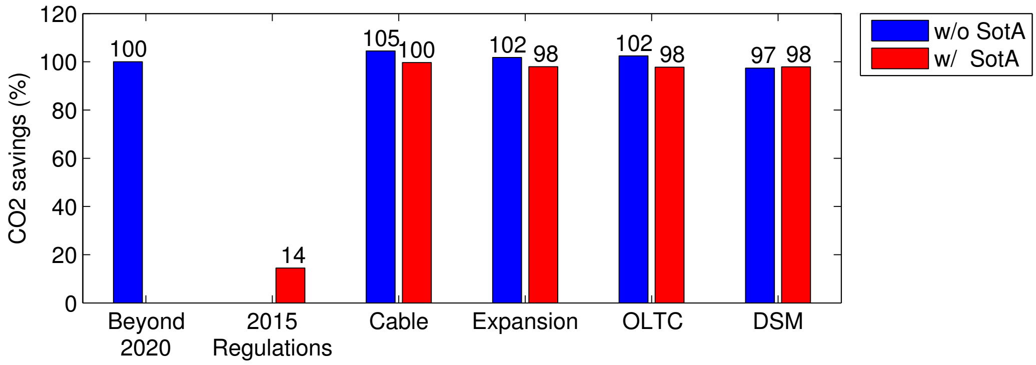


Figure 5.10: CO_2 balance of measures in scenario maximum PV

by the shut down according to VDE-AR-N 4105. The use of OLTCs is very economical in both scenarios, whereas battery based solutions are very expensive due to the high investment costs in 2020. Heat pump management for voltage control can lead to comfort issues which is not acceptable. The influence of the different measures on the CO_2 balance is negligible, but installation restrictions lead to high reductions in the CO_2 savings.

6 Conclusions and Future Prospects

6.1 Grid Operation and Planning

6.1.1 Measure Selection

Section 3.3 shows that undervoltage rather than overvoltage is the main issue in 2020 in the considered grids. In the suburban new grid the maximum and minimum voltages are 1.10 pu and 0.83 pu respectively. In a maximum PV scenario overvoltage is the main issue (see section 5.4).

- Six measures are able to prevent voltage level violations:
  - Change of all main connection cables
  - Grid expansion via additional parallel cable
  - Installation of on-load tap-changer
  - Installation of distribution grid FACTS
  - Installation of distributed storage for voltage control
  - Demand side management of heat pumps in smart grid
- The most cost efficient measure to prevent undervoltage and overvoltage is the installation of an OLTC. This is valid in the reference scenario as well as the maximum PV scenario as shown in section 5.3 and section 5.4. If not considering state of the art measures the installation of an OLTC costs only 0.36% of the end-users' energy costs in the considered grid in 2020. Other studies (e.g. [10], [39]) do also identify OLTC as a possible measure to reduce grid extension costs. In this work this is confirmed and additionally verified against DSM and other appliance based measures. Demand side management of heat pumps either introduces comfort issues for the end-user (reference scenario) or is more than three times as expensive as OLTC (maximum PV scenario) at least if no state of the art measures are considered. Comfort issues for the end-users are not acceptable from the manufacturers' point of view. DSO based measures, especially OLTCs, are therefore seen as the prefered measures to ensure the conformity with EN 50160 voltage levels.

- Electric storage based measures like DG-FACTS and distributed storage are, similar to [10], identified to reduce the grid extension necessity. From an economic perspective however they are not yet competitive to the use of OLTCs or the change of cables.
- The possible CO_2 savings are similar between the different measures. The savings are, however, significantly decreased if the anticipated penetration levels can not be reached in 2020.

As shown in section 1.1 currently grid extension is planned according to individual connection requests. This is due to the grid operator regulations that were established when no major changes were expected in the distribution grids. [10] identified the current regulations as not suitable for the necessary investments to integrate the anticipated numbers of distributed generators. Additionally [39] recommends to explicitly add OLTCs as a preferred measure to the regulations. This work identifies anticipatory grid planning as beneficial. It is therefore recommended to adapt the DSO regulations accordingly. Additionally it is recommended to consider possible future HP connections in the grid planning process in order to enable higher heat pump penetrations and the connected carbon saving potential.

6.1.2 Robustness of Results

The simulations in chapter 3 and chapter 5 show the voltage behaviour and the influence of different measures for exemplary grids. Changes in grid topology, equipment and penetration levels have an influence on the results. As every grid is different it is important to assess the results on changes in these boundary conditions. Changes in grid topology and equipment but also an increase or decrease of appliance penetration change the voltage influence and therefore increase or decrease voltage band violations. If the penetrations of appliances change independently from the appliance type, the voltage characteristic of the grid is changed as shown in section 3.1. PV generators create voltage peaks during the day, whereas CHP systems increase the voltage level evenly. Heat pumps cause voltage decrease in the morning and the evening, especially during the heating period. Compared to the reference scenario there are two possibilities how changes in boundary conditions can change the voltage behaviour. Either there are no voltage level violations due to reduced loop impedance or appliance penetrations, or overvoltage rather than undervoltage is the main issue. If there are no voltage level violations end-user based measures might cause installation and operation costs whereas DSO based measures would not have to be implemented. The conclusion that DSO based measures should be preferred is true in this case, as they only have to be implemented within grids that show voltage level violations.

If there are no undervoltage but overvoltage issues, the shutdown at overvoltage according to VDE-AR-N 4105 is able to guarantee overvoltage protection. If the generation is only limited for a few hours per year it is more cost efficient to choose the shut down rather than installing an OLTC. The reduced generation, however, decreases the incentives to invest in generators, which has to be considered regarding the carbon saving goals. At some point, which is very individual for each grid, the installation of an OLTC is more economic than the shut down of generators. This circumstance can be used within an optimised grid planning process in order to identify the optimal time for the grid enforcement measure. In any case DSO based measures, especially OLTCs, are the measure of choice on the long term. However, as the voltage control possibilities of OLTCs are limited if the voltage behaviour of feeders differ from each other and cable based grid extension measures take a long time to implement, DG-FACTS will play an important role in some areas. The exact share will depend on the reduction in costs for batteries.

6.1.3 Future Prospects

The influence of appliances on the voltage level as well as the economic and comfort evaluations should be validated in real grids. In order to enable a big data basis, grid operators are in an important position for the realisation of such a project.

In order to enable the most cost efficient grid extension, future work should develop an optimised grid planning process. First steps in this direction are proposed in [39]. Part of that work is an adapted grid operator regulation as well as grid planning processes that are based on anticipated connection numbers.

Options how comfort reductions can be minimised when utilising DSM should be explored, especially regarding use cases other than voltage control. Optimisation potential might be present in storage sizing as well as heat pump controls and dimensioning.

6.2 Grid Codes and Connection Requirements

6.2.1 Requirements for Appliances

As DSO based measures are recommended in order to integrate the high anticipated appliance penetrations, no additional requirements for appliances are identified. For heat pumps this applies since from a manufacturers point of view end-user comfort reductions are not acceptable. For generators the shut down at overvoltage according to VDE-AR-N 4105 is sufficient to ensure overvoltage protection, therefore no additional requirements apply. This is in principle consistent to [10] and [39] were no major savings for demand side management could be identified but generator shut down is seen as a cost saving measure. This work, however, sees an delicate equilibrium between cost savings for grid extension and the willingness to invest in renewable generators which is crucial to reach the anticipated installation goals.

6.2.2 Current Regulations

As shown before the state of the art measures reactive power control according to VDE-AR-N 4105 as well as 70% PV power limitation according to the renewable energy act are not necessary for voltage control. Especially the reactive power control introduces unnecessary costs for end-users. The measures have, however, an influence on parameters other than the voltage level, like grid loading, energy markets, frequency stability and others that is not evaluated within this work.

The connection restriction of generators to a maximum voltage rise of 3% by all generators was established when the voltage level at the transformer was adjusted to up to 1.05 pu in order to prevent undervoltage. As generators shut down at overvoltage it proofed to be unnecessary from a voltage level perspective, especially if the voltage at the transformer is set to 1.0 pu to enable higher generator penetrations. It is therefore recommended to replace this restriction by connection rules that utilise the complete $\pm 10\%$ voltage band for loads and generators. The adaptation of technical requirements is also identified as a major cost saving potential by [10].

As shown in section 3.1 the connection of CHP and HP devices in the same grid reduces each other's voltage influence even without communication between the appliances. It is recommended to utilise this effect by promoting the connection of one or the other technology to grids with high penetrations of the particular other technology. This approach can reduce necessary grid extension very economically [111].

6.2.3 Future Prospects

Even though no additional requirements for controls or communication are identified for voltage control, smart grid functionalities can introduce an economic and comfort gain for the end-user. Examples for already existing functions in Bosch appliances are the smart grid ready label for heat pumps in Germany and the usage of communication between PV inverter and heat pump to maximise the PV self consumption. Further work should, therefore, investigate the potential of that gain, technical requirements as well as the necessary political boundary conditions.

In order to evaluate if the state of the art measures that are not necessary from a voltage level perspective are necessary for other tasks, a detailed investigation on these measures is recommended. The goal is to quantify the benefit in order to enable informed decisions on their continuity.

The focus of this work is the voltage level and equipment loading on the low voltage grid. In order to gain a complete picture it is recommended to evaluate the influence of high penetrations of HP, CHP and PV appliances on power quality aspects like harmonics, unbalance, frequency stability and others on all voltage levels.

A Regulatory Boundary Conditions

Table A.1: EN 50160 regulations for power quality (continuous phenomena) [22][21]

Phenomenon	Limit
Frequency	50 Hz $\pm$ 1 % for 99.5 % of time
	50 Hz $+$ 4 % $-$ 6 % for 100 % of time
Voltage Change	$\pm$ 10 % of nominal voltage
	$+$ 10 % $-$ 15 % of nominal voltage for a maximum of 5% of the 10 min mean values of a week interval
Flicker	Long-term flicker magnitude $P_{lt} \leq 1$ for 95 % in a week interval
Unbalance	Negative sequence component has to be within 0 to 2 % of positive sequence component for 95 % of the 10 min mean values in a week interval
Harmonics	Magnitude within the limits specified in a table stating order and relative voltage amplitude of the harmonics for 95 % of the 10 min mean values in a week interval

Table A.2: VDE-AR-N 4105 regulations regarding connection and operation of generators [22]

Connection Criteria		Operation requirements	
Phenomenon	Limit	Measure	Requirement
Voltage	$\pm$ 3 % of voltage without Distributed Generation	Voltage Stability	Generators have to be able to participate on voltage stability measures of grid operator
Flicker	Long-term flicker magnitude of all generators $P_{lt} \leq 0.5$	Voltage Response	Reactive power response according to fixed $\cos(\varphi)$ or $\cos(\varphi)$ characteristic given by grid operator
Harmonics	Magnitude within the limits specified in a table stating order and relative voltage amplitude of the harmonics	Frequency Response	No automatic disconnection due to frequency deviations between 47.5 and 50 Hz. Modulate output power to a given characteristic between 50.2 and 51.5 Hz
Unbalance	$\Delta P_{phases} \leq 4.6$ kVA	Grid Safety Management	Reduction of active power output to, or below, a percentage of P_{max} given by grid operator

B Simulation Model

B.1 Load Profile Data

Table B.1: Overview Load Profiles

People	User Type	Electric Energy (kWh/a)	DHW Energy (kWh/a)	Maximum Temperature Setting (°C)
1	Athlete 1	1519	365	23
1	Athlete 2	1343	370	23
1	Commuter	819	402	23
2	Standard	2117	1176	23
2	Pensioner	2020	1153	24
3	Standard 1	3846	1463	23
3	Standard 2	3404	1901	23
4	Standard	4007	2297	23
4	Efficient	2558	1664	23
4	Luxurious	5563	2297	23
8	Standard	8217	5001	23

Table B.2: Overview Load Profiles Heat Power

People	User Type	Suburban Q_{new} (kWh/a)	Suburban Q_{ref} (kWh/a)	Suburban Q_{old} (kWh/a)	Urban Q_{new} (kWh/a)	Urban Q_{old} (kWh/a)
1	Athlete 1	11252	14977	27869	2926	7179
1	Athlete 2	10960	14633	27390	2803	7018
1	Commuter	9879	13560	25097	2615	6736
2	Standard	14646	17748	41639	3806	8092
2	Pensioner	13516	16168	30343	4246	7538
3	Standard 1	13754	16871	30788	3218	6958
3	Standard 2	13937	16576	29423	3754	7336
4	Standard	11479	14225	27374	2484	5647
4	Efficient	12278	15171	28430	2978	6449
4	Luxurious	10750	13284	26312	1669	4947
8	Standard	9908	12668	25759		

Table B.3: Average relative heat demand per flat

House Type	Detached new	Detached refurbished	Detached old	Multi family new	Multi family old
Average heat demand (kWh/a)	12034	15080	29129	3050	6790
Living area (m^2)	184	130	130	60	60
Relative heat demand (kWh/m^2a)	65	116	224	51	113
Classification heating index [64]	low	medium	high	low	medium

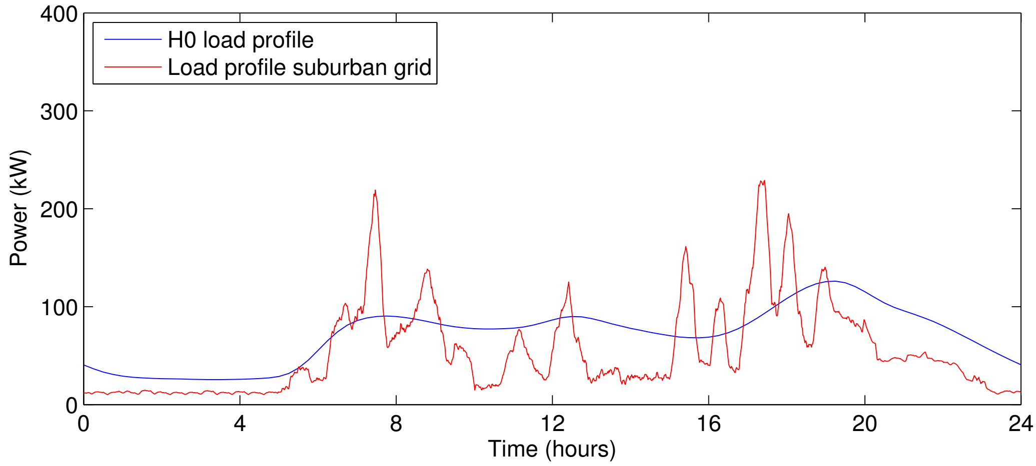


Figure B.1: BDEW H0 profile compared to suburban load profile

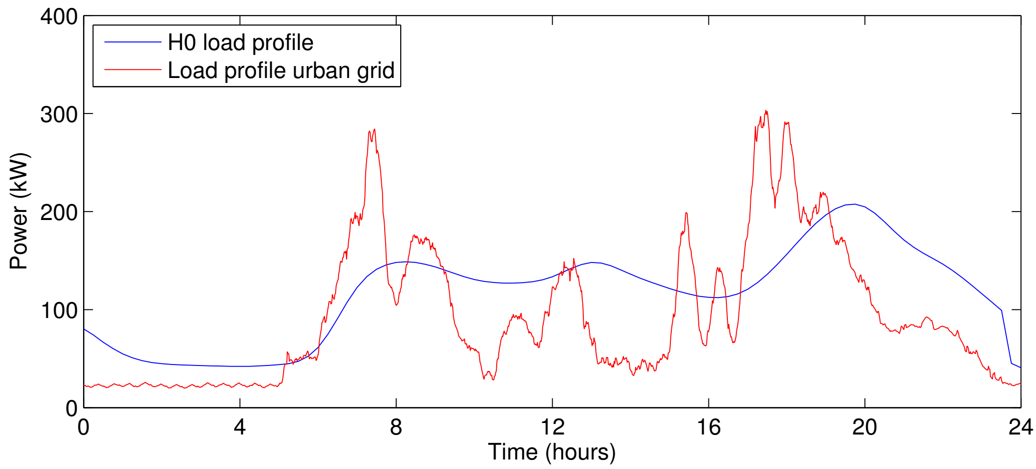


Figure B.2: BDEW H0 profile compared to urban load profile

B.2 Component Models

CHP Model

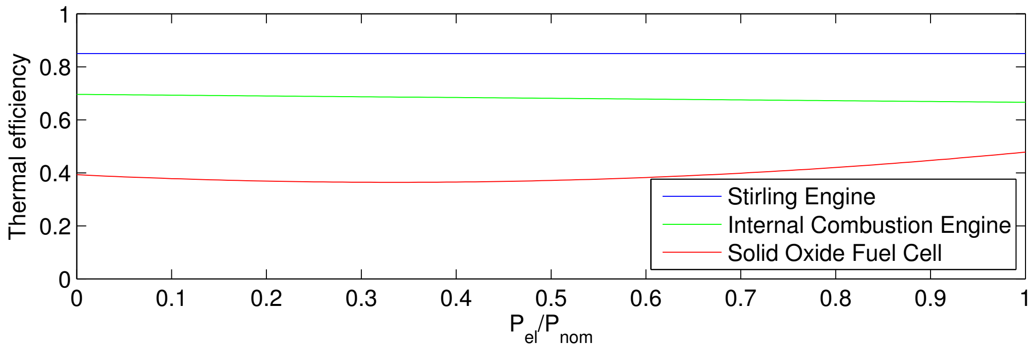


Figure B.3: CHP thermal efficiency

Heat Storage Model

Table B.4: Maximum supply and return temperatures of heating system

		ST_{max} / °C	RT_{max} / °C
New Building	Radiator	55	45
	Floor heating	40	35
Old Building	Radiator	70	55
	Floor heating	50	40
Hot Water	CHP	70	15 (fixed)
	HP	60	15 (fixed)

B.3 Cable Parameters

Table B.5: Cable parameters

	NAYY 4x25 RE	NAYY 4x35 RE	NAYY 4x70 SE	NAYY 4x150 SE	NAYY 4x240	NAYY 4x300	NFA2X 4x25	NFA2X 4x95
Urban	Old	New	Old	New				
Suburban		New		New			Old	Old
I_{rated} (A)	102	123	179	275	364	419	107	245
	[112]	[112]	[112]	[112]	[113]	[113]	[114]	[114]
I_{max} (kA)	1.90	2.66	5.32	11.40	18.2	22.8	1.30	5.20
	[113]	[113]	[113]	[113]	[113]	[113]	[114]	[114]
R' (Ω/km)	1.200	1.040	0.443	0.248	0.125	0.1	1.200	0.320
	[113]	[113]	[113]	[113]	[113]	[113]	[115]	[115]
R'_0 (Ω/km)	4.800	4.160	1.772	0.992	0.5	0.4	4.800	1.280
	[116]	[116]	[116]	[116]	[116]	[116]	[116]	[116]
X'_L (Ω/km)	0.088	0.086	0.082	0.080	0.080	0.088	0.077	0.072
	[113]	[113]	[113]	[113]	[113]	[113]	[117]	[117]
X'_{L0} (Ω/km)	0.352	0.344	0.328	0.320	0.320	0.352	0.308	0.287
	[116]	[116]	[116]	[116]	[116]	[116]	[116]	[116]
C' (µF/km)	0.300	0.320	0.350	0.450	0.550	0.620	0.131	0.144
	[115]	[115]	[115]	[115]	[115]	[115]	[116]	[116]
C'_0 (µF/km)	0.180	0.192	0.210	0.270	0.330	0.372	0.016	0.017
	[116]	[116]	[116]	[116]	[116]	[116]	[116]	[116]

B.4 Transformer Parameters

Table B.6: Transformer parameters

	Suburban		Urban	
	new	old	new	old
$P_{nominal}$ (kVA)	630	400	630	630
V_{HV} (kV)	21	21	10.5	10.5
V_{LV} (kV)	0.42	0.42	0.42	0.42
uk (%)	4.00	4.00	4.00	4.00
ukr (%)	1.03	2.20	1.03	2.10
uk0 (%)	4.00	4.00	4.00	4.00
uk0r (%)	1.03	2.20	1.03	2.10

B.5 Grid topology

Table B.7: Classification of typical grid types according to [30]

	Grid Type	Transformer power	Load density	Cable	Feeder length
A	Urban	400 kVA 630 kVA	High	NAYY 4x120 NAYY 4x150 NAYY 4x185 NAYY 4x240	$\leq$ 300m
B	Block Buildings	400 kVA 630 kVA	High	NAYY 4x150 NAYY 4x185 NAYY 4x240	$\leq$ 300m
C	Business Park	400 kVA 630 kVA	Medium to High	NAYY 4x120 NAYY 4x150 NAYY 4x185 NAYY 4x240	$\leq$ 400m
D1	Detached Houses Old	160 kVA 250 kVA 400 kVA	Medium	Al/NF A2X 4x50 Al/NF A2X 4x70 Al/NF A2X 4x95	$\leq$ 400m
D2	Detached Houses New	160 kVA 250 kVA 400 kVA	Medium	NAYY 4x120 NAYY 4x150 NAYY 4x185	$\leq$ 400m
E	Village	160 kVA 250 kVA 400 kVA	Medium	Al/NF A2X 4x70 Al/NF A2X 4x95	$\leq$ 600m
F	Rural	100 kVA 160 kVA 250 kVA	Low to Medium	Al/NF A2X 4x70 Al/NF A2X 4x95	$\leq$ 1000m
G	Rural (doubly fed)	100 kVA 160 kVA 250 kVA	Medium	Al/NF A2X 4x25 Al/NF A2X 4x35 Al/NF A2X 4x50 Al/NF A2X 4x70 Al/NF A2X 4x95	$>$ 800m

C Appliance Characteristics

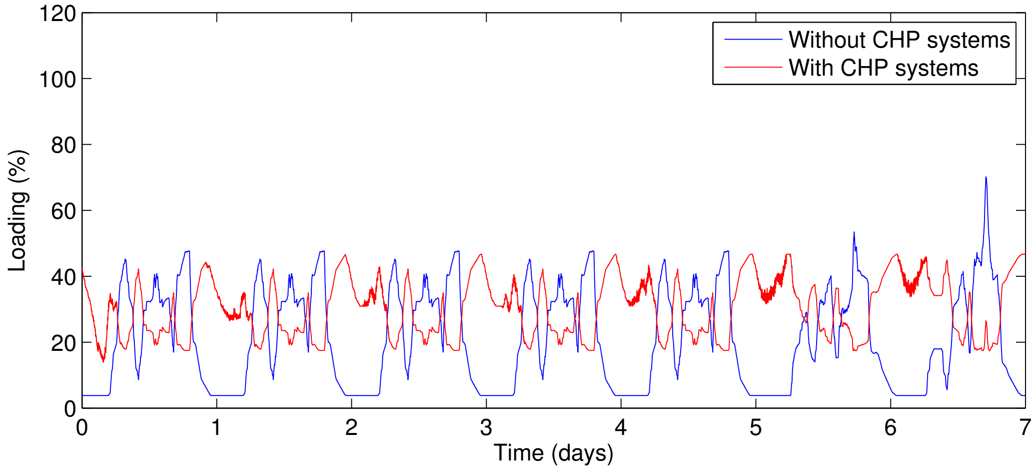


Figure C.1: Transformer loading characteristic of CHP systems (suburban old grid)

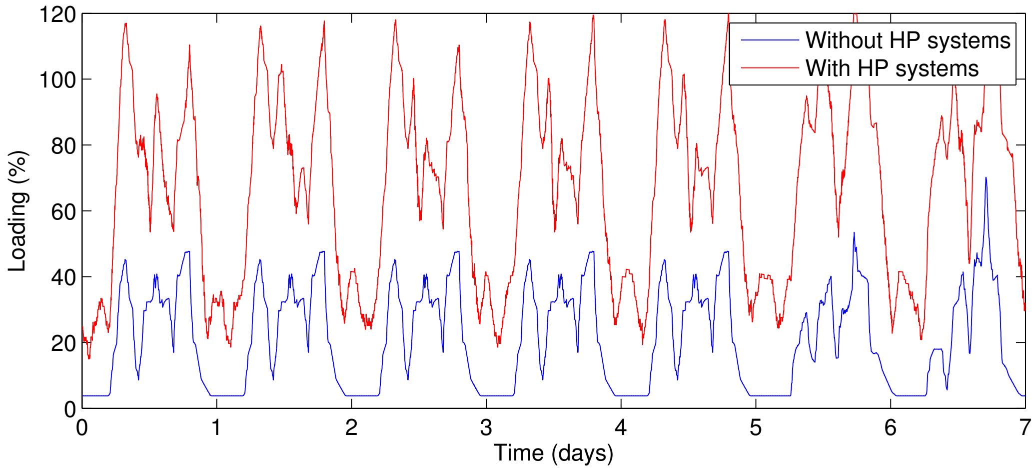


Figure C.2: Transformer loading characteristic of HP systems (suburban old grid)

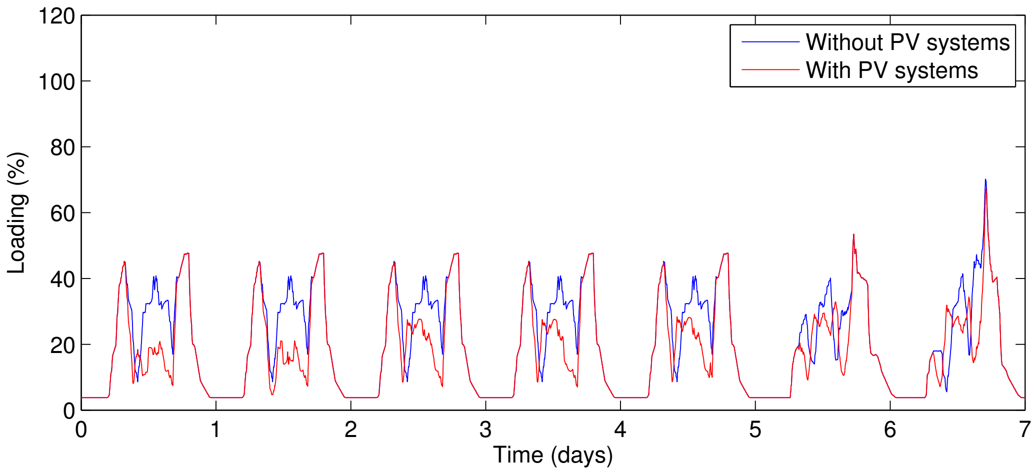


Figure C.3: Transformer loading characteristic of PV systems (suburban old grid)

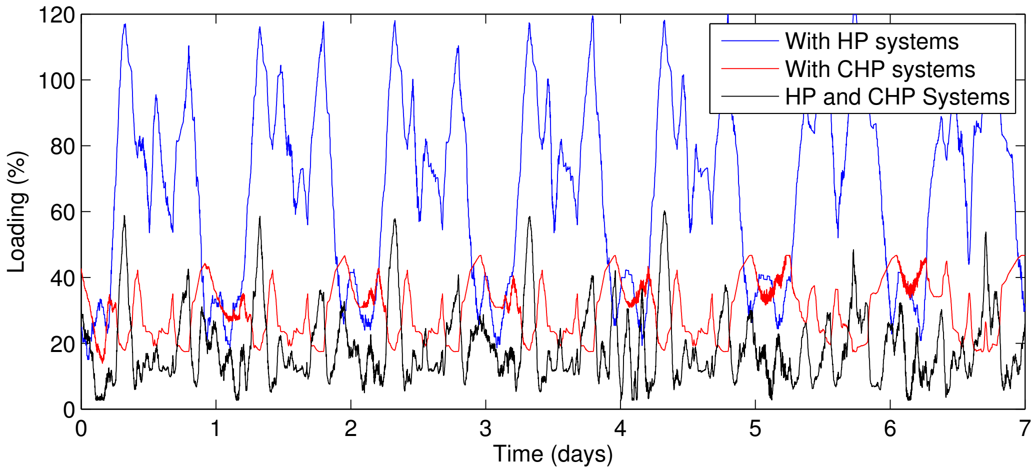


Figure C.4: Transformer loading characteristic of combined CHP and HP systems (suburban old grid)

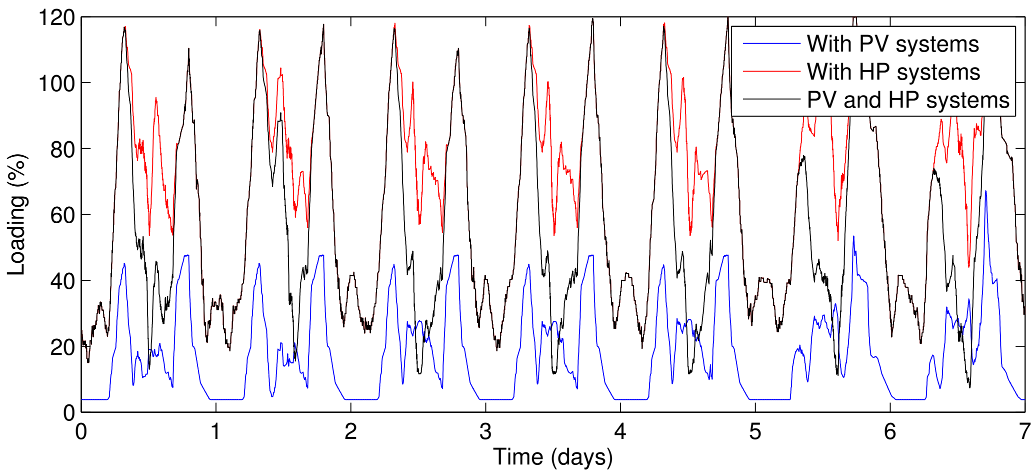


Figure C.5: Transformer loading characteristic of combined PV and HP systems (suburban old grid)

D 2020 Scenario

D.1 Literature 2020 Scenario Development

Table D.1: Literature sources for 2020 scenario development

Year	Study	Publisher	CHP	HP	PV	
	German Federal Government					
2009	Die Entwicklung der Energiemärkte bis 2030 - Energieprognose 2009	BMWi			X	[118]
2010	Energieszenarien für ein Energiekonzept der Bundesregierung	BMWi			X	[119]
2010	Leitstudie im Auftrag des Bundesministeriums für Umwelt	BMU	X	X	X	[86]
2010	National Renewable Energy Action Plan - Germany		X	X	X	[120]
2011	Energieszenarien 2011	BMWi			X	[121]
2012	Leitstudie im Auftrag des Bundesministeriums für Umwelt	BMU	X	X	X	[80]
2012	Antwort auf kleine Anfrage der Fraktion Bündnis 90 / die Grünen	Bundestag		X		[87]
	Industrial Associations					
2009	Strom-Ausbauprognose der Erneuerbare-Energien-Branche	BEE			X	[122]
2009	Ausbauprognose der Erneuerbare-Energien-Branche Teil 2: Wärmeversorgung 2020	BEE		X		[123]
2011	Branchenprognose 2011	BWP		X		[84]
2012	Micro-CHP Market Statistics & Forecast	Delta EE	X			[82]
	Universities / Institutes					
2009	Dynamische Simulation der Stromversorgung in Deutschland nach dem Ausbauszenario der Erneuerbaren-Energien-Branche	IWES			X	[124]
2010	Grid Study II. Integration of Renewable Energy Sources in the German Power supply System from 2015 - 2020 with an Outlook to 2025	dena			X	[125]
2011	Cogeneration Case Studies Handbook	CODE	X			[126]
2012	Ökonomische und ökologische Analyse von Brennstoffzellen Heizgeräten	IFEU	X			[127]
2013	Estimation of the economic addressable market of micro-CHP and heat pumps based on the status of the residential building sector in Germany	MICROGEN	X	X		[83]
	Federal Network Agency					
2013	Netzentwicklungsplan der Bundesnetzagentur - Draft 2013	BNA			X	[81]
	Non Governmental Organisations (NGOs)					
2009	Plan B 2050	Greenpeace	X		X	[128]
2009	Modell Deutschland: Klimaschutz bis 2050	WWF		X		[129]

D.2 Distribution of Appliances in the Grids

Table D.2: Distribution of Appliances in Grid Suburban New

House	HP	CHP	PV	House	HP	CHP	PV	House	HP	CHP	PV	House	HP	CHP	PV
1			X	43	X			85			X	127			
2	X		X	44			X	86	X		X	128	X		X
3	X		X	45			X	87				129			X
4				46	X		X	88	X		X	130	X		X
5			X	47				89			X	131	X		
6	X		X	48	X		X	90	X		X	132		X	
7			X	49			X	91	X			133			X
8	X			50	X		X	92			X	134	X		X
9			X	51	X			93	X		X	135	X		X
10	X		X	52			X	94	X		X	136	X		
11	X		X	53	X		X	95		X		137			X
12	X			54	X		X	96	X		X	138	X		X
13			X	55				97	X		X	139	X		
14	X		X	56	X		X	98	X		X	140			X
15		X	X	57			X	99	X			141			X
16	X			58	X		X	100			X	142	X		X
17	X		X	59	X			101			X	143			X
18	X		X	60			X	102	X		X	144	X		
19	X		X	61			X	103				145			X
20				62	X		X	104	X		X	146	X		X
21			X	63		X		105			X	147	X		X
22	X		X	64	X		X	106	X		X	148	X		
23	X		X	65			X	107	X			149			X
24	X			66	X		X	108			X	150	X		X
25			X	67	X			109			X	151			X
26	X		X	68			X	110	X		X	152	X		
27	X			69	X		X	111				153			X
28			X	70	X		X	112	X		X	154	X		X
29	X		X	71	X			113			X	155	X		X
30	X		X	72	X		X	114	X		X	156	X		
31				73			X	115	X			157		X	X
32	X		X	74	X		X	116			X	158	X		X
33		X	X	75	X			117		X		159	X		X
34	X		X	76			X	118	X		X	160	X		
35	X			77			X	119				161			X
36			X	78	X		X	120	X		X	162	X		X
37	X		X	79				121	X		X	163	X		X
38	X		X	80	X		X	122	X		X	164	X		
39				81			X	123	X			165			X
40	X		X	82	X		X	124			X	166	X		X
41	X		X	83	X			125	X		X				
42	X		X	84			X	126	X		X				

Table D.3: Distribution of Appliances in Grid Suburban Old

House	HP	CHP	PV	House	HP	CHP	PV	House	HP	CHP	PV	House	HP	CHP	PV
1				43				85				127			
2				44			X	86				128	X		X
3				45				87				129			
4				46				88				130			
5			X	47				89			X	131	X		
6				48			X	90				132			
7				49				91				133			X
8	X			50				92				134			
9			X	51				93				135			
10				52			X	94				136			
11				53				95	X			137			
12				54				96			X	138			X
13				55				97				139			
14				56	X		X	98				140			X
15			X	57				99				141			
16				58				100				142	X		
17				59				101			X	143			X
18				60			X	102				144			
19			X	61				103				145			
20				62				104				146			
21				63				105				147			X
22				64				106				148			
23				65			X	107				149			
24				66				108				150			
25			X	67				109			X	151			X
26				68				110				152			
27	X			69				111				153			
28				70				112				154			
29				71				113			X	155			
30			X	72			X	114				156			
31				73				115				157			
32				74				116				158			X
33				75				117				159			
34				76				118			X	160	X		
35				77			X	119				161			
36			X	78				120				162			
37				79	X			121				163			X
38				80				122				164			
39				81				123				165			
40			X	82			X	124			X	166			X
41				83				125							
42				84				126							

Table D.4: Distribution of Appliances in Grid Urban New

House	HP	CHP	PV	House	HP	CHP	PV	House	HP	CHP	PV	House	HP	CHP	PV
1	X			10		X		19	X			28		X	X
2		X		11	X		X	20		X	X	29	X		
3	X		X	12		X		21	X			30	X		
4		X		13		X		22		X		31		X	X
5	X			14	X			23	X			32	X		
6	X			15		X	X	24			X	33		X	
7		X	X	16	X			25				34	X		X
8				17		X		26		X		35			
9	X			18	X			27	X			36		X	

Table D.5: Distribution of Appliances in Grid Urban Old

House	HP	CHP	PV	House	HP	CHP	PV	House	HP	CHP	PV	House	HP	CHP	PV
1				10				19				28			
2				11				20		X		29			
3				12				21				30			
4				13				22				31			
5			X	14				23				32			
6				15				24			X	33			
7				16				25				34			
8				17				26				35			
9				18				27				36			

Table D.6: Appliance parametrisation for different house types

	Detached House			Apartment Building	
Power	New	Refurbished	Old	New	Old
Stirling	1 kW_{el}	1 kW_{el}	1 kW_{el}	-	-
ICE	1 kW_{el}	1 kW_{el}	1 kW_{el}	5 kW_{el}	5 kW_{el}
SOFC	0.7 kW_{el}	0.7 kW_{el}	0.7 kW_{el}	-	-
HP (Air/Water)	8 kW_{th}	10 kW_{th}	13 kW_{th}	20 kW_{th}	-
HP (Brine/Water)	8 kW_{th}	10 kW_{th}	13 kW_{th}	20 kW_{th}	-
PV	4 kW_{el}	6 kW_{el}	6 kW_{el}	6 kW_{el}	6 kW_{el}

D.3 Results

D.3.1 Suburban New

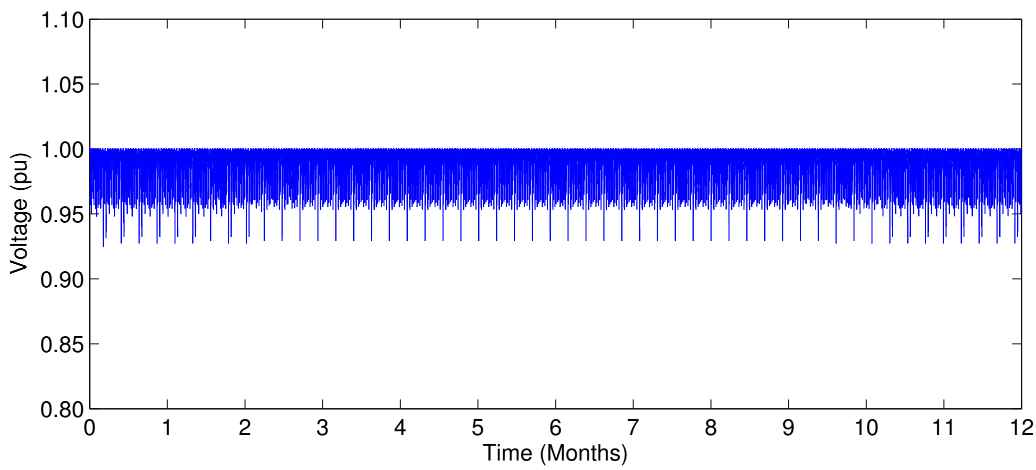


Figure D.1: Voltage at the end of the longest feeder in suburban grid new w/o appliances

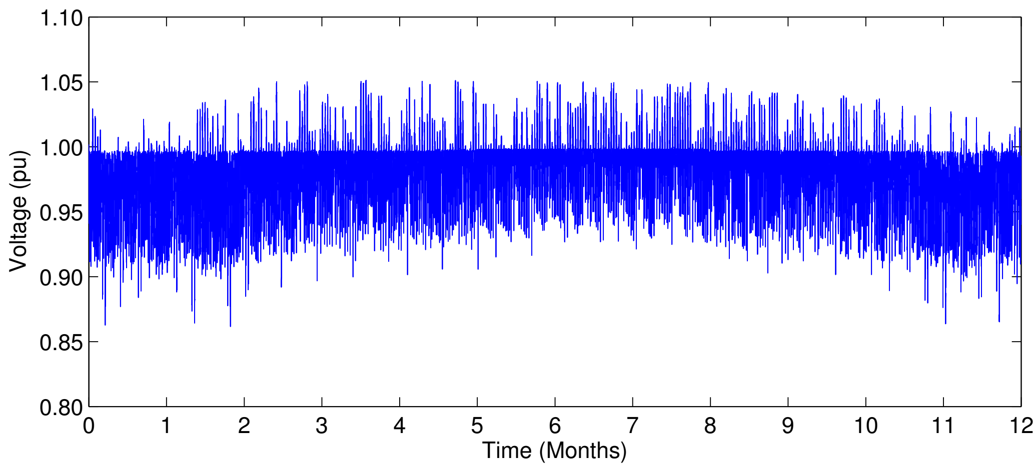


Figure D.2: Voltage at the end of the longest feeder in suburban grid new w/ appliances

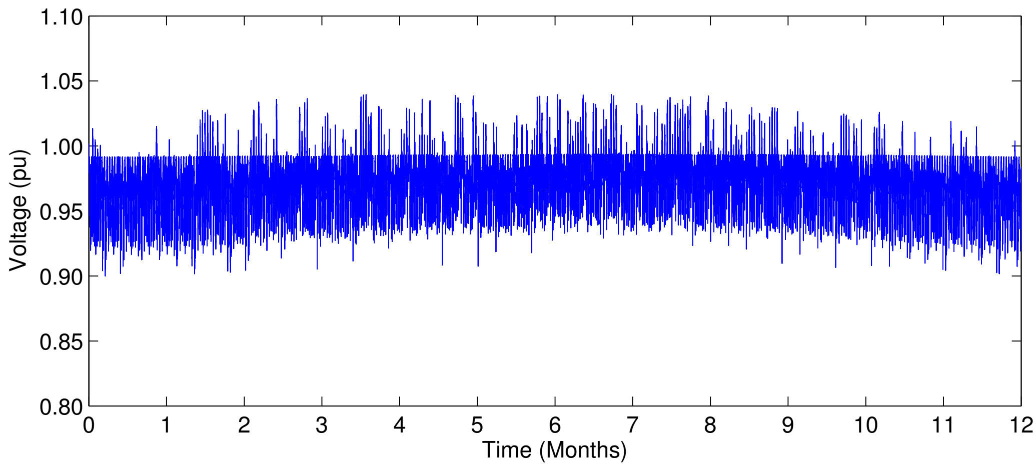


Figure D.3: Voltage at the end of the longest feeder in suburban grid new w/o appliances including MV grid fluctuations

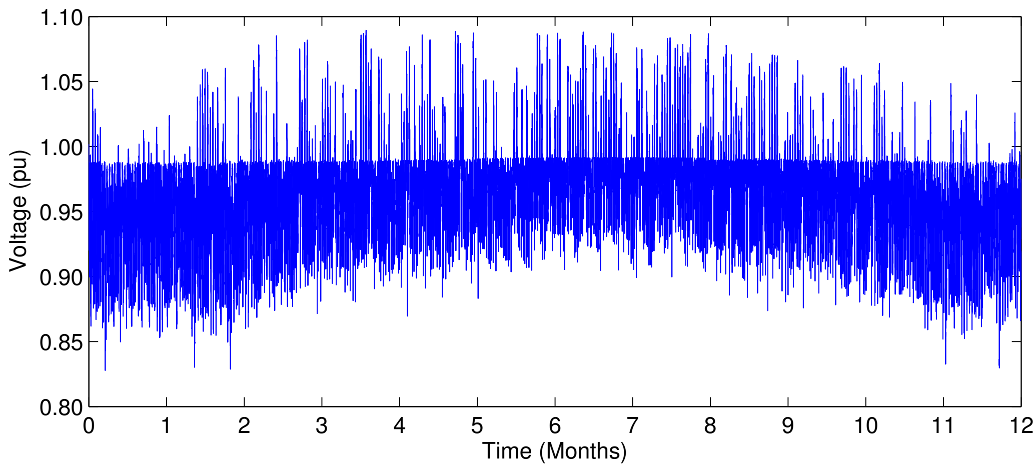


Figure D.4: Voltage at the end of the longest feeder in suburban grid new w/ appliances and MV grid voltage fluctuations

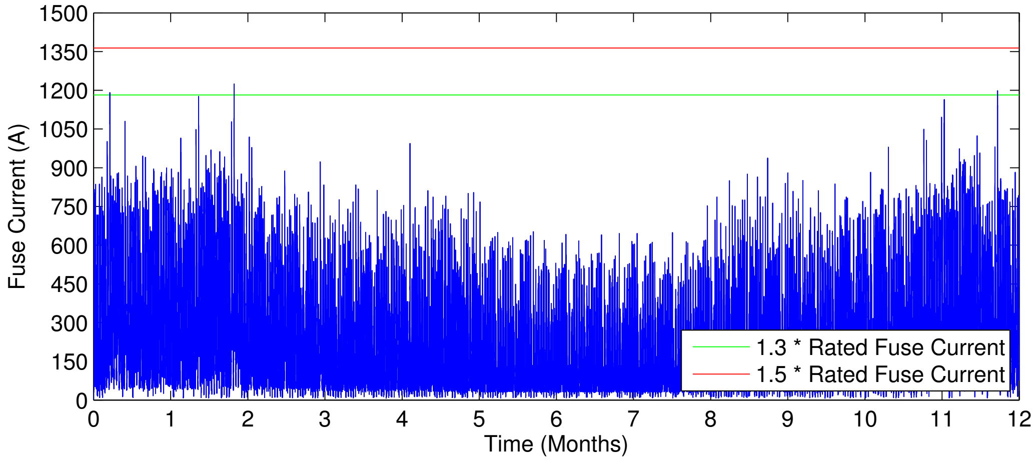


Figure D.5: Current at transformer in suburban grid new w/ appliances and MV grid voltage fluctuations

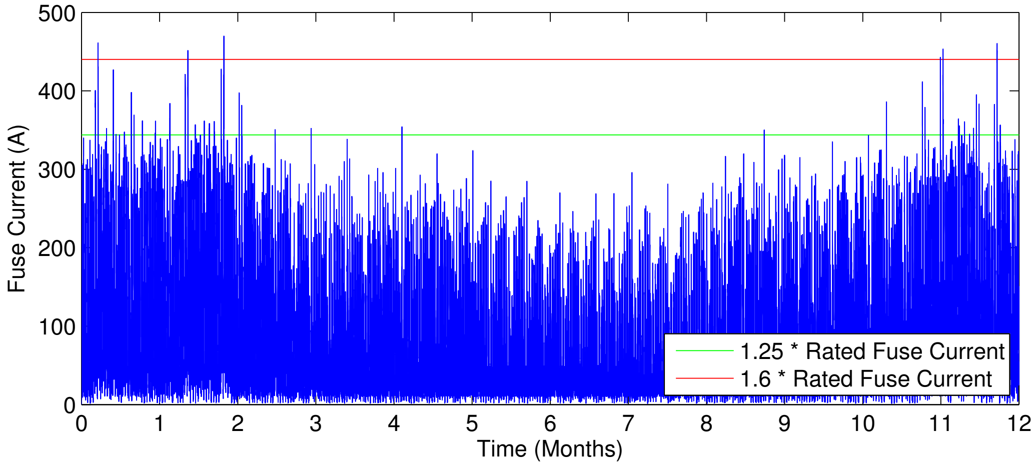


Figure D.6: Current at beginning of considered feeder in suburban grid new w/ appliances and MV grid voltage fluctuations

D.3.2 Suburban Old

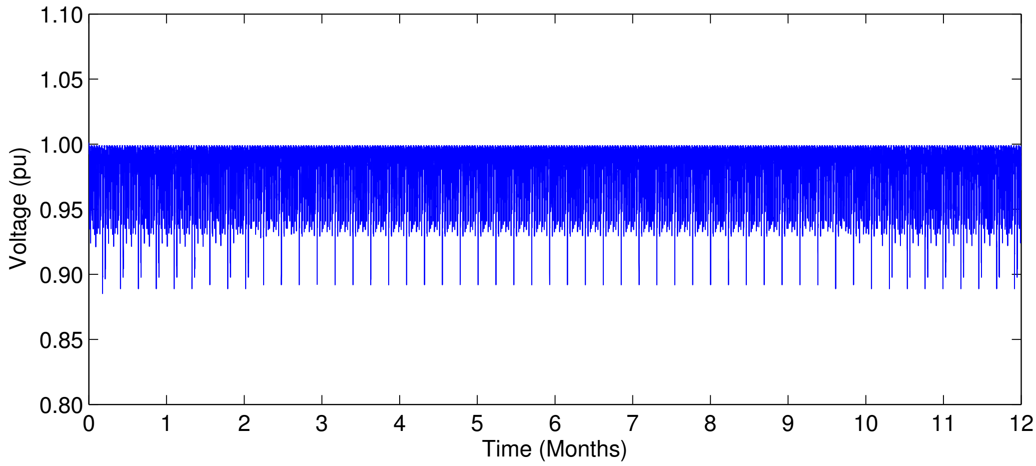


Figure D.7: Voltage at the end of the longest feeder in suburban grid old w/o appliances

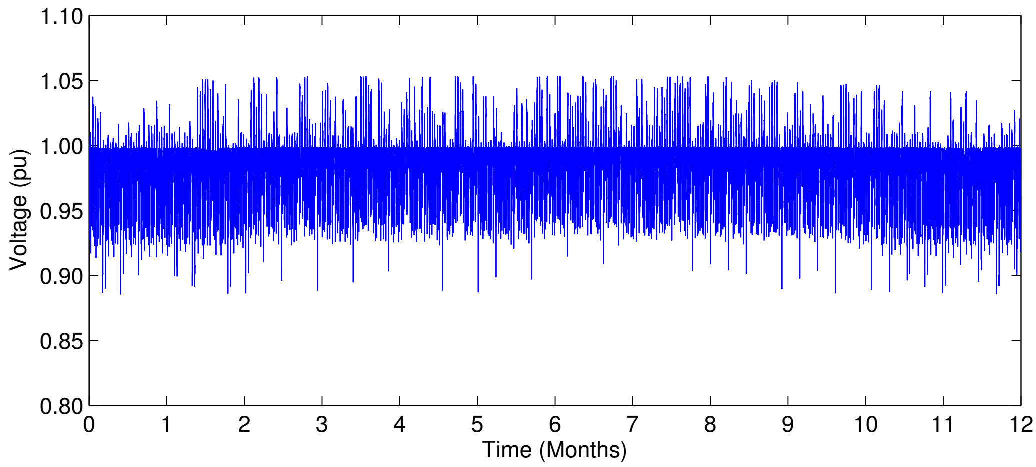


Figure D.8: Voltage at the end of the longest feeder in suburban grid old w/ appliances

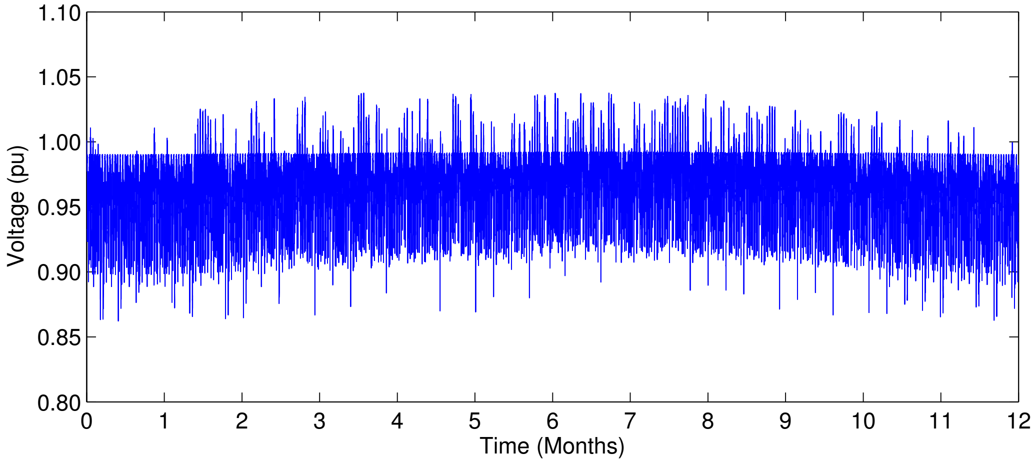


Figure D.9: Voltage at the end of the longest feeder in suburban grid old w/o appliances including MV grid fluctuations

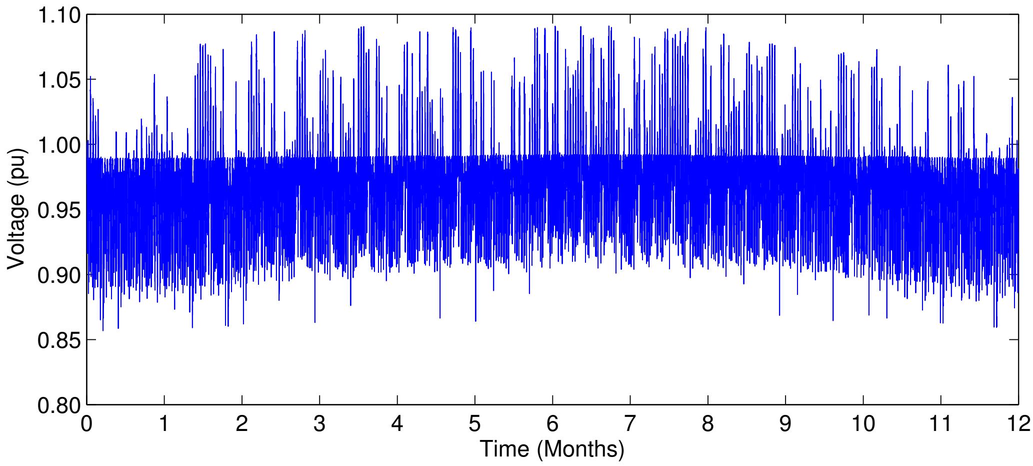


Figure D.10: Voltage at the end of the longest feeder in suburban grid old w/ appliances and MV grid voltage fluctuations

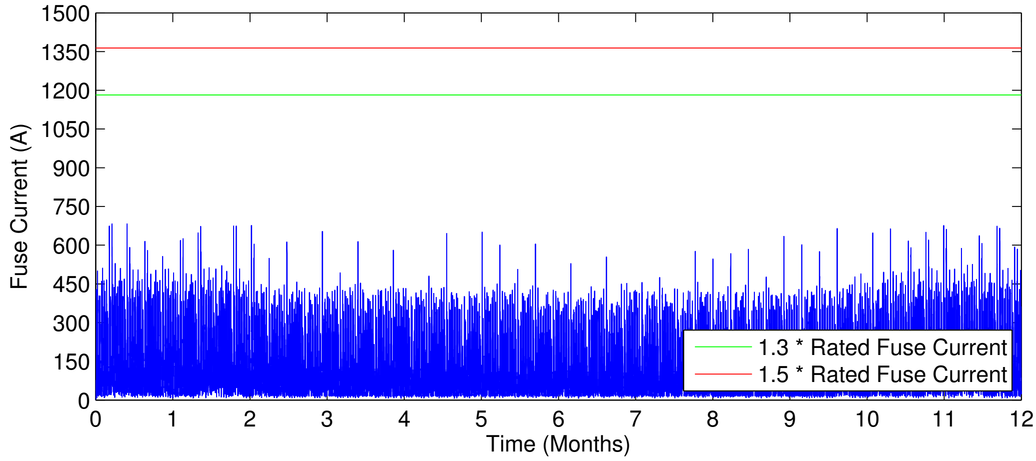


Figure D.11: Current at transformer in suburban grid old w/ appliances and MV grid voltage fluctuations

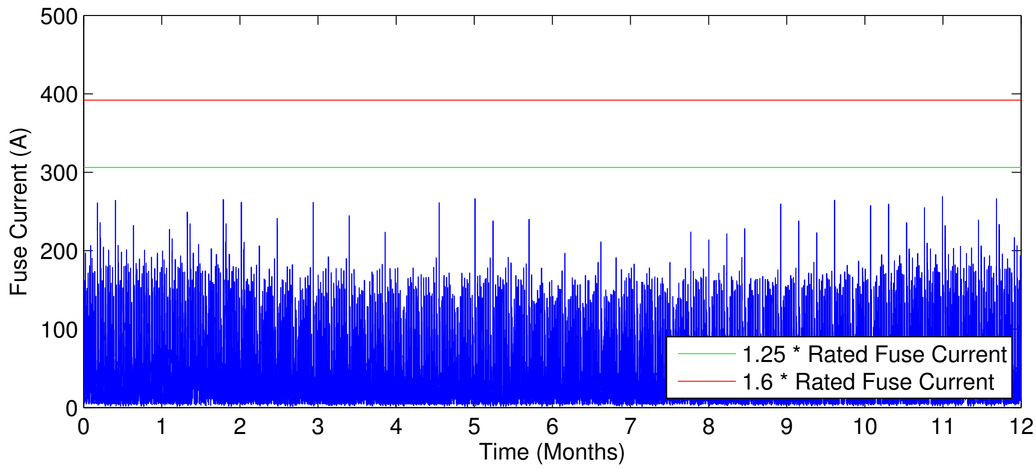


Figure D.12: Current at beginning of considered feeder in suburban grid old w/ appliances and MV grid voltage fluctuations

D.3.3 Urban New

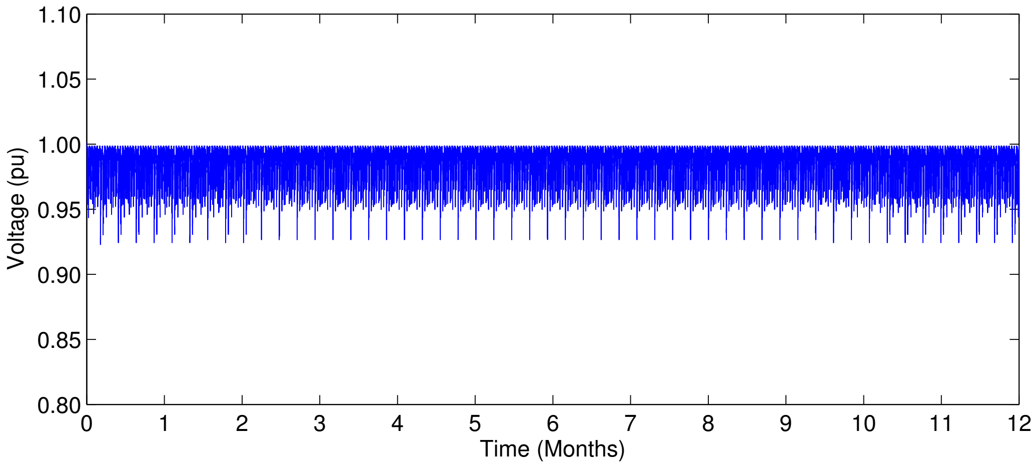


Figure D.13: Voltage at the end of the longest feeder in urban grid new w/o appliances

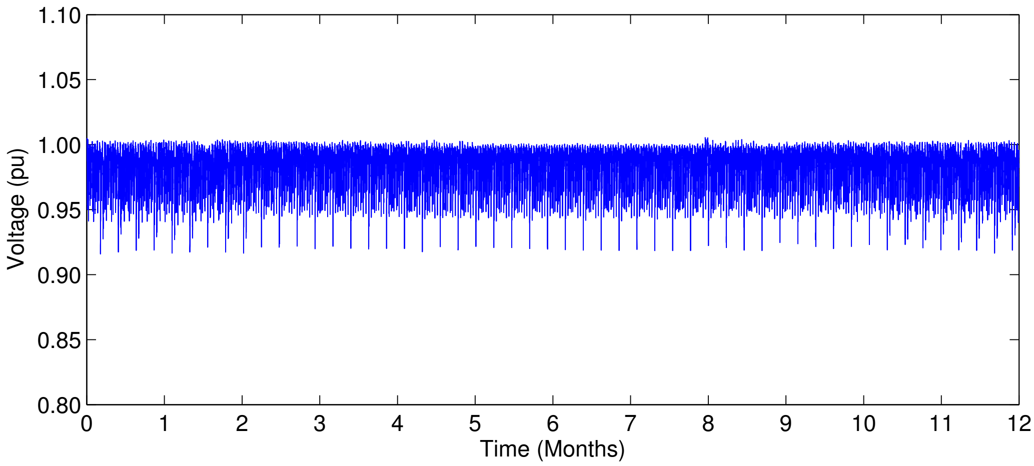


Figure D.14: Voltage at the end of the longest feeder in urban grid new w/ appliances

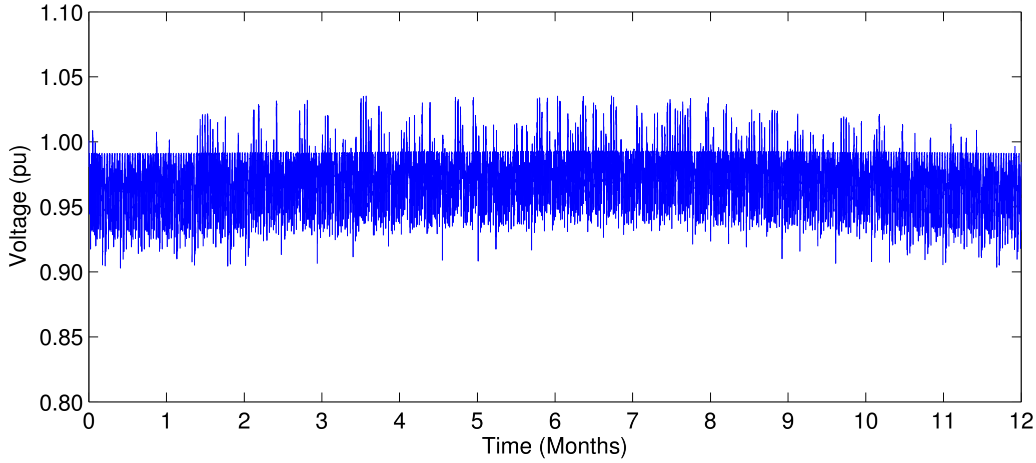


Figure D.15: Voltage at the end of the longest feeder in urban grid new w/o appliances including MV grid fluctuations

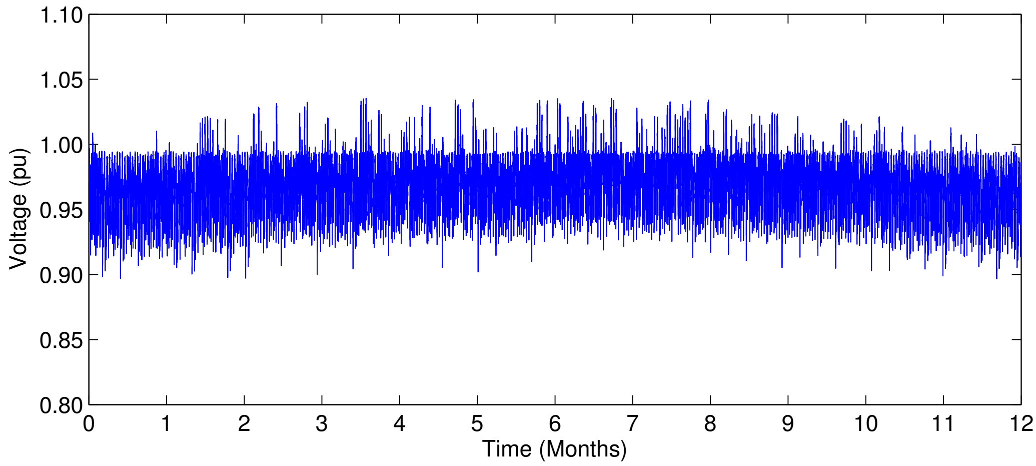


Figure D.16: Voltage at the end of the longest feeder in urban grid new w/ appliances and MV grid voltage fluctuations

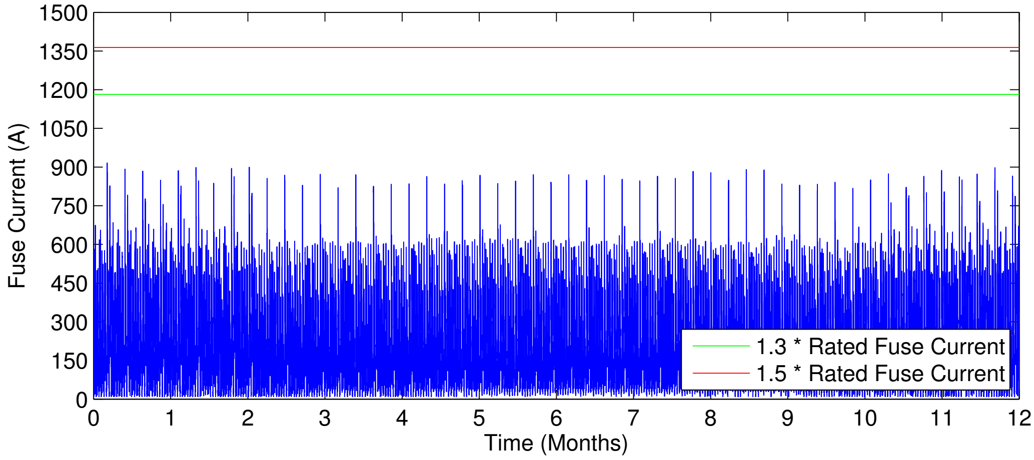


Figure D.17: Current at transformer in urban grid new w/ appliances and MV grid voltage fluctuations

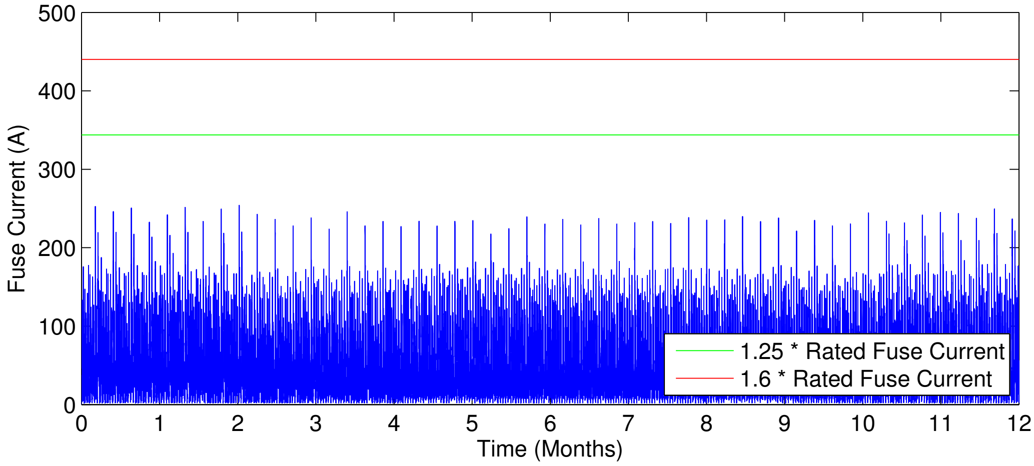


Figure D.18: Current at beginning of considered feeder in urban grid new w/ appliances and MV grid voltage fluctuations

D.3.4 Urban Old

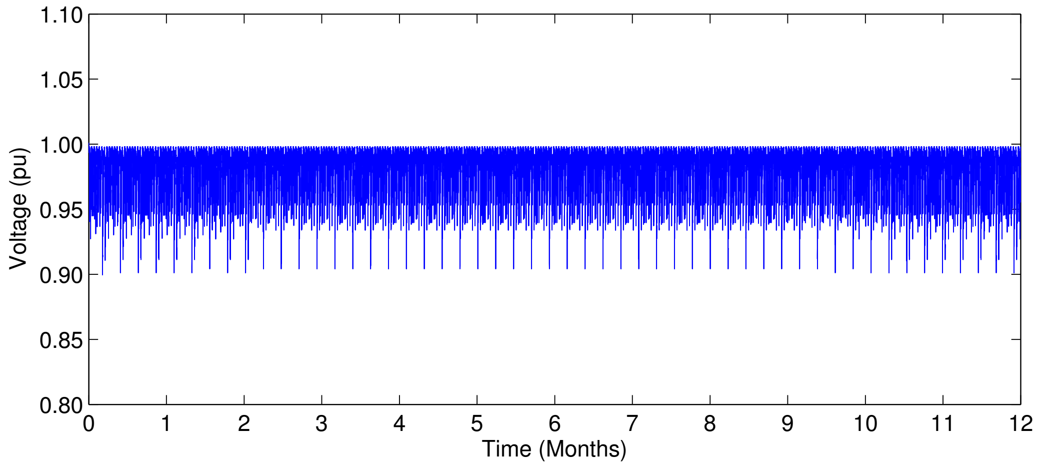


Figure D.19: Voltage at the end of the longest feeder in urban grid old w/o appliances

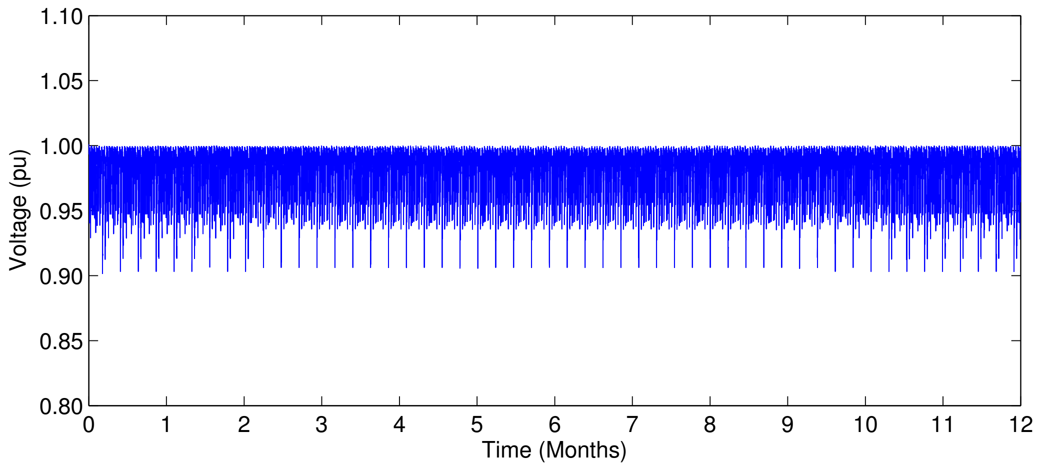


Figure D.20: Voltage at the end of the longest feeder in urban grid old w/ appliances

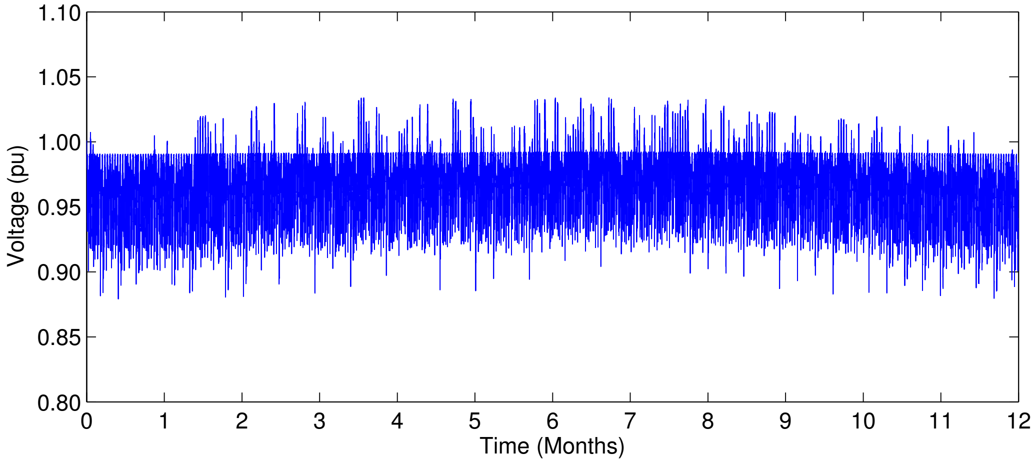


Figure D.21: Voltage at the end of the longest feeder in urban grid old w/o appliances including MV grid fluctuations

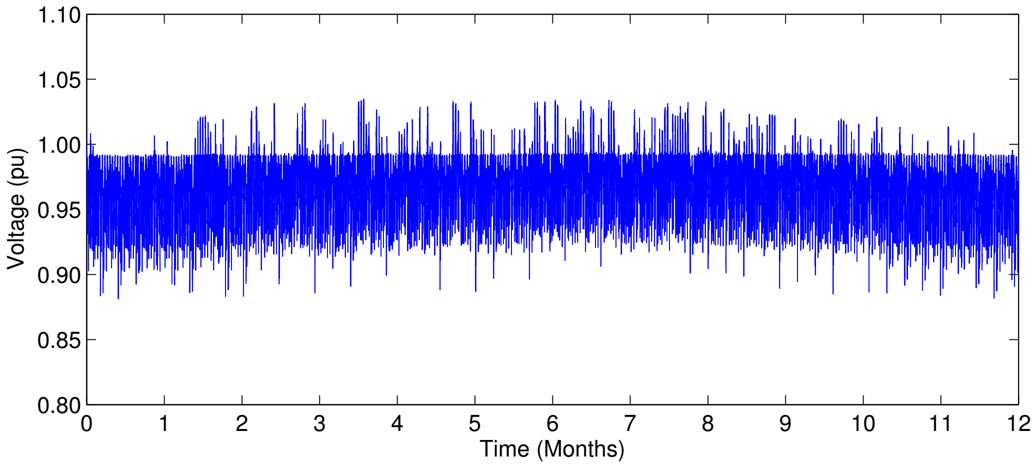


Figure D.22: Voltage at the end of the longest feeder in urban grid old w/ appliances and MV grid voltage fluctuations

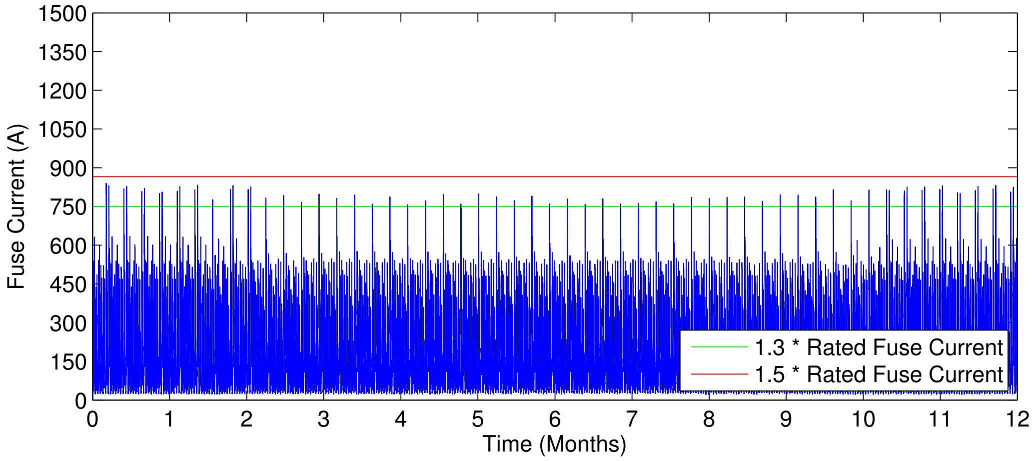


Figure D.23: Current at transformer in urban grid old w/ appliances and MV grid voltage fluctuations

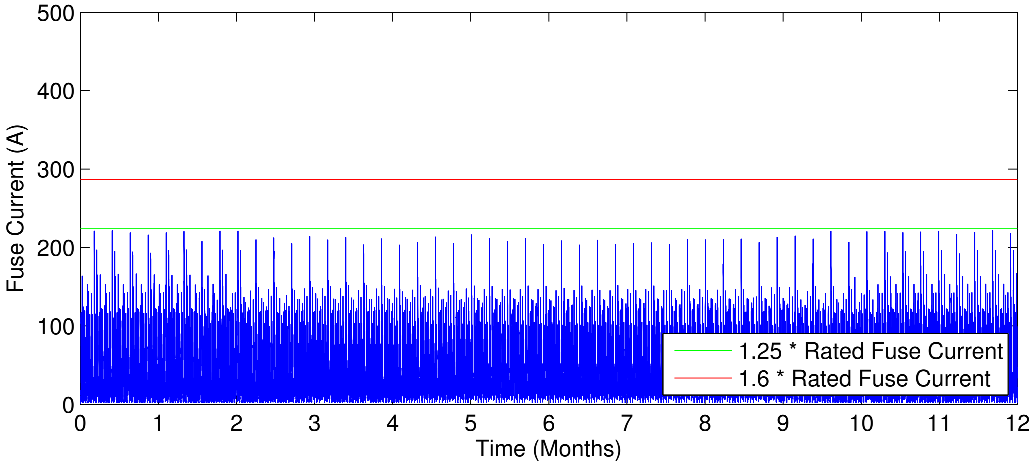


Figure D.24: Current at beginning of considered feeder in urban grid old w/ appliances and MV grid voltage fluctuations

E Measures

E.1 DSO Based

E.1.1 DG-FACTS

Table E.1: Parameters of DG-FACTS controller

Parameter	a	b	c	d
Active Power Control	0.005	0.085	0.085	0.005
Reactive Power Control	0.01	0.07	0.07	0.01

Table E.2: Dimensioning of DG-FACTS device

			Usable battery capacity (kWh)	
	Active power (kW)	Reactive power (kvar)	overvoltage regulation	undervoltage regulation
Value	99	40	0	280

E.2 End-User Based

E.2.1 Reactive power control - Generators

Table E.3: Parameters of cosV09 and cosV095 controller

Parameter	Maximum power factor overexcited	Maximum power factor underexcited	a	b	c	d
cosV09	0.9	0.9	0.01	0.08	0.08	0.01
cosV095	0.95	0.95	0.01	0.08	0.08	0.01

E.2.2 Reactive power control - Demand side

Table E.4: Parameters of cosV09HP and cosV095HP controller

Parameter	Maximum power factor overexcited	Maximum power factor underexcited	a	b	c	d
cosV09HP	0.9	0.9	0.01	0.08	0.08	0.01
cosV095HP	0.95	0.95	0.01	0.08	0.08	0.01

E.2.3 Distributed storage for voltage control

Table E.5: Parameters of distributed battery voltage controller

Parameter	a	b	c	d	Max. power sco (kW)
Active Power Control	0	0.09	0.09	0	3.2

F Data Basis for Economic Evaluation

Table F.1: VAT status of different costs for the end-user

	Status	CHP	PV	HP	Boiler	Battery	Grid
Grid gas	VAT	VAT			VAT		
Grid electricity	VAT						VAT
Grid losses	no VAT						
PV feed-in	no VAT		no VAT				
CHP feed-in	no VAT	no VAT					
CHP generation	no VAT	no VAT					
CHP avoided grid fees	no VAT	no VAT					
CHP gas energy tax refund	no VAT	no VAT					
Inverter	no VAT	VAT	no VAT	VAT		VAT	
Battery	no VAT					VAT	
Building FACTS	no VAT						
OLTC	no VAT						
Cable	no VAT						

Table F.2: VAT status of different costs for the DSO

	Status	Cables	FACTS	OLTC	Losses
Grid gas	VAT				
Grid electricity	VAT				
Grid losses	no VAT				no VAT
PV feed-in	no VAT				
CHP feed-in	no VAT				
CHP generation	no VAT				
CHP avoided grid fees	no VAT				
CHP gas energy tax refund	no VAT				
Inverter	no VAT		no VAT		
Battery	no VAT		no VAT		
Building FACTS	no VAT		no VAT		
OLTC	no VAT			no VAT	
Cable	no VAT	no VAT			

Table F.3: Annuity overview

A	C	T (years)	
A_{cable_invest}	$C_{cable} \cdot l_{cable}$	40	[53]
A_{OLTC_invest}	C_{OLTC}	40	[10]
$A_{DG-FACTS\_inverter\_invest}$	$C_{inverter} \cdot S_{DG-FACTS}$	15	[130]
$A_{DG-FACTS\_battery\_invest}$	$C_{battery} \cdot Capacity_{DG-FACTS}$	20	[131]
$A_{DG-FACTS\_building\_invest}$	$C_{building}$	40	[10]
$A_{DG-FACTS\_losses}$	$C_{grid\_losses} \cdot E_{DG-FACTS\_losses}$	0.038	
A_{grid_losses}	$C_{grid\_losses} \cdot \Delta E_{grid\_losses}$	0.038	
A_{HP_invest}	$C_{inverter} \cdot \Delta S_{HP}$	15	[130]
A_{CHP_invest}	$C_{inverter} \cdot \Delta S_{CHP}$	15	[130]
$A_{CHP\_operation}$	$(C_{CHP\_feed-in} + C_{grid\_fees}) \cdot \Delta E_{CHP\_feed-in} + C_{CHP\_generation} \cdot \Delta E_{CHP\_generation}$	0.038	
A_{PV_invest}	$C_{inverter} \cdot \Delta S_{PV}$	15	[130]
$A_{PV\_feed-in}$	$C_{PV\_feed-in} \cdot \Delta E_{PV\_feed-in}$	0.038	
$A_{storage\_inverter\_invest}$	$C_{inverter} \cdot S_{storage}$	15	[130]
$A_{storage\_battery\_invest}$	$C_{battery} \cdot Capacity_{storage}$	20	[131]
$A_{electricity\_consumption}$	$C_{electricity\_grid} \cdot \Delta E_{electricity\_grid}$	0.038	
$A_{gas\_consumption}$	$C_{gas} \cdot \Delta E_{gas\_grid} + C_{gas\_tax} \cdot \Delta E_{gas\_CHP} / \eta_{\text{CHP\_el}}$	0.038	

G Results

G.1 Reference Scenario

Table G.1: Voltage level and equipment loading in reference scenario

Measure	V_{max}	V_{min}	Trafo load	Cable load
Reference	1.09	0.83	OK	OK
Expansion	1.05	0.92	OK	OK
Cable	1.07	0.90	OK	OK
Feeder 8	1.09	0.86	OK	OK
OLTC	1.05	0.90	OK	OK
DG-FACTS	1.09	0.91	OK	OK
VDE	1.09	0.83	OK	OK
EEG	1.08	0.83	OK	OK
APC	1.09	0.83	OK	OK
APCth	1.09	0.83	OK	OK
cosP	1.08	0.83	OK	OK
cosV09	1.09	0.83	OK	OK
cosV095	1.09	0.83	OK	OK
DSM	1.09	0.89	OK	OK
DSMth	1.09	0.89	OK	OK
cosP09HP	1.10	0.86	OK	OK
cosP095HP	1.10	0.85	OK	OK
cosV09HP	1.09	0.85	OK	OK
cosV095HP	1.09	0.85	OK	OK
sco	1.09	0.83	OK	OK
stoV	1.09	0.90	OK	OK
SotA	1.08	0.83	OK	OK
SotA + Expansion	1.05	0.92	OK	OK
SotA + Cable	1.05	0.90	OK	OK
SotA + OLTC	1.05	0.90	OK	OK
SotA + DG-FACTS	1.07	0.91	OK	OK
SotA + DSM	1.08	0.89	OK	OK
SotA + stoV	1.07	0.90	OK	OK

Table G.2: Economic results reference scenario

	End-User Costs (%)		DSO Costs (%)		Total (%)
Measure	Operation	Invest	Operation	Invest	
Expansion	0	0	-0.22	1.18	0.95
Cable	0	0	-0.30	1.75	1.44
Feeder 8	0	0	-0.17	0.31	0.13
OLTC	0	0	-0.05	0.40	0.36
DG-FACTS	0	0	-0.07	8.69	8.62
VDE	0	0	0	0	0
EEG	0.55	-1.54	-0.01	0	-0.99
APC	0	0	0	0	0
APCth	0.02	0	0	0	0
cosP	0.14	1.69	0.01	0	1.84
cosV09	0.20	2.48	0	0	2.68
cosV095	0.13	1.69	0	0	1.83
DSM	0.49	0	-0.07	0	0.42
DSMth	0.76	0	-0.07	0	0.70
cosP09HP	1.08	1.47	-0.56	0	1.97
cosP095HP	0.69	1.01	-0.39	0	1.30
cosV09HP	0.85	1.47	-0.08	0	2.24
cosV095HP	0.58	1.01	-0.07	0	1.53
sco	-10.62	10.82	-0.10	0	0.09
stoV	-8.94	41.22	-0.04	0	32.26
SotA	0.69	-0.35	0	0	0.34
SotA + Expansion	0.69	-0.35	-0.23	1.18	1.30
SotA + Cable	0.69	-0.35	-0.30	1.75	1.78
SotA + OLTC	0.69	-0.35	-0.05	0.40	0.70
SotA + DG-FACTS	0.69	-0.35	-0.08	8.69	8.95
SotA + DSM	1.26	-0.35	-0.07	0	0.84
SotA + stoV	-8.12	40.87	-0.03	0	32.75

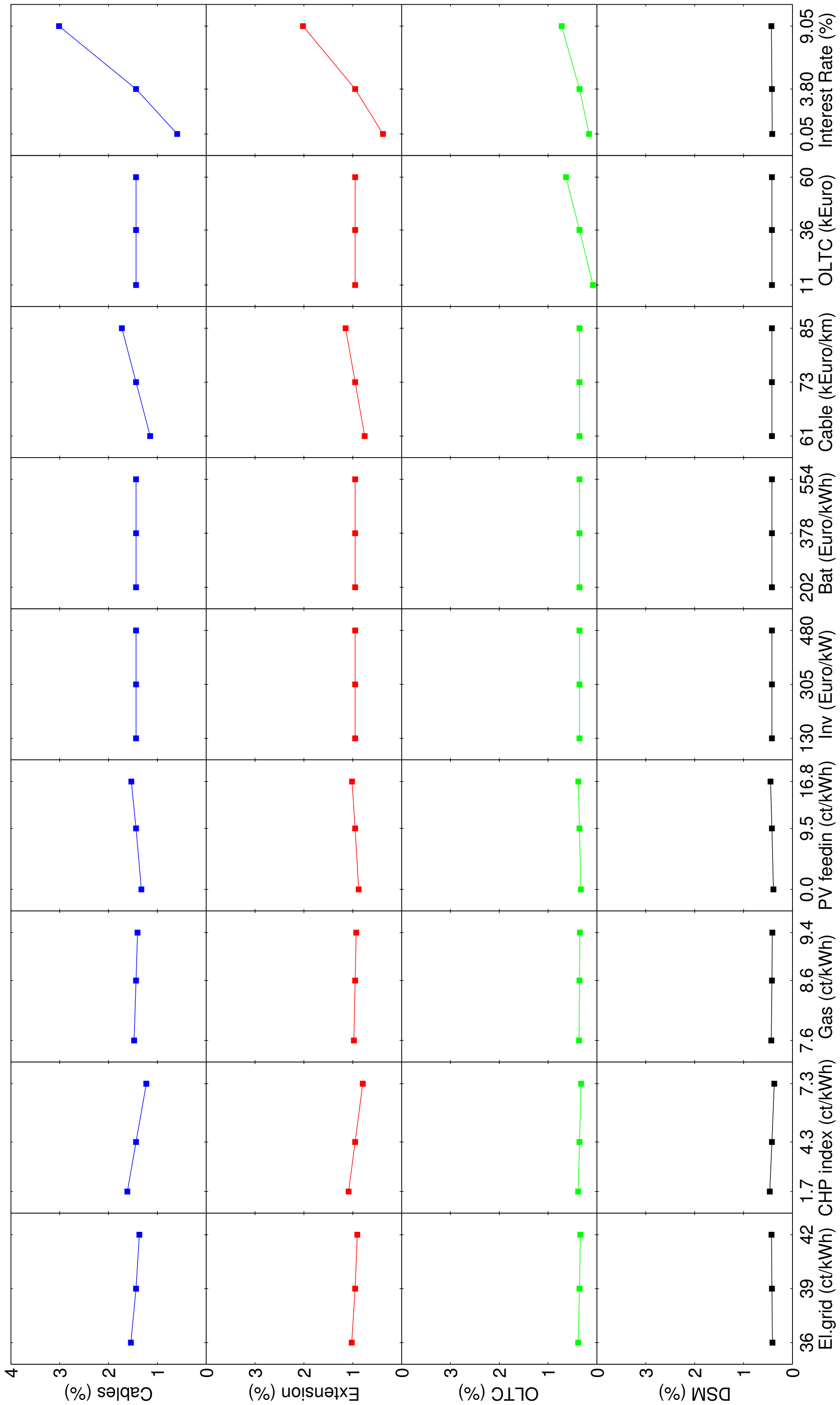


Figure G.1: Sensitivity analysis of the economic evaluation in reference scenario regarding the anticipated prices. Costs for measures are shown relative to end-user costs

G.2 Maximum PV Scenario

Table G.3: Voltage level and equipment loading in maximum PV scenario

Measure	V_{max}	V_{min}	Trafo load	Cable load
Reference	1.16	0.84	OK	overload
Expansion	1.10	0.90	OK	OK
Cable	1.10	0.90	OK	OK
Feeder 8	1.10	0.87	OK	OK
OLTC	1.08	0.93	OK	OK
DG-FACTS	1.10	0.91	OK	OK
VDE	1.10	0.87	OK	OK
EEG	1.10	0.87	OK	OK
APC	1.10	0.87	OK	OK
APCth	1.10	0.87	OK	OK
cosP	1.10	0.87	OK	OK
cosV09	1.10	0.87	OK	OK
cosV095	1.10	0.87	OK	OK
DSM	1.10	0.90	OK	OK
DSMth	1.10	0.90	OK	OK
cosP09HP	1.10	0.89	OK	OK
cosP095HP	1.10	0.88	OK	OK
cosV09HP	1.10	0.88	OK	OK
cosV095HP	1.10	0.88	OK	OK
sco	1.10	0.87	OK	OK
stoV	1.10	0.90	OK	OK
SotA	1.10	0.87	OK	OK
SotA + Expansion	1.08	0.90	OK	OK
SotA + Cable	1.07	0.90	OK	OK
SotA + OLTC	1.05	0.93	OK	OK
SotA + DG-FACTS	1.09	0.91	OK	OK
SotA + DSM	1.10	0.90	OK	OK
SotA + stoV	1.09	0.90	OK	OK

Table G.4: Economic results of maximum PV scenario

	End-User Costs (%)		DSO Costs (%)		Total (%)
Measure	Operation	Invest	Operation	Invest	
Expansion	0.32	0	-0.37	1.03	0.96
Cable	0	0	-0.57	2.17	1.56
Feeder 8	0	0	-0.33	0.38	0.04
OLTC	0	0	-0.33	0.88	0.54
DG-FACTS	0	0	-0.32	15.2	14.87
VDE	1.90	0	-0.39	0.38	1.91
EEG	2.14	-1.91	-0.41	0.38	0.23
APC	1.86	0	-0.40	0.38	1.86
APCth	1.88	0	-0.40	0.38	1.88
cosP	0.39	2.10	-0.33	0.38	2.52
cosV09	0.86	3.07	-0.32	0.38	3.99
cosV095	1.12	2.10	-0.34	0.38	3.25
DSM	1.92	0	-0.42	0.38	1.90
DSMth	2.20	0	-0.42	0.38	2.18
cosP09HP	3.22	1.82	-0.95	0.38	4.47
cosP095HP	2.77	1.25	-0.77	0.38	3.63
cosV09HP	2.70	1.82	-0.45	0.38	4.47
cosV095HP	2.46	1.25	-0.43	0.38	3.68
sco	-18.57	16.42	-0.67	0.38	–2.44
stoV	-21.80	60.20	-0.69	0.38	38.08
SotA	1.79	-0.44	-0.42	0.38	1.32
SotA + Expansion	1.79	-0.44	-0.45	1.03	1.94
SotA + Cable	1.79	-0.44	-0.66	2.17	2.86
SotA + OLTC	1.79	-0.44	-0.43	0.88	1.81
SotA + DG-FACTS	1.79	-0.44	-0.38	15.20	16.18
SotA + DSM	1.82	-0.44	-0.45	0.38	1.33
SotA + stoV	-17.92	59.76	-0.69	0.38	41.55

List of Abbreviations

AC	alternating current
BDEW	German Association of Energy and Water Industries - Bundesverband der Energie und Wasserwirtschaft
BSW	German Solar Industry Association - Bundesverband Solarwirtschaft
BTSL	Building Technology Simulation Library
CF	conglomeration factor
CHP	combined heat and power
COP	coefficient of performance
dena	German Energy Agency - Deutsche Energie Agentur
DG	distributed generation
DHW	domestic hot water
DPL	Digsilent Programming Language
DSL	Digsilent Simulation Language
DSO	distribution system operator
EMC	electromagnetic compatibility
ENTSO-E	European Network of Transmission System Operators of Electricity
FACTS	flexible AC transmission system
H0	BDEW standard load profile households
HP	heat pump
HV	high voltage
ICE	internal combustion engine
LDC	line drop compensation
LV	low voltage
MFH	multi family house
MV	medium voltage
NAV	Low Voltage Connection Act - Niederspannungsanschlussver-ordnung
NC DCC	Network Code Demand Connection Code
NC RfG	Network Code Requirements for Generators
NGO	non governmental organisation
NS protection	network and system protection
OLTC	on-load tap-changer
PCC	point of common coupling
PQ	power quality
pu	per unit
PV	photovoltaic
RT	return temperature
SFH	single family house
SOC	state of charge
SOFC	solid oxide fuel cell
ST	supply temperature
STATCOM	static synchronous compensator
TAB	Technical Connection Requirements - Technische Anschlussbedingungen
TFH	two family house
VAT	value added tax
VPP	virtual power plant

List of Formula Symbols

a	parameter for definition of proportional controller for different measures
$a_{\#}$	empiric parameters a_1, a_2 and a_3 for PV efficiency
A	annuity
A_{cable_invest}	annuity cable invest
A_{CHP_invest}	annuity CHP invest
$A_{CHP\_operation}$	annuity CHP operation
$A_{DG-FACTS\_battery\_invest}$	annuity battery invest DG-FACTS
$A_{DG-FACTS\_building\_invest}$	annuity building invest DG-FACTS
$A_{DG-FACTS\_inverter\_invest}$	annuity inverter invest DG-FACTS
$A_{DG-FACTS\_losses}$	annuity losses DG-FACTS
A_{DSO}	annuity for DSO
$A_{electricity_consumption}$	annuity electricity consumption from grid
$A_{end-user}$	annuity for end user
$A_{foreground}$	foregrounds albedo (quantum for reflection on surrounding surfaces)
$A_{gas\_consumption}$	annuity gas consumption from grid
A_{grid_losses}	annuity grid losses
A_{HP_invest}	annuity HP invest
A_{OLTC_invest}	annuity OLTC invest
$A_{PV\_feed-in}$	annuity PV feed-in gains
A_{PV_invest}	annuity PV invest
A_R	empiric parameter battery cell resistance
$A_{storage\_battery\_invest}$	annuity storage battery invest
$A_{storage\_inverter\_invest}$	annuity storage inverter invest
b	parameter for definition of proportional controller for different measures
B_R	empiric parameter battery cell resistance
c	parameter for definition of proportional controller for different measures
C	costs
$C_{battery}$	investment costs battery (€/kWh)

$C_{building}$	investment costs building for DG-FACTS (€)
C_{cable_4x150}	investment costs cable 4x150 (€/km)
C_{cable_4x300}	investment costs cable 4x300 (€/km)
$C_{CHP\_feed-in}$	CHP feed-in tariff (€/kWh)
$C_{CHP\_generation}$	CHP generation allowance (€/kWh)
$C_{electricity\_grid}$	electricity tariff (€/kWh)
C_{gas_grid}	gas tariff (€/kWh)
C_{gas_tax}	gas tax refund (€/kWh)
C_{grid_fees}	credit for avoided grid fees (€/kWh)
C_{grid_losses}	costs for grid losses (€/kWh)
$C_{inverter}$	investment costs inverter (€/kVA)
C_{OLTC}	investment costs OLTC ((€/630kVA)
$C_{PV\_feed-in}$	PV feed-in tariff (€/kWh)
C_R	empiric parameter battery cell resistance
c_{water}	relative heat capacity of water
$CO_{2\_electricity}$	relative CO_2 emissions of electricity from grid
CO_{2_heat}	relative CO_2 emissions for heating
d	parameter for definition of proportional controller for different measures
D_R	empiric parameter battery cell resistance
$E_{diffuse,tilted}$	diffuse irradiation on tilted surface
$E_{direct,horizontal}$	direct irradiation on horizontal surface
$E_{direct,tilted}$	direct irradiation on tilted surface
$E_{global,horizontal}$	global irradiation on horizontal surface
$E_{global,tilted}$	global irradiation on tilted surface
$E_{reflected,tilted}$	reflected irradiation on tilted surface
$\underline{I}_0$	source current
$\underline{I}_1$	generator current
$\underline{I}_{1R}$	current at internal impedance generator
$\underline{I}_2$	load current
I_{cell}	battery cell current
P	active power
P_{cell}	power per battery cell
P_{losses}	power losses
$\mathrm{P}_{\mathrm{nom\_suburban}}$	nominal power in suburban grids
$\mathrm{P}_{\mathrm{nom\_urban}}$	nominal power in urban grids
$\mathrm{P}_{\mathrm{peak\_suburban}}$	peak power in suburban grids
$\mathrm{P}_{\mathrm{peak\_urban}}$	peak power urban grids
$p_{resistance}$	parameter for current dependent inverter losses
p_{self}	parameter for inverter standby losses
$p_{voltage}$	parameter for voltage dependent inverter losses

Q	reactive power
$\dot{Q}_{heatsource}$	heat power heat source
$\dot{Q}_{load}$	heat power heat load
$\dot{Q}_{loss\ buffer}$	heat power losses buffer storage
$\dot{Q}_{loss\ DHW}$	heat power losses DHW
$\dot{Q}_{losses}$	heat power losses
r	interest rate
R	resistance
R_{cell}	internal cell resistance
S	apparent power
S_{nom}	nominal apparent power
SOC	state of charge
T	observation period for annuity calculations
$\dot{T}$	temperature change
T_{amb}	ambient temperature
tap	current tapping position
V	voltage
$\underline{V}_0$	source voltage
$\underline{V}_{0R}$	voltage drop internal impedance voltage source
$\underline{V}_1$	voltage at location of generator
$\underline{V}_2$	voltage at location of load
$V_{buffertank}$	volume buffer tank
V_{cell}	battery cell voltage
$V_{DHWtank}$	volume DHW tank
$\underline{V}_{L\#}$	voltage drop at cable impedance 1 to 4
$\mathrm{V_{LV}}$	voltage at low voltage side of transformer
V_{OCV}	open circuit voltage of battery cell
$\mathrm{V_{OLTCcontroller}}$	voltage input signal for OLTC controller
V_{tank}	volume tank
X	reactance
$\underline{Z}_0$	internal impedance voltage source
$\underline{Z}_1$	internal impedance generator
$\underline{Z}_2$	impedance load
$\underline{Z}_{L\#}$	impedance of cables 1 to 4
$\underline{Z}_{loop,gen}$	loop impedance generator
$\underline{Z}_{loop,load}$	loop impedance load
α	empiric parameter for PV efficiency
γ_{module}	angle between horizontal and tilted surface
γ_{sun}	angle of sun position
ΔCO_2	change in CO_2 emissions
ΔCO_{2_CHP}	change in CO_2 emissions for CHP operation

ΔE	change in electricity consumption
$\Delta E_{CHP\_generation}$	change in electricity generation by CHP
ΔE_{heat_boiler}	change in heat generation by gas boiler
ΔV	voltage change
η_{CHP_el}	electric efficiency of CHP
η_{peak_boiler}	thermal efficiency of gas boiler
η	efficiency
$\eta_{\text{el\_max}}$	maximum electric efficiency
$\eta_{\text{th\_max}}$	maximum thermal efficiency
Θ_{tilted}	angle between direct irradiation and normal vector on tilted surface
ρ_{water}	density of water

List of Measures

APC	active power control depending on voltage at PCC (generators)
APCth	active power control depending on voltage at PCC with additional use of thermal storage (generators)
Cable	change of all main cables in grid
cosP	reactive power control depending on power (generators)
cosP095HP	reactive power control depending on power with $\cos(\phi)_{\mathrm{min}}$ = 0.95 (heat pumps)
cosP09HP	reactive power control depending on power with $\cos(\phi)_{\mathrm{min}}$ = 0.9 (heat pumps)
cosV095	reactive power control depending on voltage at PCC with $\cos(\phi)_{\mathrm{min}}$ = 0.95 (generators)
cosV09	reactive power control depending on voltage at PCC with $\cos(\phi)_{\mathrm{min}}$ = 0.9 (generators)
cosV095HP	reactive power control depending on voltage at PCC with $\cos(\phi)_{\mathrm{min}}$ = 0.95 (heat pumps)
cosV09HP	reactive power control depending on voltage at PCC with $\cos(\phi)_{\mathrm{min}}$ = 0.9 (heat pumps)
DG-FACTS	distribution grid flexible AC transmission system
DSM	demand side management (heat pumps)
DSMth	demand side management and additional use of thermal storage (heat pumps)
EEG	reduction of maximum power to 70% of peak power (PV generators)
Expansion	installation of additional parallel cable to reduce voltage level in selected feeder
Feeder 8	change of main cables in feeder 8
OLTC	installation of on-load tap-changer
sco	self consumption optimisation with distributed battery storage systems
SotA	state of the art measures (VDE + EEG + cosP)
stoV	voltage control with distributed battery storage systems
VDE	shutdown at overvoltage (generators)

List of Figures

List of Tables

References

[1] United Nations. *UN and Climate Change: Secretary-General: Webpage*. 2015. URL: http://www.un.org/climatechange/the-secretary-general/.

[2] European Commission. *The 2020 climate and energy package: Webpage*. URL: http://ec.europa.eu/clima/policies/strategies/2020/index_en.htm (visited on 23/10/2015).

[3] C. Klessmann et al. Status and perspectives of renewable energy policy and deployment in the European Union—What is needed to reach the 2020 targets? In: *Energy Policy* 39.12 (2011), pp. 7637–7657.

[4] K. Heuck, K.-D. Dettmann and D. Schulz. *Elektrische Energieversorgung: Erzeugung, Übertragung und Verteilung elektrischer Energie für Studium und Praxis*. 9. Wiesbaden: Springer, 2013. ISBN: 978-3-8348-1699-3.

[5] D. Finon and A. Midttun, eds. *Reshaping European Gas and Electricity Industries: Regulation, Markets and Business Strategies*. 1st ed. Amsterdam: Elsevier, 2004. ISBN: 0-08-044550-0.

[6] ENTSO-E. *Regional Group Continental Europe: Webpage*. 2013. URL: https://www.entsoe.eu/about-entso-e/system-operations/regional-groups/continental-europe/ (visited on 23/10/2015).

[7] statista. *Anzahl der Stromnetzbetreiber in Deutschland in den Jahren 2006 bis 2014: Webpage*. URL: http://de.statista.com/statistik/daten/studie/152937/umfrage/anzahl-der-stromnetzbetreiber-in-deutschland-seit-2006/ (visited on 23/10/2015).

[8] Bundestag der Bundesrepublik Deutschland. *Energiewirtschaftsgesetz: EnWG 2005*.

[9] P. Schavemaker and L. van der Sluis. *electrical power systems essentials*. Chichester: Wiley, 2008. ISBN: 978-0470-51027-8.

[10] dena (Deutsche Energie-Agentur GmbH), ed. *dena Verteilnetzstudie: Ausbau- und Innovationsbedarf in den Stromverteilnetzen in Deutschland bis 2030: Research Study*. Berlin, 2012.

[11] European Commission. *Network Code on Requirements for Grid Connection Applicable to all Generators: NC RfG. Draft 2015*.

[12] European Commission. *Demand Connection Code (DCC): NC DCC. Draft 2012*.

[13] Bundestag der Bundesrepublik Deutschland. *Gesetz für den Vorrang Erneuerbarer Energien: EEG 2014*.

[14] Bundesregierung der Bundesrepublik Deutschland. *Niederspannungsanschlussverordnung: NAV 2006*.

[15] BDEW. *Technische Anschlussbedingungen für den Anschluss an das Niederspannungsnetz: TAB 2007*.

[16] VDE-AR-N 4105:2011-08. *Erzeugungsanlagen am Niederspannungsnetz - Technische Mindestanforderungen für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Niedespannungsnetz*.

[17] DIN EN 61000-3-2:2015-03. *Electromagnetic Compatibility (EMC) - Limits for harmonic current emissions (equipment input current $<=$ 16 A per phase)*.

[18] DIN EN 61000-3-12:2012-06. *Electromagnetic compatibility (EMC) - Limits for harmonic currents by equipment connected to public low-voltage systems with input current $>$ 16 A and $<=$ 75 A per phase*.

[19] DIN EN 61000-3-3:2014-03. *Electromagnetic compatibility (EMC) - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current $<=$ 16 A per phase and not subject to conditional connection*.

[20] DIN EN 61000-3-11:2001-04. *Electromagnetic compatibility (EMC) - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems - Equipment with rated current $<=$ 75 A and subject to conditional connection*.

[21] DIN EN 50160:2011-02. *Voltage characteristics of electricity supplied by public distribution networks*.

[22] M. Arnold, W. Friede and J. Myrzik. Challenges in Future Distribution Grids - A Review. In: *Renewable Energy and Power Quality Journal* 11 (2013).

[23] L. Lo Schiavo et al. Changing the regulation for regulating the change: Innovation driven regulatory developments for smart grids, smart metering and e-mobility in Italy. In: *Energy Policy* 57 (2013), pp. 506–517.

[24] R. Passey et al. The potential impacts of grid-connected distributed generation and how to address them: A review of technical and non-technical factors. In: *Energy Policy* 39.10 (2011), pp. 6280–6290.

[25] N. Jenkins, J. Ekanayake and G. Strbac. *Distributed Generation*. Vol. 1. IET Renewable Energy Series 1. London: The Institution of Engineering and Technology, 2010. ISBN: 978-0-86341-958-4.

[26] D. Wang et al. Online voltage security assessment considering comfort-constrained demand response control of distributed heat pump systems. In: *Applied Energy* 96 (2012), pp. 104–114.

[27] S. Eilenberger and M. Braun. Herausforderungen und Lösungen für das Verteilnetz von morgen. In: *Stuttgarter Hochspannungs-Symposium*. Stuttgart, 2012.

[28] N. C. Scott, D. J. Atkinson and J. E. Morrell. Use of load control to regulate voltage on distribution networks with embedded generation. In: *Transactions on Power Systems* 17.2 (2002), pp. 510–515.

[29] F. Jurado, M. Valverde and A. Cano. Effect of a SOFC plant on distribution system stability. In: *Journal of Power Sources* 129 (2004), pp. 170–179.

[30] M. Bodach. Energiespeicher im Niederspannungsnetz zur Integration dezentraler, fluktuierender Energiequellen. PhD Thesis. Chemnitz: Technische Universität Chemnitz, 2006.

[31] S. Nykamp et al. Statistics for PV, wind and biomass generators and their impact on distribution grid planning. In: *Energy* 45 (2012), pp. 924–932.

[32] A. Baggini, ed. *Handbook of Power Quality*. Chichester: John Wiley & Son Ltd, 2008. ISBN: 978-0-470-06561-7.

[33] G. Kerber. Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen. PhD thesis. München: Technische Universität München, 2010.

[34] S. Bhattacharyya, S. Cobben and J. Toonen. Impacts of large-scale integration of PV based generations in a mash-connected low voltage network. In: *22nd International Conference and Exhibition on Electricity Distribution (CIRED)*. 2013.

[35] L. Spitalny, M. Diekerhof and J. Myrzik. Potenzial und Effizienzbetrachtung beim Lastmanagement von Wärmepumpen im Sektor der privaten Haushalte. In: *Konferenz für nachhaltige Energieversorgung und Integration von Speichern (NEIS)*. Hamburg, 2013.

[36] Y. Shi, F. Marra and C. Traeholt. Integration of Fuel Cell Micro-CHPs on Low Voltage Grid: A Danish Case Study. In: *Asia-Pacific Power and Energy Engineering Conference (APPEEC)*. 2012.

[37] L. Mihet-Popa et al. Development and Modeling of Different Scenarios for a Smart Distribution Grid. In: *International Symposium on Applied Computational Intelligence and Informatics (SACI)*. Timisoara, 2013.

[38] S. Müller, B. Wille-Haussmann and C. Wittwer. Potential of CHP and heat pumps systems to compensate fluctuating renewable energy generation in Germany. In: *VDE Kongress*. Stuttgart, 2012.

[39] Bundesministerium für Wirtschaft und Technologie. *Moderne Verteilernetze für Deutschland: Verteilernetzstudie: Research Study No. 44/12*. Ed. by Bundesministerium für Wirtschaft und Technologie. Berlin, 2014.

[40] L. Chao et al. Performance of OLTC-based control strategies for LV networks with photovoltaics. In: *IEEE Power & Energy Society General Meeting*. 2015.

[41] B. Gwisdorf. Praxisgerechte Anwendung innovativer Netzkonzepte mittels Grenzkurvenanalyse zur Unterstützung von Netzplanungsvorgängen. In: *Internationaler ETG Kongress*. Würzburg, 2011.

[42] T. Bülo et al. Voltage Control in Active, Intelligent Low-Voltage Distribution Networks. In: *VDE Kongress*. Stuttgart, 2012.

[43] J. Jahn. Energiekonditionierung in Niederspannungsnetzen unter besonderer Berücksichtigung der Integration verteilter Energieerzeuger in schwachen Netzausläufern. PhD thesis. Kassel: Universität Kassel, 2007.

[44] F. A. Viawan, A. Sannino and J. Daalder. Voltage control with on-load tap changers in medium voltage feeders in presence of distributed generation. In: *Electric Power Systems Research* 77 (2007), pp. 1314–1322.

[45] T. Borchard et al. Spannungsregelungsstrategien für Verteilnetze. In: *EW - Das Magazin für die Energiewirtschaft* 5 (2011), pp. 42–46.

[46] F. Provoost et al. Self Controlling Autonomous Operating Power Networks. In: *International Conference on Electricity Distribution - CIRED*. Vol. 18. Turin, 2005.

[47] R. d. Graaff et al. Series controllers in distribution systems: A survey of benefits in relation to DG. In: *International Conference on Future Power Systems (FPS)*. Amsterdam, 2005.

[48] A. J. Schwab. *Elektroenergiesysteme: Erzeugung, Transport, Übertragung und Verteilung elektrischer Energie*. 3rd ed. Heidelberg: Springer, 2012. ISBN: 978-3-642-21958-0.

[49] Y.-H. Song and A. Johns, eds. *Flexible AC Transmission Systems (FACTS)*. London: IET, 1999. ISBN: 0852967713.

[50] X.-P. Zhang, C. Rehtanz and B. Pal. *Flexible AC Transmission Systems: Modelling and Control*. Energy Systems. Heidelberg: Springer, 2012. ISBN: 978-3-642-28240-9.

[51] F. Provoost, J. Myrzik and W. Kling. Optimized Voltage Control in Autornomously Controlled Networks. In: *International Conference on Future Power Systems (FPS)*. Amsterdam, 2005.

[52] F. A. Viawan and D. Karlsson. Coordinated voltage and reactive power control in the presence of distributed generation. In: *IEEE Power and Energy Society General Meeting*. 2008.

[53] T. Stetz, F. Marten and M. Braun. Improved Low Voltage Grid-Integration of Photovoltaic Systems in Germany. In: *IEEE Transactions on Sustainable Energy* 4 (2013), pp. 534–542.

[54] M. Brunner, S. Tenbohlen and M. Braun. Heat pumps as important contributors to local demand-side management. In: *Powertech*. Grenoble, 2013.

[55] C. Brandoni et al. Heat pumps and demand side management for renewable energy integration in sustainable communities. In: *International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE)*. 2014.

[56] C. Matrose et al. Positioning strategies for decentralized energy resources providing reactive power control. In: *VDE Kongress*. Stuttgart, 2012.

[57] L. Jörissen. APPLICATIONS – STATIONARY — Residential Energy Supply: Fuel Cells. In: *Encyclopedia of Electrochemical Power Sources*. Ed. by Jürgen Garche. Amsterdam: Elsevier, 2009, pp. 108–123.

[58] M. Pielke and M. Kurrat. Integrations- und Marktstrategien von Mini-BHKW in Wohnobjekten für den Energieversorger. In: *6. Internationale Energiewirtschaftstagung*. Wien, 2009.

[59] R. Becker. Optimierung thermischer Systeme in dezentralen Energieversorgungsanlagen. PhD thesis. Dortmund: TU Dortmund University, 2006.

[60] E. Hauptmeier. KWK-Erzeugungsanlagen in zukünftigen Verteilungsnetzen: Potenzial und Analysen. PhD thesis. Dortmund: TU Dortmund University, 2007.

[61] J. Widén et al. Impacts of distributed photovoltaics on network voltages: Stochastic simulations of three Swedish low-voltage distribution grids. In: *Electric Power Systems Research* 80 (2010), pp. 1562–1571.

[62] C. Schulz. Systembetrachtung zur integration von Mini-Blockheizkraftwerken in das elektrische Versorgungsnetz. PhD thesis. Braunschweig: TU Carolo-Wilhelmina, 2007.

[63] VDI 4655:2008-05. *Reference load profiles of single-family and multi-family houses for the use of CHP systems*.

[64] co2online. *Heizspiegel: Vergleichswerte zu Heizenergieverbrauch, Heizkosten und CO2-Emissionen für das Abrechnungsjahr 2012*. Berlin, 2013. URL: http://www.heizspiegel.de/index.php?id=193\&type=0\&jumpurl=fileadmin\%2Fhs\%2Fheizspiegel\%2Fheizspiegel-pdf\%2Fheizspiegel-bund-2013-abrechnungsjahr-2012-web.pdf\&juSecure=1\&locationData=193\%3Att_content\%3A62486\&juHash=0d9157a56a9d40309b5f27ccb5c3ca7c72ac2f82 (visited on 24/10/2015).

[65] U.S. Department of Energy. *EnergyPlus Energy Simulation Software: Weather Data*. URL: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=6_europe_wmo_region_6/country=DEU/cname=Germany (visited on 24/10/2015).

[66] H. Schmidt and D. Sauer. Wechselrichter Wirkungsgrade. In: *Sonnenenergie* 21.4 (1996), pp. 43–47.

[67] P. Perrin. Simulationsbasierte Analyse der Einflussfaktoren auf Betriebszahlen von Wärmepumpenanlagen. PhD thesis. Braunschweig: Technische Universität Carolo-Wilhelmina zu Braunschweig, 2012.

[68] V. Quaschning. Simulation der Abschattungsverluste bei solarelektrischen Systemen. PhD thesis. Berlin: Technische Universität Berlin, 1996.

[69] H. G. Beyer, G. Heilscher and S. Bofinger. A robust model for the MPP performance of different types of PV-modules applied for the performance check of grid connected systems. In: *Europe Solar Congress (EUROSUN)*. Freiburg, 2004.

[70] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. *Rolle der Solarstromversorgung in zukünftigen Energieversorgungsstrukturen - Welche Wertigkeit hat Solarstrom? Research Study FKZ 03MAP0075*. Ed. by Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. Berlin, 2008.

[71] V. Wesselak et al. *Regenerative Energietechnik*. 2nd. Berlin: Springer, 2013. ISBN: 978-3-642-24164-2.

[72] Scheffler Jörg. Bestimmung der maximal zulässigen Netzanschlussleistung photovoltaischer Energiewandlungsanlagen in Wohnsiedlungsgebieten. PhD thesis. Chemnitz: TU Chemnitz, 2002.

[73] A. Forsyth. Defining Suburbs. In: *Journal of Planning Literature* 27.3 (2012), pp. 270–281.

[74] W. Kruschel et al. Dezentrale Spannungsregelung in intelligenten Niederspannungsnetzen: Leistungselektronische Komponenten zur Erhöhung der Aufnahmekapazität für erneuerbare Erzeugungseinheiten. In: *Internationaler ETG Kongress*. Würzburg, 2011.

[75] W.-T. Huang et al. Dynamic Simulation and Analysis of a Low-Voltage Micro-grid. In: *International Conference on Computing, Measurement, Control and Sensor Network* (2012), pp. 245–248.

[76] G. Kerber, R. Witzmann and H. Sappl. Voltage Limitation by Autonomous Reactive Power Control of Grid Connected Photovoltaik Inverters. In: *International Conference-Workshop Compatibility and Power Electronics (CPE)*. Badajoz, 2009.

[77] B. Gwisdorf et al. Technical and economic evaluation of voltage regulation strategies for distribution grids with a high amount of fluctuating dispersed generation units. In: *Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply (CITRES)*. Waltham, 2010.

[78] F. Marra et al. Energy Storage Options for Voltage Support in Low-Voltage Grids with High Penetration of Photovoltaic. In: *Innovative Smart Grid Technologies Europe (ISGT)*. Berlin, 2012.

[79] Bundesnetzagentur. *Datenmeldungen sowie EEG-Vergütungs-sätze: Webpage*. 2014. URL: `http://www.bundesnetzagentur.de/cln_1421/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/ErneuerbareEnergien/Photovoltaik/DatenMeldgn_EEG-VergSaetze/DatenMeldgn_EEG-VergSaetze_node.html` (visited on 24/10/2015).

[80] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. *Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global: Leitstudie 2011: Research Study FKZ 03MAP146*. Ed. by Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. Berlin, 2012.

[81] Bundesnetzagentur. *Netzentwicklungsplan Strom 2013: Erster Entwurf der Übertragungsnetzbetreiber*. Berlin, 2013.

[82] Delta-ee Micro-CHP Service. *Micro-CHP Market Statistics & Forecast: Research Study*. Ed. by Delta-ee Micro-CHP Service. Edinburgh, 2012.

[83] L. Spitalny, J. Myrzik and T. Mehldorn. Estimation of the economic addressable market of micro-CHP and heat pumps based on the status of the residential building sector in Germany. In: *International Conference on Microgeneration and Related Technologies (MICROGEN)*. Napoli, 2013.

[84] Bundesverband Wärmepumpe e.V. *BWP-Branchenstudie 2011: Szenarien und politische Handlungsempfehlungen*. Ed. by Bundesverband Wärmepumpe e.V. Berlin, 2011.

[85] baulinks. *Bundesregierung erwartet bis 2020 über eine Millionen installierte Wärmepumpen in Deutschland: Webpage*. 29.05.2012. URL: `http://www.baulinks.de/webplugin/2012/0882.php4` (visited on 24/10/2015).

[86] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. *Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global: Leitstudie 2010: Research Study FKZ 03MAP146*. Ed. by Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. Berlin, 2010.

[87] Bundestag der Bundesrepublik Deutschland. *Antwort der Bundesregierung: Förderung von Wärmepumpen: Drucksache 17/9214*. Berlin, 28/03/2012.

[88] B. u. S. Bundesministerium für Verkehr. *Wohnen und Bauen in Zahlen 2011/2012*. Ed. by B. u. S. Bundesministerium für Verkehr. Berlin, 2012. URL: `buergerinfo@bmvi.bund.de`.

[89] Bundesregierung der Bundesrepublik Deutschland. *Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäude: EnEV 2002*.

[90] Statistisches Bundesamt. *zensus 2011: Gebäude und Wohnungen*. Ed. by Statistisches Bundesamt. Berlin, 2013.

[91] DIN EN 60269-1:2010-03. *Niederspannungssicherungen - Teil 1: Allgemeine Anforderungen*.

[92] Bundesministerium für Wirtschaft und Technologie. *Zahlen und Fakten Energiedaten: Nationale und Internationale Entwicklung*. URL: `http://www.bmwi.de/BMWi/Redaktion/Binaer/energie-daten-gesamt,property=blob,bereich=bmwi,sprache=de,rwb=true.xls` (visited on 24/10/2015).

[93] Bundestag der Bundesrepublik Deutschland. *Kraft-Wärme-Kopplungsgesetz: KWKG 2002*.

[94] Bundestag der Bundesrepublik Deutschland. *Energiesteuergesetz: EnergieStG 2006*.

[95] Netze BW. *Preisblatt Entgelt für dezentrale Einspeisung*. 2014. URL: `https://www.netze-bw.de/media/geteilte-medien/docs/veroeffentlichungspflichten/dezentrale-erzeugung/entgelte-fuer-dezentrale-einspeisung.pdf` (visited on 24/10/2015).

[96] eex. *KWK Index Deutschland*. URL: http://www.eex.com/de/marktdaten/strom/spotmarkt/kwk-index/kwk-index-download (visited on 24/09/2014).

[97] M. Meinhardt, B. Burger and A. Engler. *PV-Systemtechnik - Motor der Kostenreduktion für die photovolaische Stromerzeugung*. Berlin, 2007. URL: http://www.fvee.de/fileadmin/publikationen/Themenhefte/th2007/th2007_05_2.pdf (visited on 24/10/2015).

[98] Frankensolar. *SMA Sunny Island 6.0H: Catalog 2013*.

[99] Roland Berger Stategy Consultants. Technology & Market Drivers for Stationary and Automotive Battery Systems. In: *International Energy & Power Supply Conference (Batteries)*. Nice, 2012.

[100] J. Marshall. *Are Cheap Batteries Around the Corner for Electric Vehicles?* 2013. URL: http://www.pgecurrents.com/2013/07/18/are-cheap-batteries-around-the-corner-for-electric-vehicles/ (visited on 24/10/2015).

[101] A. Cheung. *Battery Innovation: Incremental or Disruptive?* 2013. URL: http://about.bnef.com/summit/content/uploads/sites/3/2013/11/BNEF_2012_03_19__University_Battery_Innovation.pdf (visited on 24/10/2015).

[102] R. Hensley, J. Newman and M. Rogers. *Battery technology charges ahead*. URL: http://www.mckinsey.com/insights/energy_resources_materials/battery_technology_charges_ahead (visited on 24/10/2015).

[103] VDI 2067:2012-09. *Economic efficiency of building installations*.

[104] Deutsche Bundesbank. *Deutsche Bundesbank Zinsstatistik: EZB-Zinssätze*. 2014. URL: http://www.bundesbank.de/Redaktion/DE/Downloads/Statistiken/Geld_Und_Kapitalmaerkte/Zinssaetze_Renditen/S11BTTEZBZINS.pdf;jsessionid=0000yxdyouIpt1bUuuLy5vXEq07:-1?__blob=publicationFile (visited on 24/10/2015).

[105] DIN 18599-2:2011-12. *Energetische Bewertung von Gebäuden - Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung - Teil 2: Nutzenergiebedarf für Heizen und Kühlen von Gebäudezonen*.

[106] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. *El-KW-Park-DE-2020 (PRIMES): Kraftwerksmix zur Stromerzeugung in Deutschland*. URL: http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={0E0B2796-9043-11D3-B2C8-0080C8941B49} (visited on 24/10/2015).

[107] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. *Gas-Heizung-DE-2020 (Endenergie): Zentralheizung für Erdgas mit atmosphärischem Brenner*. URL: http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={2D81847C-BCFB-4FBC-A883-980974363443} (visited on 24/10/2015).

[108] *Buderus Energy Centre: Logapower FC10: Brochure*. URL: http://www.ibz-info.de/download/buderus_logapower_fc10.pdf (visited on 24/10/2015).

[109] *Buderus Logamax plus GBH172: Technical Data*. URL: https://productsde.buderus.com/erp/8461/de_pdf.pdf (visited on 24/10/2015).

[110] T. Zoerner. *Nachgefragt bei ENBW: Lastabwurf der Wärmepumpen und anderer unstetiger Lasten: Webpage*. 13.03.2013. URL: http://blog.stromhaltig.de/2013/03/nachgefragt-bei-enbw-lastabwurf-der-warmepumpen-und-anderer-unstetiger-lasten/ (visited on 24/10/2015).

[111] J. Harrison. Capturing value from micro CHP. In: *Energy & Environment Summit*. Copenhagen, 2011.

[112] Nexans. *Power Cables 1 - 30 kV: Catalog*. 2010.

[113] faberkabel. *Starkstromkabel NAYY: Catalog*. 2013.

[114] Proxima. *NFA2X: Catalog*. 2013.

[115] Tele-Fonika Kable. *Power Cables 1 - 30 kV: Datasheet: Catalog*. 2007.

[116] D. Oeding and B. Oswald. *Elektrische Kraftwerke und Netze*. 7th ed. Heidelberg: Springer, 2011. ISBN: 978-3-642-19245-6.

[117] E. Kuhnert and F. Wiznerowicz. *Eigenschaften von Energiekabeln und deren Messung*. Frankfurt (Main): EW Medien und Kongresse, 2012. ISBN: 978-3-8022-0968-0.

[118] Bundesministerium für Wirtschaft und Technologie. *Die Entwicklung der Energiemärkte bis 2030: Energieprognose 2009: Research Study*. Ed. by Bundesministerium für Wirtschaft und Technologie. Berlin, 2010.

[119] Bundesministerium für Wirtschaft und Technologie. *Energieszenarien für ein Energiekonzept der Bundesregierung: Research Study No. 12/10*. Ed. by Bundesministerium für Wirtschaft und Technologie. Berlin, 2010.

[120] Federal Republic of Germany. *National Renewable Energy Action Plan in accordance with Directive 2009/28/EC on the promotion of the use of energy from renewable sources*. Berlin, 2010.

[121] Bundesministerium für Wirtschaft und Technologie. *Energieszenarien 2011: Research Study No. 12/10*. Ed. by Bundesministerium für Wirtschaft und Technologie. Berlin, 2011.

[122] Bundesverband Erneuerbare Energien e.V. *Stromversorgung 2020 Wege in eine moderne Energiewirtschaft: Strom-Ausbauprognose der Erneuerbaren-Energien-Branche*. Ed. by Bundesverband Erneuerbare Energien e.V. Berlin, 2009.

[123] Bundesverband Erneuerbare Energien e.V. *Wege in die moderne Energiewirtschaft Teil2: Wärmeversorgung 2020: Ausbauprognose der Erneuerbare-Energien-Branche*. Ed. by Bundesverband Erneuerbare Energien e.V. Berlin, 2009.

[124] Fraunhofer IWES. *Dynamische Simulation der Stromversorgung in Deutschland nach dem Ausbauszenario der Erneuerbaren-Energien-Branche: Research Study*. Ed. by Fraunhofer IWES. Kassel, 2009.

[125] dena (Deutsche Energie-Agentur GmbH). *dena Grid Study II: Integration of Renewable Energy Sources in the German Power Supply System from 2015 - 2020 with an Outlook to 2025*. Ed. by dena (Deutsche Energie-Agentur GmbH). Berlin, 2011.

[126] Cogeneration Observatory and Dissemination Europe (CODE). *Cogeneration Case Studies Handbook*. Ed. by Cogeneration Observatory and Dissemination Europe (CODE). Brussles, 2011.

[127] M. Pehnt et al. *Ökologische und ökonomische Analyse von Brennstoffzellen-Heizgeräten*. Heidelberg / Osnabrück / München, 2012.

[128] Greenpeace. *Klimaschutz: Plan B 2050: Energiekonzept für Deutschland*. Ed. by Greenpeace. Hamburg, 2009.

[129] World Wide Fund for Nature (WWF). *Modell Deutschland. Klimaschutz bis 2050: Vom Ziel her denken*. Ed. by World Wide Fund for Nature (WWF). Berlin, 2009.

[130] Öko Institut e.V. *PROSA Photovoltaik Wechselrichter: Entwicklung der Vergabekriterien für ein klimaschutzbezogenes Umweltzeichen*. Ed. by Öko Institut e.V. Freiburg, 2012.

[131] Sony Energy Devices Corporation. *Light up the power: 1.2kWh Olivine Stromspeicher Modul: Datasheet*. München, 2012.

Scientific Activities

Publications

Scientific Journals:

Arnold, M; Friede W.; Myrzik J.: Challenges in Future Distribution Grids - A Review. In *Renewable Energy and Power Quality Journal* (2013) Vol. 11.

Scientific Conferences:

Arnold, M; Friede W.; Myrzik J.: Investigations in low voltage distribution grids with a high penetration of distributed generation and heat pumps . In: *Universities Power Engineering Conference (UPEC)*. Dublin, 2013.

Arnold, M; Friede W.; Myrzik J.: Simulation of 2020 scenario of suburban low voltage grid . In: *VDE Kongress*. Frankfurt am Main, 2014.

Arnold, M; Friede W.; Myrzik J.: Comparison of current and future voltage regulation measures on German low voltage grids . In: *Powertech*. Eindhoven, 2015.

Professional Journals:

Arnold, M; Friede W.; Myrzik J.: Challenges in Future Distribution Grids . In *Sun and Wind Energy*. Online Issue, 09/2013. URL: http://www.sunwindenergy.com/news/challenges-future-distribution-grids

Invited Talks:

Arnold, M; Friede W.; Myrzik J.: Using residential heating systems for load management applications in smart cities . In *PES General Meeting*. Denver, 2015.

Student Thesis Supervision

Henkel, L.: Implementierung von dynamischen Gebäudemodellen in DIgSILENT PowerFactory . Bachelor thesis. Dortmund: TU Dortmund University, 2013.

Misra, A.: Battery Storage System to Buffer Electricity from Fuel Cell Micro Cogeneration Systems . Master thesis. Munich: TU München, 2014.

El khallali, M.: Installation eines Batteriesystems zur Zwischenspeicherung von Strom aus einem Brennstoffzellen-Mikro-Kraft-Wärme-Kopplungssystem . Bachelor thesis. Darmstadt: Darmstadt University of Applied Sciences, 2014.

Rupp, L.: Auswertung von Feldtestdaten eines Batteriesystems zur Zwischenspeicherung von Strom aus Brennstoffzellen-Mikro-Kraft-Wärme-Kopplungssystem . Master thesis. Stuttgart: Stuttgart University, 2014.