CODEN:LUTEDX/(TEIE-5337)/1-126/(2014)

Industrial Electrical Engineering and Automation

Grid Capacity Issues with Distributed Generation

A German case study

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June 24, 2014

Abstract

Climate change is more evident than ever as reflected in The European union's environmental directives which say that the carbon emission must be reduced by 20% and 20% of the used energy must come from renewable energy sources until 2020. In Germany political decision has been made that the nuclear power will be replaced by renewable energy in long term.

The purpose of the Master Thesis is to investigate how high penetration of photovoltaic affects the electrical grid on a distribution level concerning active power and map the potential for different renewable energy sources in Germany. Using a simulation model and grid data received from E.ON the goal is to map what problems that may occur and evaluate different measures for solving the problems. The data and information collection have been done by interviews and literature studies. The simulation program that has been used is DIGSILENT Power Factory where all the simulations have been static ones. Different load profiles for households have been handed by an internal source in E.ON and evaluated before inserted in the simulations. The studied measures for balancing the active power are battery storages of different technologies, load shifting and biomass power plants. The investigated battery technologies were Li-ion batteries, Lead-acid batteries and Vanadium Redox flow batteries. The main purpose of evaluating three different technologies is the costs for each technology. Battery storages and load shifting have been used for all load profiles, the biomass power plants have been used while the PV output has been low.

The results showed that Germany is able to increase its wind and PV output in the future. Implementation of battery storage and load shifting will balance the grid and less power will be taken from the transmission grid. Load shifting is very hard to analyze and utilize but assumed to have low capital costs. Load shifting in households is also a very immature technology. Storing energy is the most effective measure for balancing the active power because of the valuable property to store energy and use when it is needed. But the costs of battery storages are high even if no costs of power electronics were included. Implementation of a 10 MW biomass power plant will balance the active power while low production of PV and high demand.

Sammanfattning

Miljöhotet är vår tids största problem och för att komma till bukt med problemet är en integration av förnybara energikällor ett måste. Miljöhotets allvar avpseglas i EU's direktiv om att ha elproduktion med 20 % förnybart och sänka utsläppen av växthusgaser med 20 % till 2020. I Tyskland har även beslut tagits om att stänga den befintliga kärnkraften på grund av kärnkraftsolyckan i Fukushima. Kärnkraften som under lång tid varit en tillförlitlig energikällor behöver där med ersättas.

Syftet med examensarbetet är att undersöka hur stor mängd solceller påverkar elnätet på en distributionsnivå gällande aktiv effekt samt att kartlägga potentialen för olika förnybara energikällor i Tyskland. Med hjälp av en simuleringsmodell och nätdata från E.ON var målet att kartlägga vilka problem som kan uppstå och utvärdera olika åtgärder för att lösa problemen. Insamlingen av data och information har gjorts genom intervjuer och litteraturstudier. Simuleringsprogrammet som har använts var DIGSILENT Power Factory där alla simuleringar har varit statiska. Olika lastprofiler för hushållen har överlämnats av en intern källa i E.ON och utvärderas innan de implementerades i simuleringarna. De studerade åtgärderna för att balansera aktiv effekt är batterilager av olika teknologier, laststyrning och biomasskraftverk. De undersökta batteriteknikerna var litiumbatterier, blybatterier och flödesbatterier. Det huvudsakliga syftet med att utvärdera tre olika tekniker är kostnaderna för varje teknik. Batterilager har använts för samtliga lastprofiler, biomassakraftverk har använts då PV produktionen har varit låg och lasten hög och laststyrning har använts för profiler med hög produktion.

Resultaten från simuleringarna visar att höga spänningar i nätet uppkommer vid hög integration av PV. Batterier är den mest effektiva åtgärden för att undvika överbelastade transformatorer och kablar men är kopplat till höga kostnader och höga förluster på grund av batteriernas verkningsgrad. Laststryning fungerar till viss del för att undvika överbelastingar i nätet. Laststyrning kommer att behövas för att kunna jämna ut de stora förflyttningarna av energi. Både laststyrning och batterier kan användas för att sänka de höga spänningarna i nätet som uppkommer med stor produktion från solkraft. Med överkomliga storlekar på biomasskraftverk kan dessa täcka upp lasttoppar. Biomassverk kan idag styras av värmebehovet men kommer med en större del av förnybara energikällor behöva användas som reglerkraft och därmed styras av elektricitetsbehovet

Acknowledgments

The Master thesis is introduced by E.ON Technologies GmbH in Gelsenkirchen Germany and done at the University of Lund, faculty of engineering in the department of Industrial Electrical Engineering and Automation.

We would like to thank first of all our supervisors at E.ON, Mr. Alexander Knake and Mrs. Antje Cieleit for their expertise, understanding and patience. We would like to show a great gratitude to our supervisor at Lunds University, Assoc. Prof. Olof Samuelsson for his great inputs. A special thanks goes to Dr. Petra Behrens and Mr. Peter Sigenstam for introducing us to the project. A very special thanks goes to the Codes and Standards team at E.ON for all their friendly help and taking care of us during our time in Germany.

At last but not least, we would like to thank our families for their understanding, through the duration of our studies.

Introduction

This initial chapter contains the background, purpose and restrictions of the Master Thesis.

Background

The ambition to reduce the emission of greenhouse gases and to have larger part of renewable energy in the energy production is based on the European Union's environmental directives which say that the carbon emission must be reduced by 20% and 20% of the used energy must come from renewable energy sources until 2020. In Germany political decision has stated that the nuclear power will be replaced by renewable energy in long term. The plan is that all nuclear power plant will be closed until 2022. The phase out of nuclear energy until 2022 and the expansion of renewable energy sources are key issues of the German federal government's energy concept. The goal of the concept is to secure that 40 % of the gross electricity consumption is to be supplied from renewable energy sources at the end of 2050. The new Energy-transition ("EnergieWende") means large amounts of variable and unpredictable renewable energy sources, for example over 30 GW of onshore wind power, offshore wind power in the future (30 to 50 GW) and 30 GW solar power on medium- and low-voltage level. All these factors in combination with the scheduled shut-down of all nuclear power plants will make planning and operation of the electric power system more difficult including bottlenecks and reliability problems [2].

Since the installed photovoltaic(PV) capacity is not homogeneously spread across Germany, some regions are already experiencing a very high PV penetration of more than 200 kWp km^2 compared to the nationwide average of 39 kWp km^2. In these regions, the increasing power feed-in may result to high local voltage magnitudes which might give rise to demanding grid reinforcement actions, causing an increment of the whole PV grid integration expenses in Germany. Grid reinforcement measures can be reduced by curtailing the active power feed-in of the PV systems [3]. One of the biggest challenges in the reconstruction to an energy system with a larger part of renewable energy is the expansion of both the distribution grid and transmission grid. To be able to transfer large amount of energy from regions with energy excess to regions with deficit, large investments are needed to enhance the transmission grid.

Many of the renewable energy sources are directly connected to the distribution grid which means that even the distribution grid and the connection between transmission and distribution might need to be upgraded [1]. In order to rebuild and strengthen the grid on all different levels, investigation is required to locate where existing grid is too weak and what other problems that may occur. Grid extensions are costly measures and other technologies might come to hand.

Purpose and Task

The purpose of the Master Thesis is to gain knowledge about how high penetration of photovoltaics affects the electrical grid on a distribution level concerning active power and map the potential for different renewable energy sources in Germany.

The goal of the thesis is to evaluate the current technical possibilities to balance the active power in distribution grid. Therefore the different tools and techniques like load shifting, storage and power producers will be studied and characterized. Advantages and disadvantages for the tools and techniques will be drawn, from literature studies, interviews and simulations. An example grid is received from an internal source in E.ON in order to check the general feasibility and to look for possible restrictions like grid congestions. As a result, conclusions are drawn if it makes technically sense to use the different techniques to balance the active power in the distribution grid. If this is the case, recommendations will be made for follow-up projects to prove the benefits for E.ON.

The Thesis has been divided in to two main tasks, a literature study investigating grid capacity issues, concerns related to integration of renewable energy sources in the distribution grid, potential of renewable energy and relevant measures that can be used. The other part is a case study of an area in Germany with a lot of photovoltaics penetration.

Restrictions

The Thesis does not investigate the dynamic effects created by photovoltaics. Measures for balancing reactive power have not been evaluated in the Master Thesis.

Division of Work

Both authors have been involved in all steps of the master thesis; however the workload and responsibility for every step have not been the same. Nofel Dakhel has been responsible for the interviews and collecting, summarizing and processing the data while Olof Bohgard has been responsible for the evaluate the simulation models and running the simulations. The writing of the report has been equally shared.

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Chapter 1

Grid impact of Distributed Generation

The aim of this chapter is to introduce the impacts of the distributed generation on the distribution and transmission grid.

1.1 Germany's Transmission and Distribution Grid

The current German grid is designed to connect the conventional power plants (especially large coal-fired and nuclear power plants) with high demand areas. In the northern parts of Germany, wind energy development is increasing fast, due mostly to the offshore power plants planned for the North and Baltic Seas but also because of the onshore wind. In the southern part of Germany, the production is dominated by nuclear power and fossil fuel plants. The geographical difference in the power production results in massive variations in the power flow. Even if north-to-south lines exist, bottlenecks have become more usual because of the incapability of transmitting necessary wind power from the north to the south. Germany can no longer support reliability of supply in the European interconnected grid to the level it has done until now, because of the new Energy-transition ("Energiewende") which means large amounts of variable and unpredictable renewable energy sources and a scheduled shut down of all nuclear reactors. As Germany becomes a net importer of electricity rather than a main exporter it will result in major consequences on the grid widely in Europe. Grid capacity is the other main concern, in mid 2012, a total of 15 out of the 24 most crucial grid expansions identified in 2009 were delayed with between one and five years and only 214 km of 1834 km of transmission lines had been finished [7].

Electric power systems are generally structured both for transportation of huge amounts of electricity over longer distances (transmission) and to distribute the electricity to the customers (distribution). Generation, transmission, distribution and consumption use different voltage levels. The use of high voltage levels is for long distances electricity transportation, where focus is on minimizing losses. The usage of lower voltage levels at shorter distances allows smaller dimensions of the equipment and therefore lower costs. Figure 1.1 below shows an overview of the different layers in the German power grid [4].

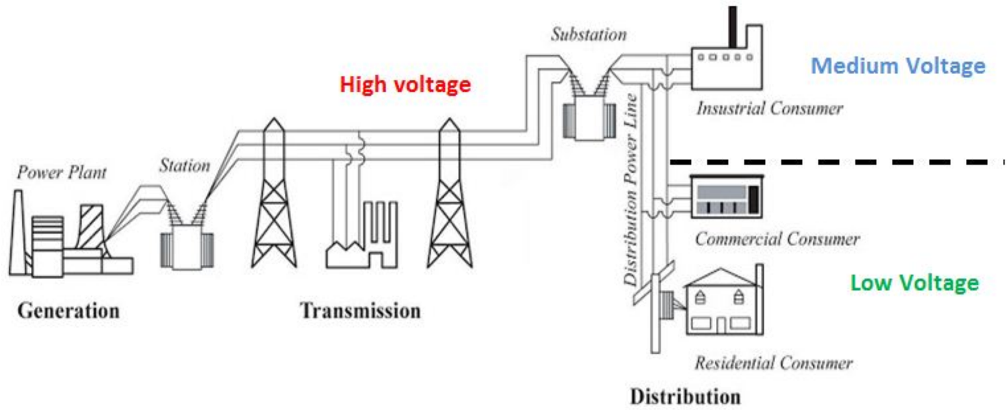

Figure 1.1: Overview of the different voltage layers in the grid [6].

1.1.1 Transmission Grid

Germany has four different transmission system operators (Trans Power (TenneT), 50 Hertz Transmission, Amprion and EnBW transport networks) who own and operate the transmission system. Transmission grids are normally AC, which can freely be transformed to higher or lower voltages. The German transmission grid has a voltage of 220 kV or 380 kV and the total length of all transmission lines is about 35 000 km [7].

At ultra-high voltages (UHV), 1000 kV AC or 800 kV DC, losses are even lower than at 380 kV AC, but the investments cost will be too high to be profitable. Thus, the transmission system allows low-loss transmission of electricity over long distances both in Germany and across its borders. There have been some considerations in Germany regarding transformation of AC lines to DC to increase their capacity. More and more, DC lines are being implemented in the transmission system for the main purpose to connect offshore power plants to onshore grids via undersea cables [7].

1.1.2 Distribution Grid

The German distribution high voltage grids are 60 kV and higher. Their total line length is about 77 000 km. The medium-voltage distribution grid is between 6 kV and 60 kV and the total line length is approximately 479 000 km. The medium-voltage grid distributes electricity to secondary substation or directly to larger facilities such as hospitals or factories. The low-voltage distribution grids are 0.4 kV with a total line length of approximately 1 123 000 000 km. The low-voltage grid is used for end user distribution such as households, smaller industries and commercials. In this area, a variety of regional and local network operators are active [7].

Rural areas with low-density loads are usually served by overhead lines connected to transformers and switches. Cities with high-density loads are served by underground cable systems, transformers and switches installed underground or in cabinets on ground level.

There are three different types of low-voltage grids that are commonly used. A common and simple type is the radial grids, which means that customers are positioned along a line that branches off and ends at the last customer, see figure 1.2. The radial grids have economical benefits because only one feed-in station is needed and usage of thinner cables in the end are possible. With radial grids it is also easy to disconnect short circuit faults and to coordinate the protection system. Another type is the meshed grids, to ensure reliable supply, most grids use a mesh structure and that means that the power lines of any given power supply source are interconnected with those of other sources. If a fault occurs in one line, power can be redirected from elsewhere while the damaged line can be fixed. The meshed grids (figure 1.3 may have several such possible connection points to other networks, through which an alternative current path can be obtained. Looped grids are similar to meshed grids. The differences are that they have one main feed in station and one in reserve. They also lack permanent coupling but have controllable reclosers [8].

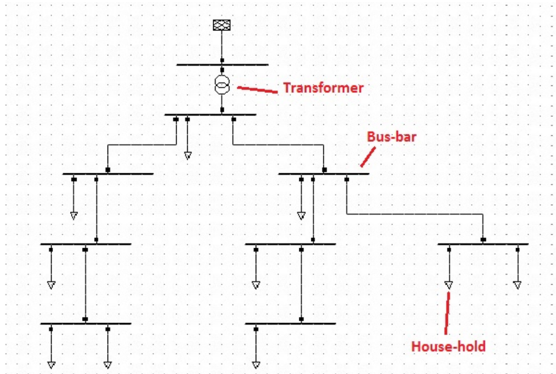

Figure 1.2: An example of a radial grid.

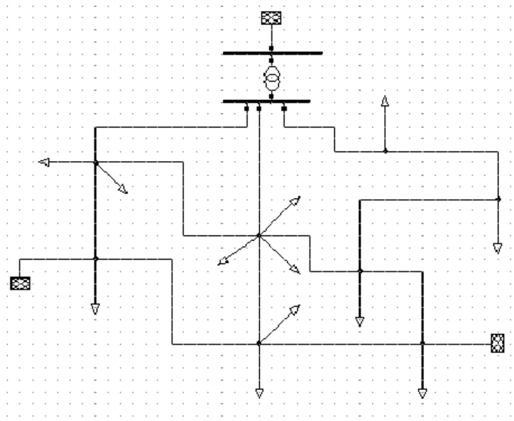

Figure 1.3: An example of a meshed grid.

1.2 Distributed Generation

Small scale generating technologies that are connected to the electric distribution grid is called Distributed Generation. T.Ackermann defines distributed generation as "The location of distributed generation is defined as the installation and operation of electric power generation units connected directly to the distribution network or connected to the network on the customer site of the meter" [13]. Distributed generation units allow end users to produce their own electricity and also deliver to the electrical grid.

The energy losses can be reduced if a distributed generation system is deployed on a feeder, which have several branches connected with different loads, especially if it is deployed close to the most significant loads. If the power production from the distributed generator system is much higher than the load consumption, the current again rises leading to an increase in the line losses on the feeder may occur due the surplus power that flows towards the substation. Thus, it is an advantage if the distributed generator units are deployed on the right places on the feeder [10]. The resistance (R) of the feeder and the current (I) through the feeder defines its losses (P_{loss}). The losses increases with I^2, so if the current is reduced to one third, the line losses would be reduced by a factor of nine.

$$P_{loss} = R \cdot I^2 \tag{1.1}$$

1.3 Photovoltaics

Photovoltaics energy sources are constructed by one or more solar panels, which in turn consist of photovoltaic cells. The photovoltaic cell is manufactured of semiconducting material and it is the photovoltaic effect that create the electricity from photons. An average output voltage from a photo voltaic cell is around 0.6 V and by connecting many cells in series, higher voltages levels can be achieved. The solar modules produces DC voltage which suites applications in households that commonly uses DC voltages as voltage sources. In order to connect solar plants to the grid it is necessary to invert and transform the DC voltage. This is done to get the same magnitude and frequency as the voltage in the grid. To maximize the output of the solar cells it is important to consider the location and tilt of the solar panels [11].

There are more than one million PV power plants (in various sizes) in Germany, where more than 98% are connected to the distribution low-voltage grid and produces solar electricity close to the consumers. Only 15% of the total PV capacity in Germany comes from PV plants over 1 MW. Thus, the feed-in of solar energy is mainly decentralized and barely makes any demands on an expansion of the German transmission grid. A high penetration of distributed generation units in the low-voltage grid may result in surplus power generation on sunny days and under such circumstances, the transformers feed power back into the medium-voltage grid. An equal distribution of PV installations across all the grid actually reduces the necessity of grid expansion.

Figure 1.4 shows levels of irradiance across Germany. In order to maximize the solar electricity generation, PV modules are oriented towards the south and are installed with an inclination of approximately 30–40° to the horizontal surface. The total incident irradiance on the modules increases by approximately 15% when tilting the PV module compared to the horizontal surface. This results to an increment of the average incident irradiation to around 1200 kWh/m^2 per year all over Germany [12].

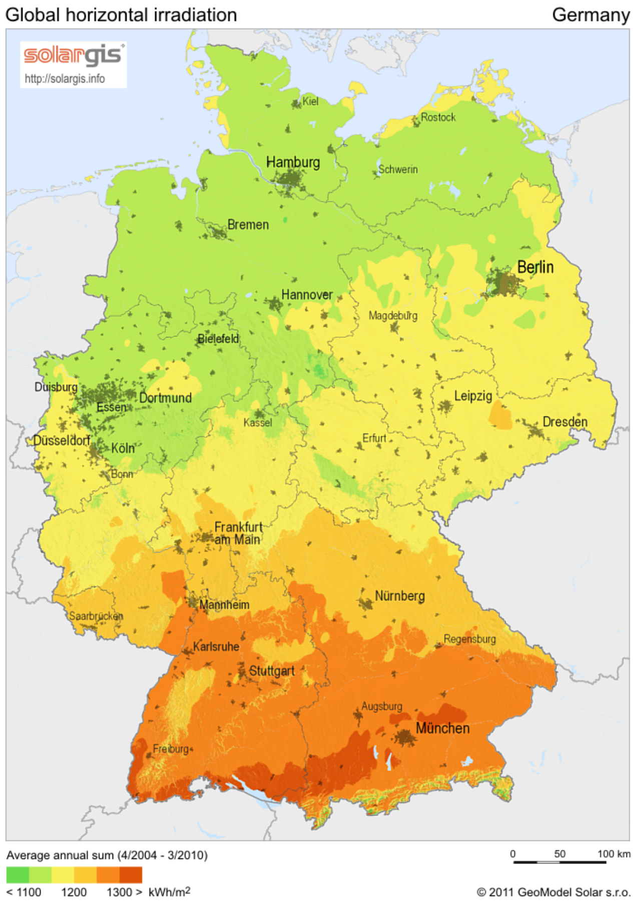

Figure 1.4: Irradiance levels across Germany [14]

PV is together with wind power the fastest growing energy sources in the world [15]. In a report from the German Solar Industry Association statistics says that the solar production was 4.7% of the German electricity production with a production of 28060 GWh 2012. The production has increased with over 100% since 2010 in 2012. Predictions state that PV will constitute with 10% of the total electricity production in Germany 2020. Most of the PV is and will be located in south of Germany where the irradiance is relatively high [17]. Figure 1.5 shows the future scenario of distribution of solar power in Germany and as it can be seen, the highest penetration of solar will be established in the southern part but also in the west of Germany.

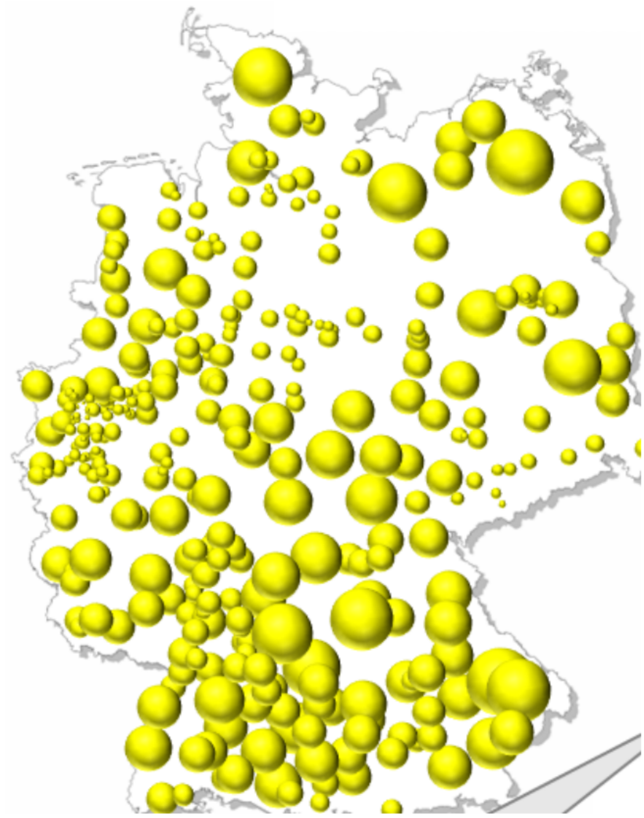

Figure 1.5: Future scenario of installed solar power in Germany in 2033 [16].

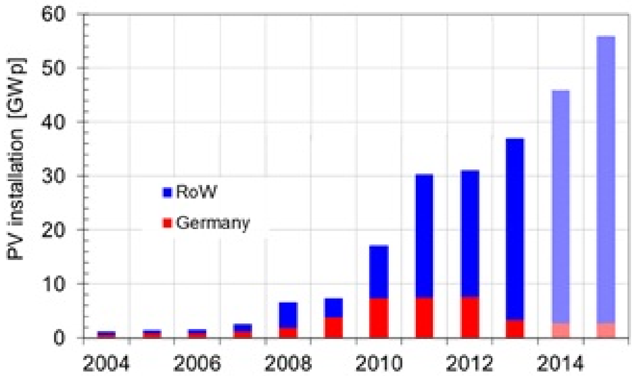

Figure 1.6: Development of yearly installed PV power in Germany and globally (RoW) [12]

The limited in time and the unpredictable production of solar energy causes problem for the power system, both short term and long term especially when a larger part of the electricity production consist of PV. Larger PV-plants connected to the grid also affects the grid in terms of frequency stability, frequency control, power quality and transient stability. The PV power plants are connected to the grid through power electronics and thereby not contributing with any inertia which making the forecast of the production more important [18].

Many of the problems with grid-connected PV are caused by the conversion of DC-voltage to AC-voltage and these raises demands on the inverters in the PV-system. Control systems and filters are needed to control the active and reactive power output and to suppress the harmonics that the power electronic generates [19].

The PV plants were from the beginning manufactured to get the highest possible active power output because the production of reactive power is not rewarded economically yet. This has created problems with the reactive power levels in the grid when the solar power plants are not producing power e.g. during the night. The inverters could compensate this problem but are usually turned off during night to extend the lifetime of the inverters [20].

Large investments are being made in order to decrease the cost and to improve the reliability, efficiency and performance of PV modules and power electronics for PV systems. Flexible thin-film PV modules have been developed to reduce the manufacturing costs [21].

The presence of non-dispatchable PV units raises an important issue with the overvoltage in the low voltage distribution grid. The typical load profile for a household is relatively low while power generation peaks; resulting to reverse power in the feeders and thus overvoltage arises [22]. The reverse power flow changes the normal voltage profile along the network length. Figure 1.7 shows a voltage profile with consumption but without any PV modules connected; it is decreasing along the network length and generally the system is designed to keep the voltage drop at the end of the feeder to less than 4%. A voltage profile with a PV module connected is shown in figure 1.8. The voltage curve is of a special concern where the loads of the households are low and the production of the PV modules is high. This results to an increase of voltage along the network length and the voltage at the end of the feeder reaches a value higher than the upper acceptable voltage limit [23].

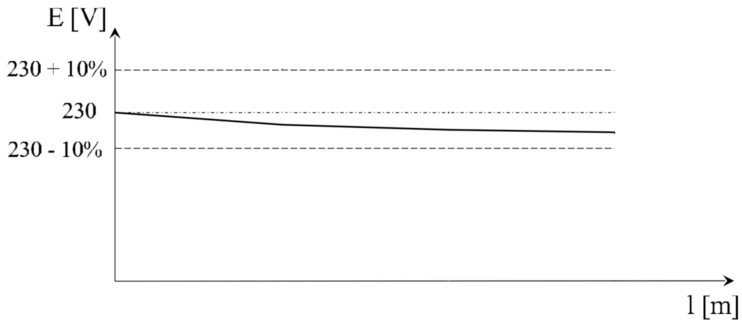

Figure 1.7: Voltage curve along low voltage feeder without PV modules connected [23].

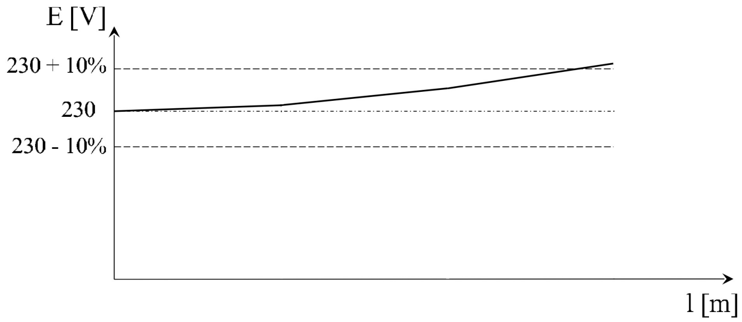

Figure 1.8: Voltage curve along low voltage feeder with PV modules connected [23].

1.4 Wind Energy

A wind turbine is a machine which converts wind power to electricity. Wind turbines are connected to the low voltage and medium voltage distribution grid. In terms of total generating capacity, the turbines that make up the majority of the capacity are quite big, in range of 1.5 to 5 MW. These large wind turbines are mainly used in larger utility grids and connected to the transmission grid.

Figure 1.9 shows two power curves for onshore wind turbines in 2011 and an approximation of one in 2030. The relative output will be much greater in the future much because of the wind harnessing of higher wind speeds. Note that the electrical power output is expressed as percentage of the rated power $\left(\frac{W}{W_{installed}}\right)$ [29].

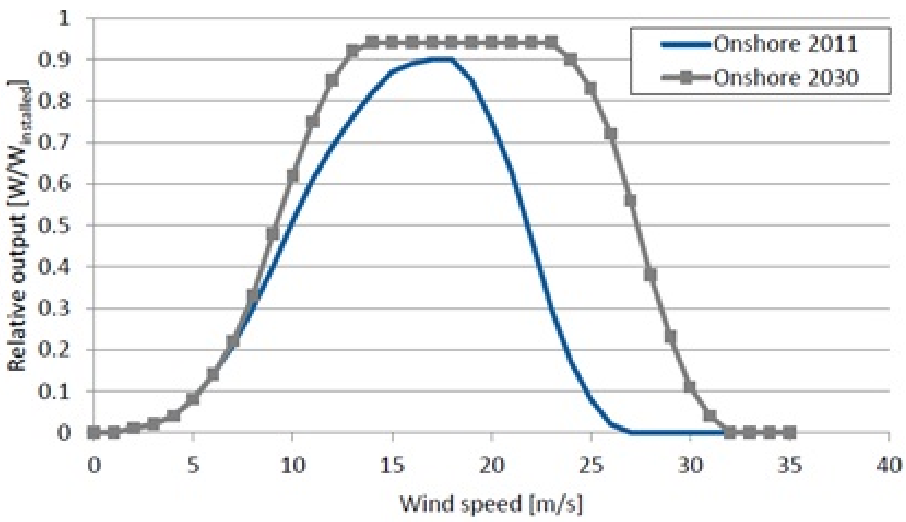

Figure 1.9: Example of wind turbine wind curve [29].

One of the challenges in the wind power integration is that the output production is not constant and mostly fluctuate below the rated power, which results in frequency fluctuations and occurrences of voltage flicker at the buses in the power system connected to the wind turbines. This fact can cause instability problems in the power system, especially when there are loads in the grid which are very sensitive to variations of voltage and frequency. Integrating wind power generation into the electric grid can also create operational difficulties for the transmission system operator. The existing transmission system was built to meet the operating features of conventional power plants and not for a variable source of energy such as wind power [26].

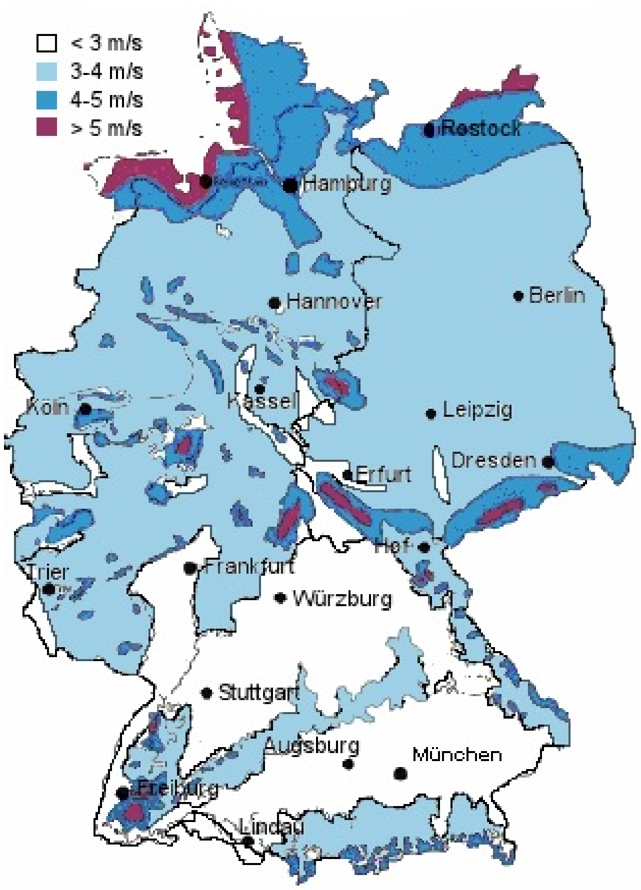

Figure 1.10: Wind speed map at 10 m height over German territory [30].

Figure 1.10 shows the wind speed all over German territory, it can be seen that yearly average wind speed is highest in the north. Most of the off-shore power plants are located in the North-sea with an installed capacity of 577.5 MW [16]. Much more are being planned and by 2030, a capacity of 25 000 MW from both

Nordic-sea and Baltic-sea power plants are to be connected to the mainland according to the plans of the German Federal Government [32]. Figure 1.11 shows the scenario for future wind power generation in Germany, as it can be seen that the highest amount of installed wind power will be located in the northern parts, and as said before, especially in the Nordic- and the Baltic sea .

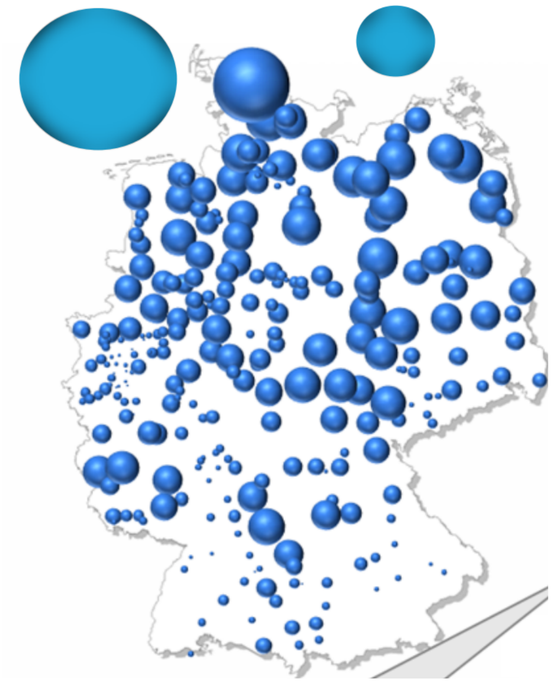

Figure 1.11: Future scenario of installed wind power in Germany in 2033 [16].

A study from the German Federal Environment Agency has concluded that approximately 13.8% of the German territory could be used for onshore wind energy harnessing. This area would mean that the total capacity of the installed wind turbines could be around 1 200 GW and the yearly generated power would be approximately 2 900 TWh and according to [34] it is five to six times the yearly German electricity consumption. Table 1.1 below shows the potential of south, middle and north Germany. It can be seen that the highest potential is in the north, although a big potential was also charted for the central and southern part of Germany. With a high penetration of wind power in the north, the bulk power transfer from the north to the south will increase and the need of measure for balancing the active power is highly recommended to implement [33].

Area	Area potential [km^2]	Capacity Potential [GW]	Output Potential [TWh]
North Berlin, Brandenburg, Bremen, Hamburg, Mecklenburg-Western Pomerania, Lower Saxony, Saxony-Anhalt, Schleswig- Holstein (= 38.9 % of German territory)	22 900	500	1 400
Central Hesse, North Rhine-Westphalia, Rhineland-Palatinate, Saxony, Thuringia (= 30.7 % of German territory)	11 200	300	700
South Baden-Württemberg, Bavaria, Saarland (= 30.4 % of German territory)	15 300	400	800
Germany overall	49 400	1 200	2 900

Table 1.1: Wind power potential for Germany [33].

Table 1.2 presents the current installed wind power and the number of turbines in every region of Germany. Figure 1.12 shows how the installed wind power is mapped for different regions. The most installed wind power is in the northern parts (offshore wind power is in the northern part also) of Germany.

Region	Power [kW]	Number of Turbines
Unclassified	1 579 000	847
Offshore	2 957 000	672
Baden-Württemberg	695 000	461
Bayern	838 000	449
Berlin	2000	1
Brandenburg	5 563 000	3 620
Bremen	201 000	109
Hamburg	182 000	120
Hessen	726 000	572
Mecklenburg- Vorpommern	1 814 000	1 700
Niedersachsen	7 212 000	5 200
Nordrhein-Westfalen	3 432 000	2 630
Rheinland-Pflaz	2 042 000	1 290
Saarland	165 000	96
Sachsen	1 280 000	983
Sachen-Anhalt	4 483 000	2 850
Schleswig-Holstein	3 282 000	2 580
Thüringen	1 231 000	834
Total	37 680 000	25 000

Table 1.2: Number of wind turbines and installed wind power in Germany [35].
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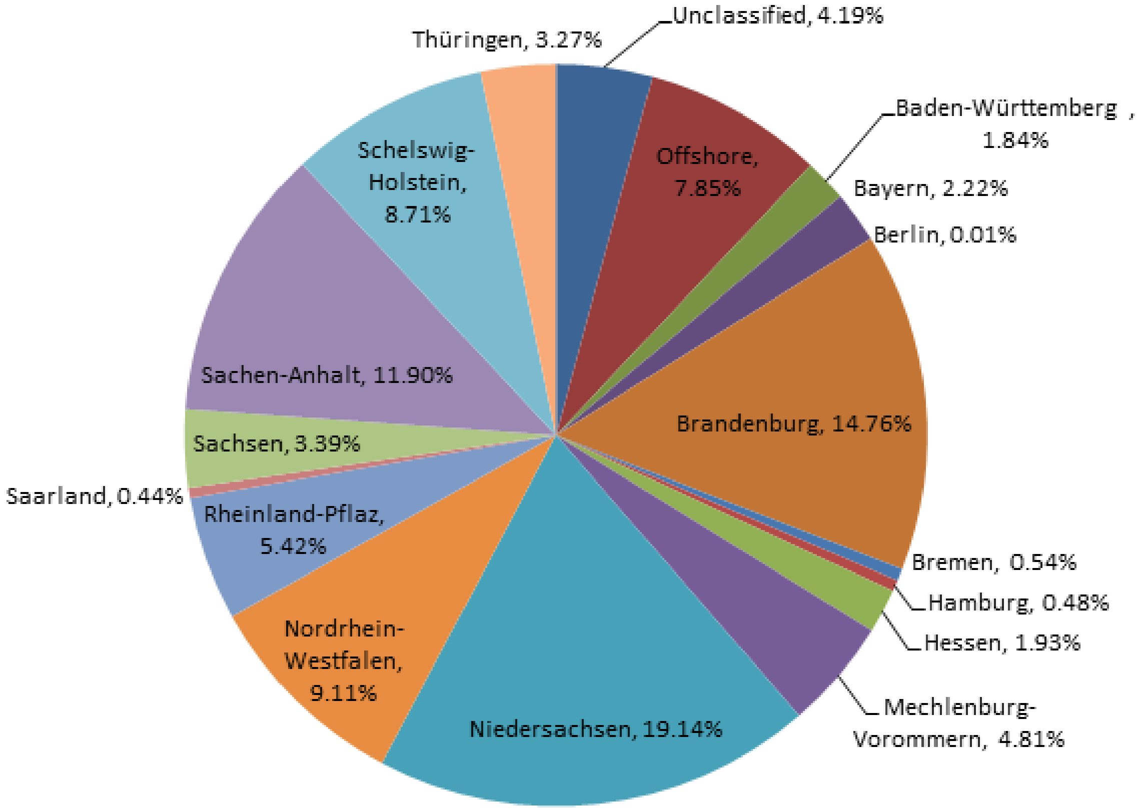

Figure 1.12: The installed wind power divided on different areas in Germany from 03/2014 [35]

1.5 Grid code

A grid code is a technical specification or standard which describes the restrictions that a facility connected to a public electricity grid has to meet to guarantee safe, secure and economic operation of the power grid. The facility can be generating plants, a consumer or a legal entity. The grid code is defined by an authority responsible for the system integrity and grid operation [37].The grid codes refer for new planned connected units.

1.5.1 German Transmission Code 2007

The German Transmission Code guideline [37] is very essential regarding connection of power plants to the transmission grid. "The system and Network codes for the German TSOs (Transmission System Operators) cover most of the important rules which form the procedure and economic basis of grid usage and serve the operational and technical coordination between TSOs, DSOs (Distribution System Operators) and grid users. The transmission code is frequently reviewed and updated whenever considered needed. It is continuously refined in accordance with the current state of art in terms of economic and technical developments within the energy industry and on the basis of the governing legal provisions". There is also one European grid code "ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators" [38] which provides some different requirements to be defined by the TSOs in each European country. The common outline of grid connection requirements for electricity generating facilitates is defined by the ENTSO-E Network Code.

There are some important understandings that the TSOs have established concerning the operation and the responsibility of the power system. The first understanding is that TSO is responsible for the maintenance of the power balance within its control area[1] and the DSOs are responsible of the maintenance of the voltage limits and loading of the equipment in the grid such as transformers and cables. The local conditions in the transmission and distribution grid are affected by the grid security. If overloading of equipment, violation of voltage limits or loss of (n-1) security[2] occurs, a risk of disturbance in the grid security raises. The network operator is responsible for the removal of the disturbance in his control area.

The connection owner[3] should request the TSO to inspect if the grid conditions at the planned grid connection point are suitable. Thus, the TSO shall investigate if the installation of the equipment can be functioned without disturbing the transmission grid and the supplied power to the TSO's grid still can be transferred.

When the grid is disturbed, it deviates from normal operating conditions and the generating unit has to be automatically disconnected from the grid if its

[1] Area for which a TSO holds responsibility for control

[2] The (n-1) security expresses the ability of the transmission system to lose a linkage without causing an overload failure elsewhere

[3] A connection owner is any natural or legal person whose electrical installation is immediately connected through a supply connection to the network of the system operator

frequency is less than 47.5 Hz or above 51.5 Hz or in case of loss of steady-state[4] or transient stability[5]. It is the responsibility of the network operator to bring the normal conditions back. Concerning generation units depending on renewable energy sources, they must be controlled in terms of active power output. “All renewable-based generating units must reduce their active power with a gradient of 40% of the generator’s instantaneously available capacity per Hz while in operation, at a frequency of more than 50.2 Hz”.

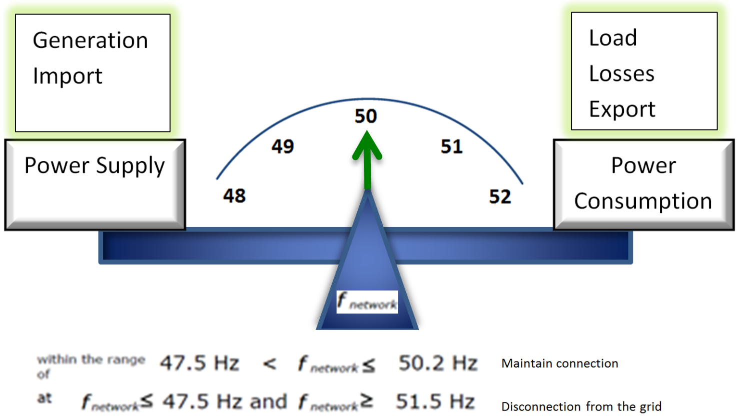

Figure 1.13: Definition of the frequency limits [37].

Congestion exists if the (n-1) security cannot be maintained because of the load flow in the grid. If congestion occurs on the transmission system, congestion management shall take action and that might affect the imports and exports between control areas. “Congestion may also occur within a short time as a result of unexpected operational situations or in the event of schedule events which are likely to give rise to load flows exceeding the available capacity” [37].

1.5.2 Guideline for Generating Plants Connected to the Medium-Voltage Grid by BDEW

The guideline summarizes the important aspects which have to be taken into account for the connection of generating plants (wind turbines, PV plants, biomass plants) to the network operator’s medium-voltage grid. The guideline complements the low-voltage guideline (section 1.5.3) and transmission guideline which takes concerns to the particular characteristics of the different voltage levels individually. Similar to the high and extra high voltage level, generating plants connected to the medium-voltage grid have to contribute to the grid support in the future. Therefore if failures happens, the generating units must not immediately be disconnected from the grid, the generating units have to contribute

[4]If the electric power system previously in the steady state reverts to this state again following a sufficiently “minor” fault, it has steady-state stability

[5]If an electric power system which has suffered a “major” failure through transient phenomena and then gets back to its original steady state, it shows transient stability

to support the voltage in the medium-voltage grid.

Generating units shall be connected to the medium-voltage grid at a suitable connection point. The network operator shall examine the suitable connection point which ensures secure grid operation and at the same time be able to transfer requested power. The requested active power and the maximum apparent power (S_{Amax}) of the generation unit have to be investigated in technical terms by the network operator after generation unit's owner filed its application foam. After that, the network operator will determine the suitable connection point in the grid.

Generating units may cause higher loading on lines, transformers and other equipment. That is why it is necessary to examine the loading capacity of the grid equipment regarding to the already connected generating units. The maximum apparent power for most generating units can be used as a basis for the thermal loading of the grid equipment. The sum of the total maximum active power (P_{Emax}) divided by the minimum power factor (λ) which is determined by the network operator, gives the maximum apparent power:

$$S_{Amax} = \frac{\sum P_{Emax}}{\lambda} \tag{1.2}$$

Under normal operating circumstances of the grid, the magnitude of the voltage changes caused by all generating units at a connection point in the medium voltage, must not exceed 2% compared to the voltage magnitude without the additional generating unit connected. In event of disconnection of one or more generating units at the same time, the voltage change at every point in the grid is limited to 5%. However, generating units which have a connection in subordinated low-voltage grid shall be defined of other values which are described in the guideline "Generating plants connected to the low-voltage network" (see section 1.5.3).

When the generation units are operating, the grid's short-circuit current increases due to the generation units' short-circuit current. To determine a generation unit's short circuit-current influence, three estimation values should be followed; for asynchronous and double-fed asynchronous generators, the short-circuit current must be six times the rated current. For synchronous generators, the short-circuit current is eight times the rated current and for generators with inverters (such as PV), onetime the rated current.

In risk of potential danger to secure system operation, islanding, congestions, rise in frequency or risk to the steady –state stability, the network operator is entitled to a temporary restrictions of the power feed-in or disconnect the generating units. The generating units must be capable of reducing their active power by maximally 10% of the agreed active power connection. The generation units' owner is responsible of the reduction of the power feed-in. The reduction to the target value must be done without delay. The target value is a percentage value related to the agreed active power connection. The power reduction must follow the same procedure as figure 1.13 [39].
In the voltage disturbances standard, the voltage magnitude variations in the medium-voltage grid and the low-voltage grid shall be ±10% of the nominal

voltage for 95% of a week. That means that the value during 95% of the time shall be between 90% and 110% of the nominal voltage. That leads to that in an extreme case; customers could be supplied at 90% of nominal voltage while for 5% of the time the voltage could be much lower [36].

1.5.3 Power generation systems connected to the low-voltage grid

The guideline summarizes the important aspects which have to be taken into account when connecting a power generation unit to the operator's low-voltage grid. The guideline is a basis for both the grid operator and the installer of the generation unit.

Generation units shall be connected at an appropriate point in the grid, which is determined by the grid operator. The grid connection shall ensure safe grid operation and the power can be drawn and transmitted. This is to guarantee that the generating unit operates without interfering and without disturbing the supply of the other customers.

Under normal operating circumstances of the grid, the magnitude of the voltage changes caused by the additional generating unit the point of common connection, must not exceed 3% compared to the voltage magnitude without the generating unit connected.

Maximum permissible short-circuit current, voltage magnitude variations from the nominal voltage and active power output shall follow the same rules as the medium-voltage guideline (section 1.5.2)

Generation units with inverters such as PV-modules shall only be connected if the ratio of starting current (I_a) and the nominal current of the generating unit (I_{nG}) is less or equal to one [40]:

$$\frac{I_a}{I_{nG}} < 1 \tag{1.3}$$

1.6 Effects on the Distribution Grid

We have seen a substantial growth of distributed energy sources or distributed generation since the 1990's. Distributed generation is an exciting solution to the increase of the energy consumption with the several remarkable benefits such as financial savings and treduction of the emissions from greenhouse gases. However if the distributed generation units are not properly installed and integrated with the power systems, the potential of them could be completely invalid. A high penetration of distributed generation might influence the operation and control of the transmission and distribution grid and leading to technical problems and instability in the grid.

There are some studies in the past examining the impact of the distributed generation in power systems which identified some important aspects concerning their connection and operation. An analysis on change of power flow direction in corporation of distributed generation integration was verified in the IEEE article, “Effects of Dispersed Generation (DG) on Distribution Systems” [42]. In reference [43] the authors investigate the influence of distributed generation on the system stability and the system reliability during peak loads. Another study that focuses on the system protection shows that an increment in distributed generation in the grid results to an increment in the short-circuit fault level [45]. However, the studies mentioned could conclude that the problems are only coupled to the medium- and low-voltage levels [41].

Connection of the distributed generation to the distribution grid may cause different technical problems. The most common problems are; overshooting in the thermal limits in the conductors, operation faults in the protection system, voltage harmonics increment in the grid and over-and-under voltage faults [41]. The effect of distributed generation units in big quantities strongly depends on the type of the distributed generation and grid type. Distributed generation units can either be connected to the distribution grid via power electronic converters or directly connected, e.g. synchronous and asynchronous generators. The power flow in the distribution grid, grid losses and the voltage control are affected in all cases [47].The most important problem that will definitely occur in the near future is the rising amount of congestions in areas with a lot of distributed generating units, both in the low- and medium-voltage grid. For example the congestion level in regions with a big penetration of PV (south of Germany) will increase in the near future. The same will happen with the regions with a big penetration of wind power (north of Germany). Ie3 and TU Dortmund [46] investigated the future grid congestions that may occur in the German low- and medium-voltage grid in 2015. The result of the study can be seen from figure 1.14. The highest amount of possible congestions may occur in the north where there is a high penetration of distributed wind turbines and in the south parts where there is a high penetration of distributed PV units. It is notable to understand that the maps do not show that in these areas, grid congestions are going to occur, it only shows the tendencies, where there are factors that foster the occurrence of grid congestions.

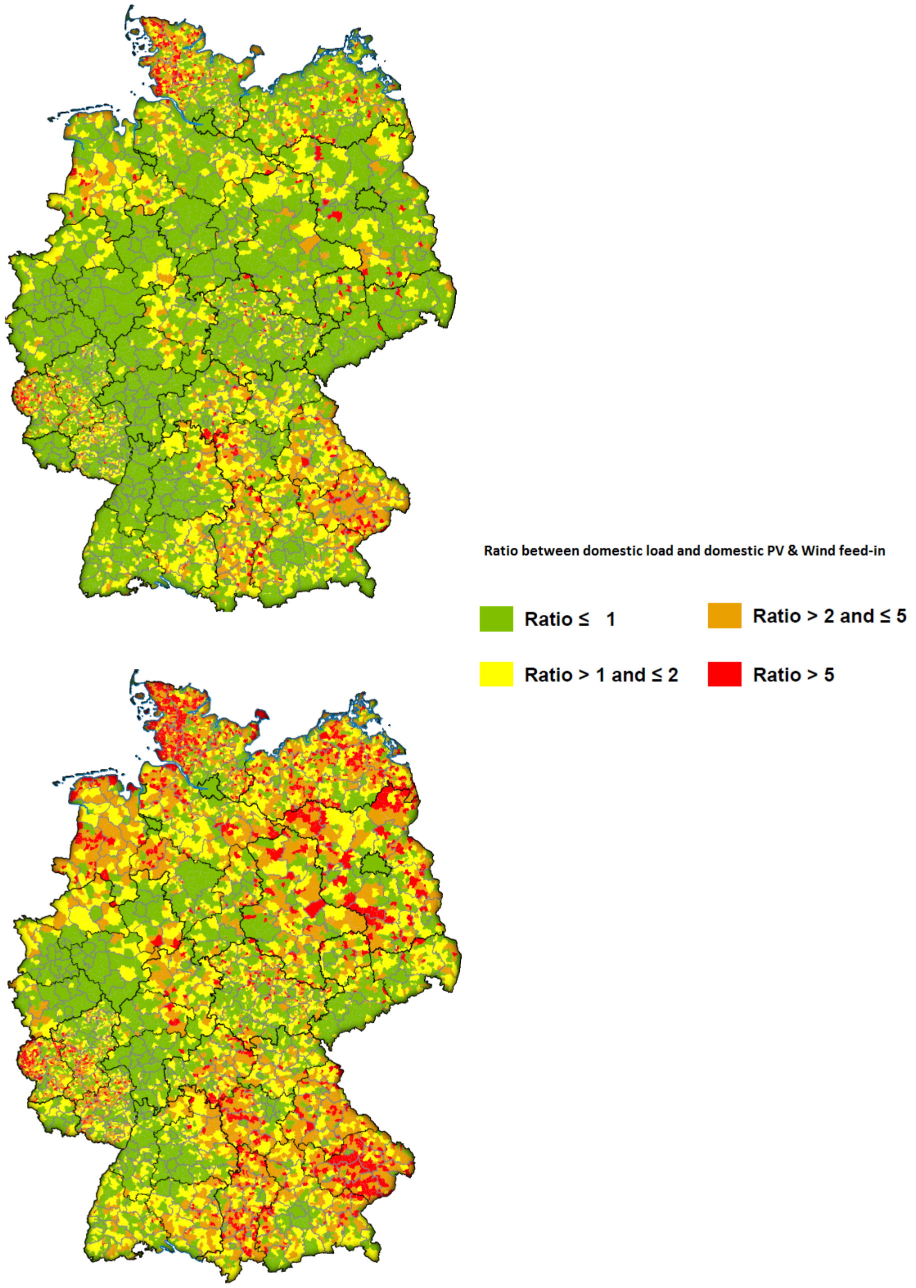

Figure 1.14: Possible congestions in the low voltage (upper) and medium voltage (lower) grid in Germany in 2015 [46].

The author in [48] investigates the impact of the customers on the power quality of the distribution grid. There are some factors that influence the power supply conditions in the distribution grid; one of them is the deviation due significant change in loads, the other is nonlinear loads connected to the distribution grid which cause higher current harmonics. Loads that vary rapidly and repeatedly in time (= flickers) may also give a negative impact on the power quality of the distribution grid. Faults that the customers are not responsible for is different faults in the grid or faults transmitted from the transmission grid. In many cases the power quality problems, especially voltage dips were caused by the customer's installations. Poor compensation, overload, short circuits, cable failures or motor starting phenomena caused the failures of their own sensitive equipment or of the other customer's equipment that are connected to the same power source. For example, a high penetration of PV could lead to transients because of the variations in power output during production (see figure 1.15). The variations in the power generation occur from the passing clouds in the sky, shadows and temperature variation.

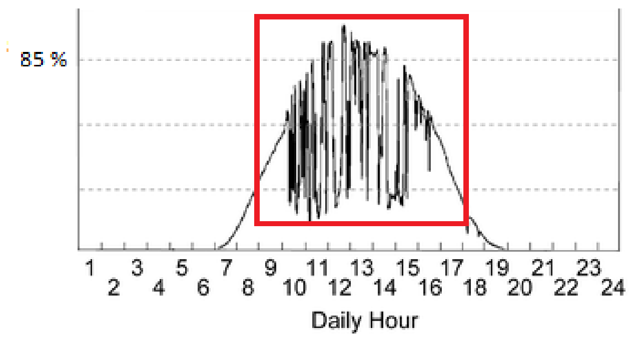

Figure 1.15: The fast variations in production in the red area cause the transients in the distribution grid [49].

1.7 Effects on the Transmission Grid

The continuous change of the generation system to more renewable energy generation facilities increases the challenges for the whole electric system in Germany. The first challenge arises from the trend towards a more decentralized power generation, which creates regions where there is a surplus of electrical energy and regions with shortage of electrical energy. The second challenge arises from the dependence of the wind and solar power supply, which shows that a lag in time between demand and supply of electrical energy occurs. The third and most important challenge is the increasing production from generation units at sits with already high full loads hours. This is because the market- participants are driven by the huge subsidization of renewable energies and the attitude to freely choose the sites for the highest possible efficiency of the generation units, without thinking of the consequences that may arise in the grid. The result of the challenges above immediately effects the stressing of the transmission grid and bulk power [6] transfers over large distances becomes much more common. The mentioned challenges above cause also new congestions and overloadings in the German transmission system.

[6]huge power amount on one single transmission line for example an off shore wind park connected to a submarine cable transfers bulk power to the mainland

One important factor is the impact of the weather conditions such as wind and snow, which results in damage to the overhead transmission lines. Wind vibrations and deviation are common pitfalls of overhead transmission lines, and are the main reasons of transmission line breakage. The rainy and snowy weather may cause icing to transmission lines and the irregular pulling force will lead to leaning of the transmission tower or line breakage. This results to new congestions and over loadings in other lines and thereby causes bottlenecks in the transmission grid [50].

Chapter 2

Grid Capacity Measures

The demands on the electricity grids have progressively increased with the liberalization. With the increase in the electricity trade, the expansion of renewable energy, the increasing separation of power generation, increasing consumption, and an increment of the fluctuations in power generation, significant investment in managing this are essential to meet these requirements in the near future. The aim of this chapter is to investigate suitable measures that can be taken in order to balancing the active power in the distribution grid.

2.1 Grid capacity measures for the Transmission grid

In order to reduce the overloadings and disturbances in the transmission lines, four main actions can be taken. The first one is to reinforce the grid, i.e. to construct new lines in the effected regions. It's a long term measure and the approval process is usually long lasting. It's the costliest but most effective measure that is carried out right now. The second possibility which is a medium term is the splitting of market region. The splitting of the maximal transfer capacity between the newly formed market zones results to a modification of the congestions. This option is already utilized in some European countries like Sweden, Norway and Italy. The third is bulk energy storage technologies like compressed air energy storage (CAES) and pumped hydro energy storage (PHES). To reduce loads during certain times in a day or to quickly discharge large amounts of stored electricity are the main purposes of bulk energy storage technologies [54]. The fourth and most common option is redispatch (section 2.1.1) which is a short term solution and is carried often in many European countries. In cases where the grid security is jeopardized the transmission system operator can take some actions to ensure secure operation on the grid. The first action (that might increase the grid losses but apart from that at small costs) is to change the grid topology to relieve the grid. The change of the grid topology is almost always most effective in case several isolated overloadings arise and the overall loading of the transmission grid is reasonable.

The existing redispatch techniques purpose is try to eliminate any present congestion and adjust the power plants dispatch to guarantee safe grid operation and minimal redispatch costs. Therefore the appropriate maximal power which flows on every branch needs to be maintained both in normal and fault operation conditions [50] [53].

2.1.1 Redispatch

When the generation of a dispatch has been carried out by the power exchanges, this dispatch is then directly communicated to the transmission system operator, who evaluates the grid situation for this certain load and generation pattern. In case that the grid security is risked, the transmission system operator can interfere into this dispatch and redirect it into other transmission lines in order to guarantee a secure operation of the grid. This process is called redispatch and can be regarded as a short term solution to deal with expected congestions and overloadings [50].

2.2 Grid capacity measures for the Distribution grid

Distributed generation and the introduction of variable fluctuating sources (such as solar or wind energy), have shown remarkable growth worldwide. The variability and non dispatchable nature of these sources have led to concerns regarding the reliability and capacity of the distribution grid. For that, different measures have to be taken in order to regulate the grid capacity of the distribution grid. There are different techniques for the distribution grid, for example energy storage, tap-changing transformers, frequency and power control strategies, load shifting etc. In this part the focus will be on energy storage and load shifting.

2.2.1 Energy Storage

Energy storage means an energy conversion process that converts different forms of energy (e.g. chemical, thermal, mechanical energy) into storing forms of different media. For energy storages, when needed, the stored energy can be converted in electrical energy and fed in to the grid. Modern energy storage technologies have been used since the middle of the 19th century. The first rechargeable lead-acid battery was invented in 1859 and the first pumped storage was built in the 1890s. Nowadays, energy storage is vital regarding the growing of renewable energy sources and maximising the grid efficiency [55]. One essential energy storage solution is the pumped hydro storage which generates and stores energy by transporting water between two reservoirs at different levels. When the electricity demand is high, the stored water is released and streamed downhill from the upper reservoir into the lower through the turbines to generate electricity. When the electricity demand is low, the turbines use the surplus energy to pump the water up to the upper reservoir. “Pumped hydro storage is an essential solution for grid reliability, providing one of the few large-scale, affordable means of storing and deploying electricity” [44].

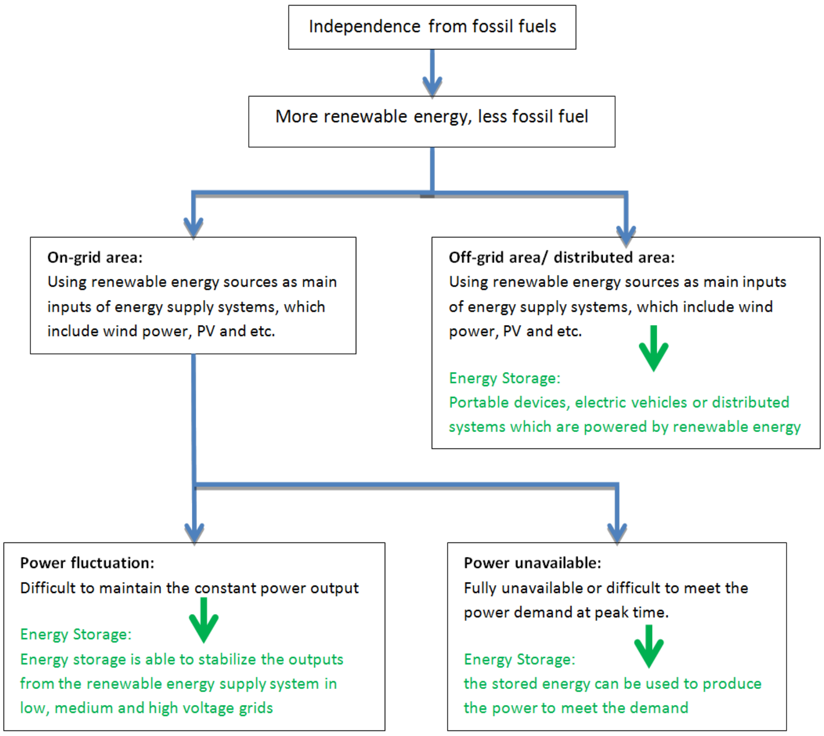

Figure 2.1: Problems in renewable energy systems and measures by using energy storage [56].

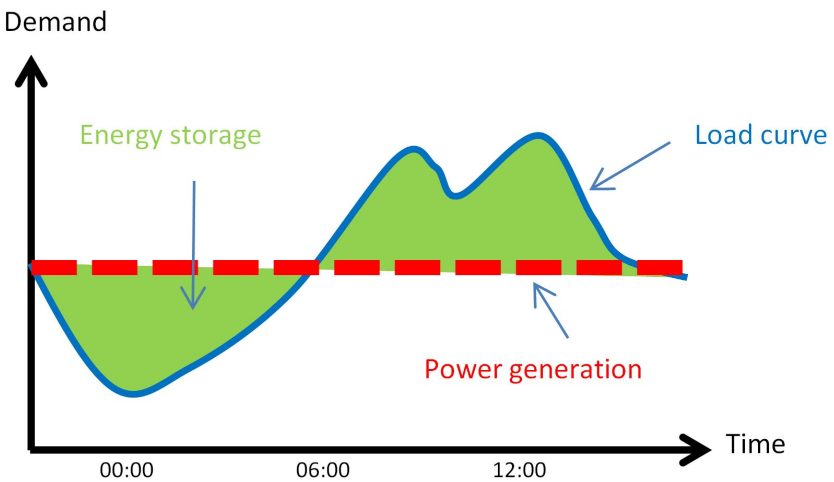

Figure 2.2: Energy storage utilization for load leveling following a demand profile [56]

Among all different measures which targets the challenges of load balance, energy storage is one of the most promising one. Electricity generation plants can operate close to the rated capacity or rated power most of the time because of the deployment of energy storages. That means that power plants like nuclear plants and coal plants can operate after the demand variation. If a suitable energy storage is deployed and suitable integrated, the power generation from a power plant can be hold to around relatively stable value (see figure 2.2). Energy storage is also critical for managing the output of intermittent renewable resources such as wind and solar power, shifting their generation capacity to be available when needed most and maximising their value. In addition, biogas and hydrogen in particular are seen in Germany as a crucial way of storing energy seasonally to provide sufficient electricity when power consumption is the highest and no solar power is available, e.g. on dark evenings of winter [55].

Storage Capacity	**Features & Functions**
Short term (minutes)	- Cover load during short-term load peaks - Decrease needs for start-up of backup generator - Store renewable energy surplus to be used later
Medium term (a few hours)	- Compensate for load leveling - Integrate surplus energy with thermal systems - Store renewable energy for compensation of weather-based changes
Long term (several hours to a couples of days)	- Provide reduction in fuel consumption - Decrease waste of renewable energy - Produce hydrogen from renewable sources
Planning (weeks to months)	- Large power storage systems (CAES, PHES and etc.) - Energy management and national energy security

Table 2.1: Functionality and features of storage system [56]

From the interviews with experts in the field of grid storage in E.ON, it is understood that the most suitable storage for distribution grids will be battery storages, specially Li-Ion, Lead-Acid and Vanadium Redox Flow batteries [57].

Batteries can be divided into two different groups, primary and secondary. The difference is that the secondary batteries are rechargeable and these are thus relevant for energy storage. Batteries consist of galvanic cells. A galvanic cell in turn consists of two electrodes immersed in a conducting material, usually a liquid electrolyte. The positive electrode is called the cathode and the negative is called the anode. Figure 2.3 below is a schematic diagram of how a battery cell looks like [55].
When an external load is connected between the terminals of the battery, a chemical reaction inside the battery occurs. It is this reaction which creates the electric energy. When the external load is switched on, electrons from the anode rides through the load to the cathode while the ions go the opposite direction, between the anode to the cathode, through the electrolyte.

The most important properties of a battery storage are listed below:

Energy density (Wh/l): A measure of the amount of energy stored per liter. It relates to the volume of the storage reservoir, for example a cylinder or a fuel tank. The higher the energy density of the storage medium is

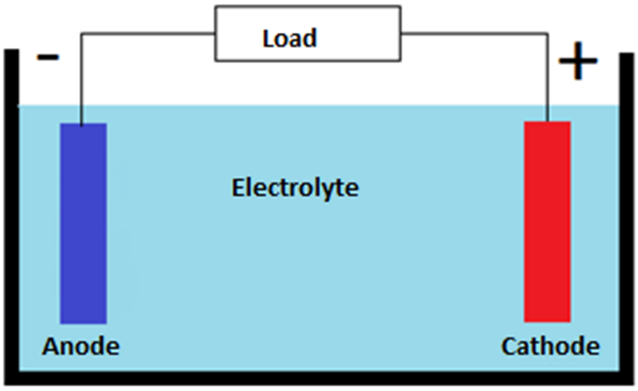

Figure 2.3: Schematic picture of a battery cell

selected, the higher amount of energy could be stored.

Power rating: A recommendation of the maximum power to be used on the device set by the manufacture. This value is generally set slightly lower than the level where the device could be damaged.

Efficiency: Energy storage systems have two primarily forms of efficiencies. The first one is the ratio between the useful output of an energy conversation and the input in energy terms (electric energy, heat energy, mechanical energy); this is called energy conversion efficiency and is mostly used for charge and discharge of batteries. The other one is round-trip efficiency also called cycle efficiency, storage efficiency or electrical efficiency. It is a percentage to indicate the amount of energy output from an energy storage system for each unit of energy input.

Discharge time duration: The amount of time that an energy storage system must be able to discharge, holding the system power rating, without recharging.

Self-discharge rate: Specifies how long an energy storage system takes to discharge while it is unused. In order to reduce self-discharge, it is suggested to store batteries and cells at relatively low temperatures.

Recharge rate: The rate at which power can be stored, for example, battery storage may take 13 hours to deplete and 18 hours to full charge.

Life time: The service time of an energy storage system. The unit for the life time is usually in years.

Li-ion Battery Storage

The cathode material of the Li-ion batteries is made of lithium metal oxide and the anode is made of graphitic carbon. The electrolyte is normally a non-aqueous organic liquid, containing dissolved lithium salts.

Li-ion batteries are primarily used as medium-term storage, but can also be used as short term storage. The Li-ion batteries are the most important battery storage technology in the portable application area (cell-phones, laptops). There are also several demonstrations in Europe where Li-ion batteries have been used as energy storage [60]. In the US, the Li-ion battery storage is already used in some areas where the grid is very weak. The central challenge with the Li-ion batteries is to reach a major cost reduction and on the same time get an acceptable lifetime and a safety process [55].

Parameters For Li-Ion Batteries	
Cycle efficiency	80 - 90 % [59]
Power rating	∼ 0 – 50 MW [59]
Energy rating	∼ 0 - 50 MWh [59]
Calendar Life	5 - 20 years [55]
Daily self-discharge	∼ 5 % [59]
Energy installation cost ($C_{E,Li-ion}$)	400 €/kWh [61]
Power installation cost ($C_{P,Li-ion}$)	1000 €/kW [61]
Main applications	Frequency control, Voltage control, Peak shaving, Load levelling, Residential storage system [55]

Table 2.2: Today's technical data of a Li-ion battery.

The most important properties of a Li-ion battery are its high energy density, specific power and specific energy. Other main properties are the fast charge and discharge time of the Li-ion battery. Table 2.2, shows that Li-ion batteries might not be suitable for long-term energy storage applications and that is because of the relatively high self-discharge time [60].

Some weaknesses of the Li-ion battery is that once the batteries are produced, they start degrading, that means that their original capacities and functions can only last for a few years whether they are in use or not. The life time of the Li-ion battery is depending on the cycle Depth-of-Discharge; therefor it can be ruined if the battery is totally discharged. That is why the Li-ion batteries are not recommended for applications in back-up power supplies [55].

Lead-Acid Battery Storage

One of the oldest battery technologies is the Lead-acid battery (also known as PbA). It's mainly used in short-term and medium-term energy storage applications. The lead-acid battery technology has the largest installed capacities all over the world (mostly due car batteries) and many existing have been in operation for up to 20 years. The storage process in the Lead-acid battery is similar to the Li-Ion battery mentioned above. The differences are that the cathode is made of PbO_2, the anode is made of Pb and the electrolyte is sulphuric acid (A) [55].

There are some successful and important examples related to the Lead-acid battery storage systems. One of them is Chino (1988) in California, a 10 MW vented[1] Lead-acid battery system which was installed as a pilot facility to evaluate battery systems and its main role was to evaluate load-leveling operations of battery storage systems. Another example is the one of the first Lead-acid battery storage facility which was the former BEWAG (1986) 8.5 MW in Berlin which was used for frequency control [58].

Parameters For Lead-acid Batteries	
Cycle efficiency	70 - 85 % [59]
Power rating	$\sim 0 - 10$ MW [59]
Energy rating	$\sim$ 0 - 40 MWh [59]
Calendar Life	5 - 15 years [55]
Daily self-discharge	< 0.1 % [59]
Energy installation cost ($C_{E,Lead-acid}$)	400 €/kWh [61]
Power installation cost ($C_{P,Lead-acid}$)	300 €/kW [61]
Main applications	Frequency control, Voltage control, Peak shaving, Load levelling, Residential storage system [55]

Table 2.3: Today's technical data of a Lead-acid battery [59].

From table 2.3 above, the Lead-acid battery have a relatively high efficiency, small daily self-discharge and most important, it have a relatively low cost. Thus the Lead-acid batteries are suitable for energy storage systems for longer period of time. One of the major disadvantages is that the Lead-acid batteries perform poor at low operating temperatures and that is why a thermal management subsystem is necessary [55]. The high operating temperature may improve the performance of the lead-acid battery in terms of higher capacity, but that will result in a reduction in the cycle time of the battery [60]. As is can be seen from table 2.3, the calendar life time of the lead-acid batteries is not as high as the calendar life time of the Li-ion batteries.

There are many different manufactures producing Lead-acid batteries, but however they are not produced in large quantities compared to the automotive market (batteries in cars and trucks). By mass-producing Lead-acid batteries in large quantities, it could result to a significant cost reduction. The cost could be even more reduced by optimization of the cell design for the needs in stationary applications [60].

[1] The electrolyte is an aqueous sulphuric acid solution

Vanadium Redox flow battery storage

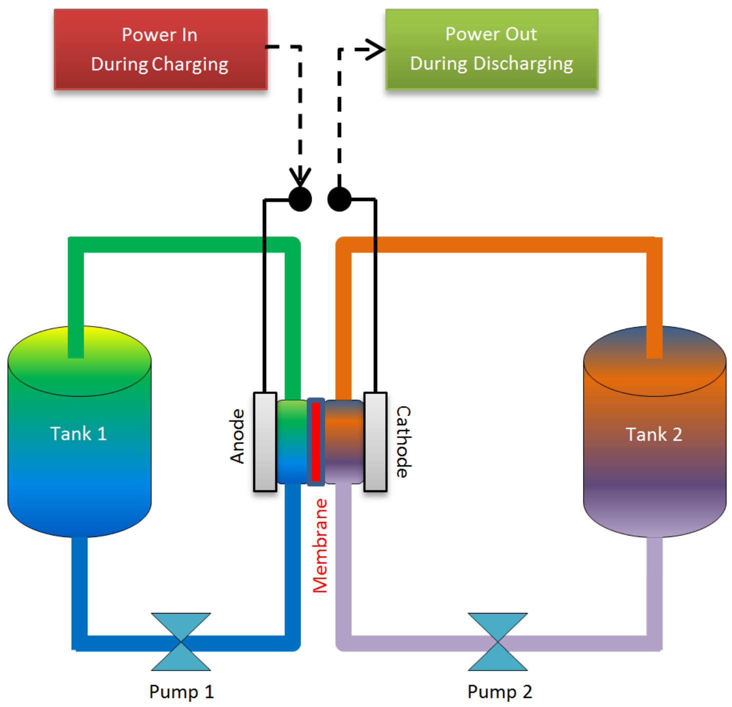

Figure 2.4: Schematic description of a Flow Battery.

The active material in the redox flow batteries is made up of salt and dissolved in a fluid electrolyte which is stored in tanks. In vanadium Redox flow batteries, the electrolytes are based on Vanadium. When an electrochemical reaction happens, carbon electrodes enable the electron flow through the load and by migrating hydrogen ions through the membrane; the electrical balance is then reached. A current is generated in the electrodes when the electrolyte flows to a redox cell. During charging, the electrochemical reaction is reversed by applying overpotential. The higher required energy density is the bigger the size of the tank needs to be [55].

From table 2.4, the unlimited power density and the construction of bigger tanks which can be done easy, makes the Vanadium Redox Flow battery very suitable for long-term energy storage. The technology can bridge the gap between medium-term storage and long-term storage [55]. Several demonstration sites with the Vanadium Redox Flow battery exist; the most relevant one is the hybrid energy storage system in the island of Pellworm in northern Germany. The hybrid system consists of one Vanadium Redox Flow battery with a capacity of 200 kW and one Li-ion battery [57].

Parameters For the Vanadium Redox Flow Battery	
Cycle efficiency	80 - 85 % [59]
Power rating	∼ 0-50 MW [59]
Energy rating	≤ 120 MWh [59]
Calendar Life	15 years [55]
Daily self-discharge	∼ 0 % [59]
Energy installation cost ($C_{E,Lead-acid}$)	400 €/kWh [61]
Power installation cost ($C_{P,Lead-acid}$)	1600 €/kW [61]
Main applications	Secondary/ Tertiary Frequency control, Long-term storage system [55]

Table 2.4: Today's technical data of a Vanadium Redox Flow battery [59]

The main advantage of the Vanadium Redox Flow battery is its independent scaling of power density and this type of batteries offers a big potential for relatively cheap "weekly" storage. The high cycle life time of this type of batteries makes them also very interesting and cost effective in the long term [55]. As seen from table 2.4, the power capital is very high and the main reason is that Vanadium is very expensive and exists in limited resources. The maintenance costs for the Vanadium Redox Flow battery is high due to the leakage caused by the acidic liquids in the tanks [60].

2.2.2 Load shifting

The process of shifting loads from peak periods to off-peak periods is called load shifting. The main purpose for the customer is to take advantage of the low electricity price in the off-peak hours when using heavy load consumption units. A distribution operator's main advantage of load shifting is that the load and voltage on the cables are decreased when the customers choose to consume more on off-peak hours rather than peak hours. So if it is properly done, load shifting is smoothing the peaks and valleys of energy during different times of the day [63]. Load shifting is considered as a simple way to achieve network load reduction because it is only a matter of appropriate usage and time management, where the operations that are normally in process during peak hours, are instead carried out or postponed to a later point in time. For the most of the business and the commercial sector, load shifting is achieved by shifting their processes and operations to night time [62].

Load shifting can be implemented in a number of ways. For example using Demand Response Programs which shifts loads by controlling the functions of e.g. refrigerators, water heaters and air conditions at peak hours. Energy storage is also an important feature of load shifting, for example pumped hydro facilities pumps water from low reservoir into higher one during off-peak hours, and then reverses the flow during peak hours to generate electricity. Off-peak electricity can also be stored in batteries, which can then be discharged during peak hours. Electrical thermal storage can also store off-peak electricity in form of thermal heat or freeze water (often during the night), and then provides heating or low power air conditioning during peak hours (often at day time).

Another electrical thermal measure is the Combo Air Conditioner and Heater. As the name says, it can produce both heating and cooling depending on the temperature of the room. This measure is used in the scenarios and has a power consumption of 1.4 kW while cooling and 1.2 kW while heating. The price of the Combo Air Conditioner and Heater (C_{CaH}) is around 600 €which is a very cheap measure for implementation of load shifting in households [69].

Electric Thermal Storage

Electric Thermal Storage is a technology for converting off-peak electrical power to heat and storing it as low cost heat. This stored heat is then used to immediate heating requirements and to provide total comfort during peak hours. This scenario is ideal for load shifting applications and can easily be integrated in the household. An Electric Thermal Storage system contains of high-density ceramic bricks and electric heating elements within the bricks. These bricks are capable of storing huge amounts of heat for long periods of time [68]. The Electrical Thermal Storage has also a very high efficiency, up to 100%. It is also a very cheap solution for energy storage, only approximately 22 €/ kW [66].Thermal storage units placed in rooms is varying in size from 1.32kW – 10.8kW [64]. Night storage heaters were installed in more than 1.5 million German households, which were operated with the off-peak electricity from the local providers. In 2008, the German Energy Conservation Ordinance (Energieeinsparverordnung) declared that the thermal Electric Thermal Storage is forbidden to use after 2020 and that all households should change their heating system until then. But in 2013, the prohibition of night storage heaters was lifted on 17.05.2013 by the Bundestag and the Electrical Thermal Storages may be operated beyond that date on [65].

The stored heat in the bricks can be calculated from the following formula:

$$q = V \cdot \rho \cdot c_p \cdot dt \tag{2.1}$$

Where:

q = Heat stored in the material
V = Volume of material
ρ = density of material (bricks= 1969 kg/m^3)
c_p = specific heat capacity of material (bricks= 921 $J/kg°C$)
dt = temperature change

Example:
Heat stored in 1 m^3 bricks heated from 25 $°C$ to 50 $°C$ can be calculated as [67]:

$$q = 1 \cdot 1969 \cdot (50 - 25) = 63470715J = \frac{63470715}{3600} = 17.6kWh$$

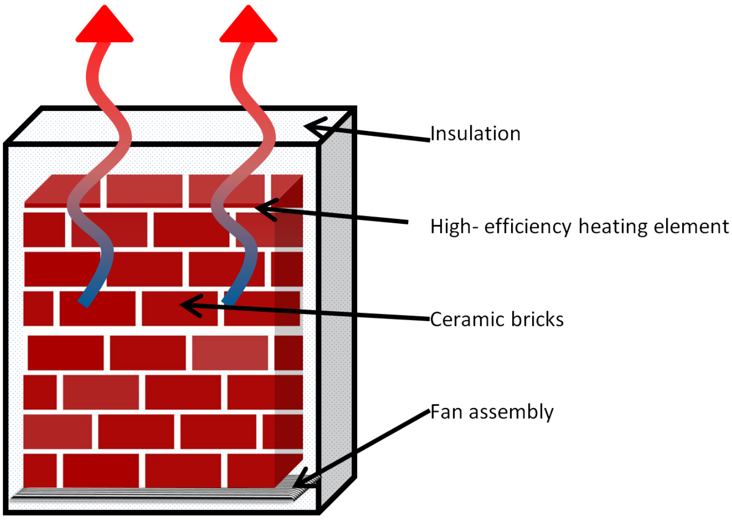

Figure 2.5: Schematic picture of an Electric Thermal Storage.

2.2.3 Biomass power plants

Biomass power plants generate carbon neutral[2] electricity from renewable organic waste that would otherwise be dumped. The generated energy is called *bioenergy*. There are two main types of biomass power plants. The first is the direct combustion biomass power plant which operates like fossil fuels power plants. A direct combustion biomass power plant burn the biomass fuel directly in the boilers to supply steam for the steam-electric generator or use the heat from the boilers for district heating. The other type is the biomass gasification power plant which converts the biomass to gas (methane) that can fuel the combustion turbines, steam generators, combined cycle technologies or fuel cells. The main advantage of biomass gasification power plant compared to direct combustion power plant is that the produced gasses can be used in variety of power plants. The biomass power plants are able to produce electricity at any time because of the combustion process technology. It's unlike the other renewable energy sources like wind and solar which only produces electricity when the wind is blowing or the sun is shining [70].

Forestry and agriculture are the main sources for the generation of bioenergy. Germany is the greatest producer of wood in EU, and wood is by far the supreme source of bioenergy in the country. Approximately 40% of German timber production is used as a source of energy; the rest is used as material. Germany is also leading the biogas market and in 2010 more than 60% of Europe's electricity from biomass was generated in Germany, with further growth to come.

Germany was using approximately 17% of its arable land for energy corps in 2011. Studies show that this share can be increased as a result of decrease in

[2]Carbon neutral is a term used to describe fuels that neither contribute to nor reduce the amount of carbon dioxide into the atmosphere [71]

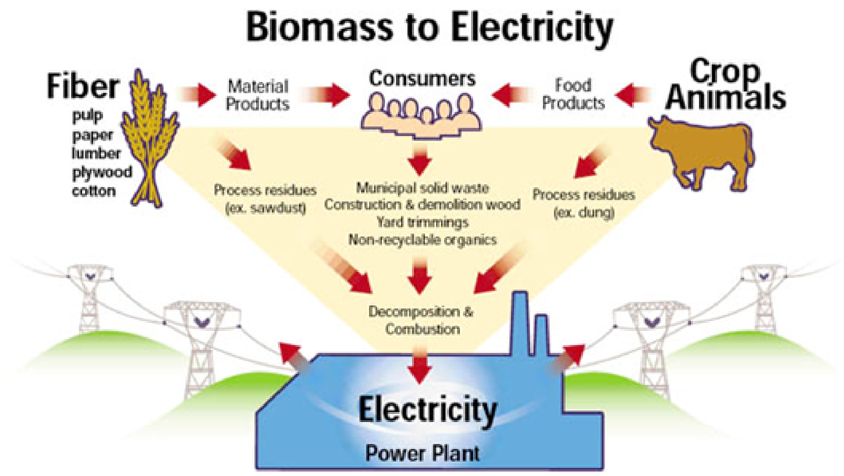

Figure 2.6: Overview of the biomass to electricity chain [76].

population in the next few decades and increasing agriculture output. The German Environmental Ministry estimated in 2012 that bioenergy made up 5.7% of the power consumption, 5.5% of fuel consumption and 9.2% of heat demand. Germany can increase those shares by reducing the total consumption.

Today, the total usage of biomass in Germany is more than 167 TWh, mainly of domestic origin. Studies show that the domestic supply could be roughly doubled, assuming maintain a completely sustainable production chain, domestic biomass potential is available in the full amount stated, the anticipated technological advancement is achieved and the produced biomass is used more efficient energy generation, Germany has the potential to meet between 8 and 12% of its current demand and between 11 and 15% of expected primary energy demand in 2020 [73].

Category	
Virgin Wood	From forestry or from wood processing
Energy corps	High yield crops grown specially for energy applications
Agriculture residues	Residues from agriculture harvesting or processing
Food waste	From food and drink manufacture, post-consumer waste and etc.
Industrial waste and co-products	From manufacturing and industrial processes

Table 2.5: The five basic categories of biomass [77].

According to recent reports, in 2015 the total cost for a gasification biomass power plant (a bubbling fluidized bed boiler biomass plant), is estimated to be between 2500€/kW and 3200€/kW. It looks much more promising when comparing biomass power plants with other renewables as it is estimated that in 2015, off-shore wind farms will cost between 2200€/kW and 2900€/kW in 2015, while concentrating solar thermal is estimated to be between 2400€/kW and 3800€/kW and photovoltaics in range of 2500€/kW and 3300€/kW. On the other hand, the total costs for wind power, nuclear and solar power plants are estimated to go down, as are biomass power plants which is expected to go down to between 2400€/kW and 3000€/kW. But according to the reports, between 2015 and 2025, the total costs of nuclear power plants goes down slightly, on the other hand the costs of the coal power plants are expected to rise significantly because of the added carbon capture and storage technologies. The costs of the biomas power plants are only for the installed power; beyond this costs for biofuel may be added in the generation stage [75].

Biomass power plants are generally located in the centre of agricultural areas and they can produce electric power all over the year. But there are some disadvantages with the connected biomass power plants. Because the location of the biomass plants is in agricultural areas, they are typically connected to a rural electric power distribution system and this kind of power systems is relatively weak. This rural distribution system is radial and the originally planning of system was meant to serve small amount of powers to local customers in the remote area. Thus, all loads are connected through several feeder portions in series to the substation. The most remarkable thing is that the peak load in typical rural power distribution systems are just above power ratings of the biomass power plants. For the period of light and base load circumstances, which occurs under about 20 hours a day, a significant amount of power produced from the biomass power plants is fed back to the power substation via the feeder lines. Biomass power plants can in most of cases be found over 10 km far from the substation. Thus, to deliver surplus power from the local feeder back to the substation causes power losses along the feeder lines. So if the power losses are too high, buying energy from distributed biomass power plants is uneconomical. However for the moment, distributed biomass power plants are not committed to provide any auxiliary services to secure entire systems but active power generation without any reactive power [72].

For the future, the use of biomass seems mostly important in two areas; the first one is fuel for air and heavy-duty vehicles. The second area is cogeneration, because cogeneration plants generate electricity and heat with the highest efficiency [74].

2.3 Effects on the Distribution Grid

Distributed energy storage which stores electrical energy during off-peak hours reduces the power wastage and also provides support to the grid during peak hours. The result of strategically placing and scheduling storage system to reduce losses on the system is an increment of the efficiency of the transmission and distribution systems. But there exist some complications because of the relative efficiencies of the energy storage and the transmission and distribution system. For example the efficiency of a battery-storage is 70-90%; the transmission and the distribution system have a combined efficiency in the range of 93-95%. Thus, higher efficiency of the transmission and the distribution system than the energy storage makes it difficult to identify cases where storage will actually increase the overall efficiency of the electrical grid [78].

Reference [79] investigates the impact of an energy-storage on the distribution system. It was observed that the stability of the system changes with addition of the energy storage device. The transient stability improved because of the decrement of the maximum deviation in the rotor speed. The addition of a battery-storage results to a better stability in terms of oscillation duration[3]. However, a battery-storage may have different impacts on the system stability parameters due the stability of a system is a very nonlinear phenomenon and depends on inertia of a component, available energy and rate of energy. In general the study showed that the addition of an energy-storage on the system improves its transient stability.

The most financial benefits from installing energy-storages will result from reduced peak-demand, time-of-use charges for customers and to avoid the costs of maintaining necessary peak and intermediate power generating ability. Another main benefit would be that end users can sell stored-power back to utilities and they in their turn can sell carbon credits earned by collecting renewable energy generation [89]. Also as the author in [80] expects that connection of energy storage before the transmission in parallel with the load will lead to significant decrease of transmission costs.

Figure 2.7 shows the effect of adding an energy-storage to a substation in a distribution grid. The most effective energy management of the energy-storage would be to charge, but not completely charge, the energy-storage during off-peak hours, for example just after midnight. During the day when less energy is required from the energy-storage, the PV system would be able to complete the recharging process of the energy-storage. It means that a smaller energy storage capacity and a smaller inverter would be needed and that affects the financial benefits in a positive manner [90].

[3]The time taken by the oscillations to reach a new equilibrium after the clearance of the fault [79]

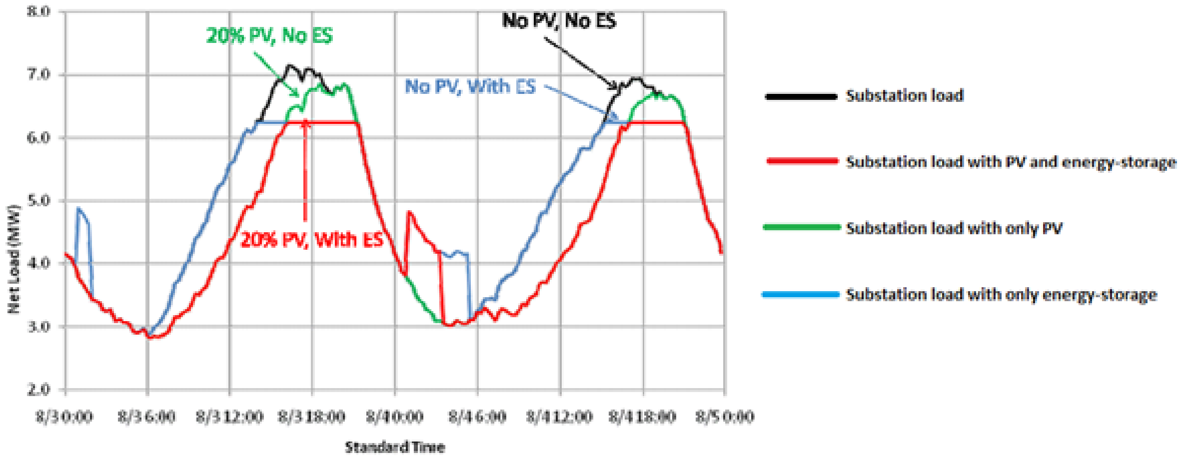

Figure 2.7: Load curves over the substation [90].

In [87] the authors investigates the mitigation of rooftop solar PV impact and evening peak support by managing available capacity of distributed energy storage systems. One of the benefits that the authors concluded that the stored power in the energy storage reduces the reverse power flow and voltage-rise problems during peak hours by injecting less power to the grid and storing the surplus electricity in the battery storage. Figure 2.8 below shows how the stored electricity in the battery storage is used to provide auxiliary electricity support on the evening peak.

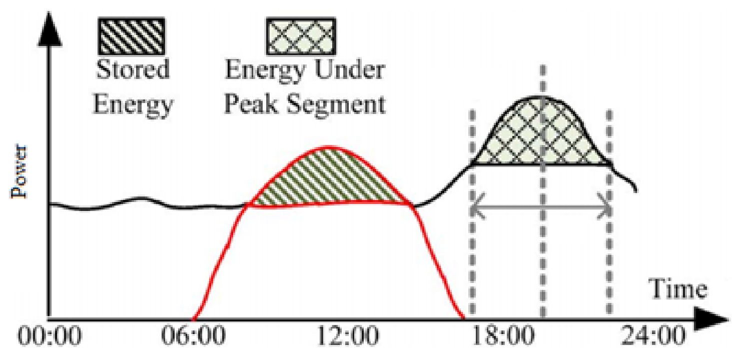

Figure 2.8: Usage of the stored power in the battery [87].

The biggest disadvantage of PV and wind power generation is their variable output, which impacts negatively on the distribution and transmission grid. The authors in [81] and [82] describe how the negative impact of the PV output can be avoided by using a battery energy-storage. The purpose of the battery energy-storage is to add power to the PV output (discharging of battery) or subtract power from the PV output (charging of battery) to smooth out the faster variations of the PV power that occur during periods with transient cloud shadows on the PV module. From figure 2.9, it can be seen that fluctuations from the PV output becomes smoother when using a battery energy-storage. This affects the distribution grid in a positive way and minimising the transients.

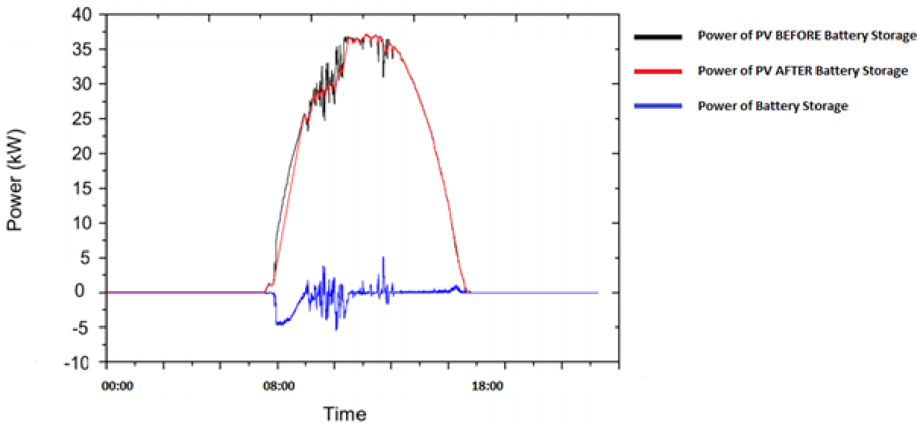

Figure 2.9: Power-output of PVs with and without a battery-storage [81].

As mentioned before, the grid suffers from the fluctuations that occur from the output of the wind turbines, especially in recent time. That is why it is important to smooth the output power fluctuations of the wind turbines. One solution for that would be the installation of the energy storage in the grid. This is a very effective measure for smoothing the power output, same as for the PV mentioned above [83]. Battery energy storage systems have potential for this application. The author in [84] investigates how a battery energy storage system can smooth the output power from wind turbines. A battery energy storage system output power limitations and capacity constraints have evident influences on the smoothing results. The results from [83] show also that smoothing of the power output of wind turbines can achieve a better economy effects. From figure 2.10, it can be seen the smoothing difference between the output power before the installation and after the installation of a battery energy storage system.

In reference [85], more advantages of the battery-energy storage system is discussed. The integration of intermittent wind power into the power grid will result to an increment in the system reserve capacity and it will reduce the economic efficiency of power systems. A well placed and suitable battery-storage system will solve the problem and achieve great advantages for both power grid and wind turbines. In the power market environment, an adoption of the battery-storage system will increase the competitiveness of wind turbines because of the achievement of the maximum efficiency of wind power. Especially under the circumstance of electricity market introducing differential price, the battery-storage system can achieve the conversion of power in time coordinate, making wind power contribute in power dispatching and optimizing the economic efficiency of the power system.

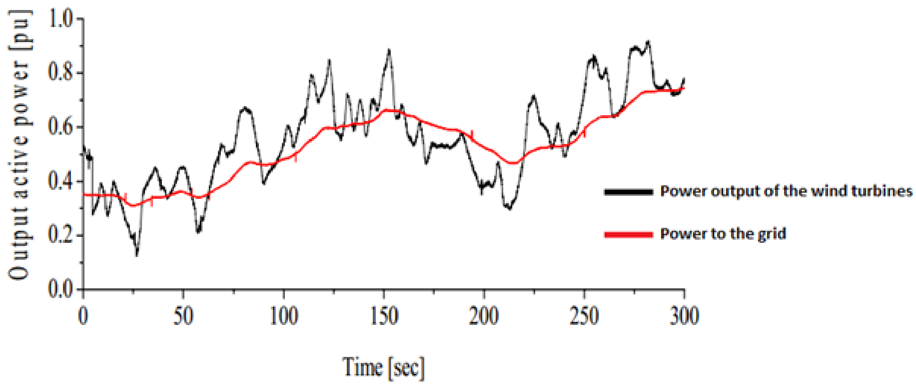

Figure 2.10: Shows the wind power plant output and supplied power to the grid, from which it is clear that the power to the grid can be smoothed enough by using the proposed battery energy storage system [83].

Large fluctuations in the load on the grid require fast adaptable but less efficient power plants and therefore, demand side load management or load shifting can increase the generation efficiency. As mentioned before, load shifting is when high demand processes during peak periods are shifted to periods where the demand is lower. For example washing machines, dish machines, freezers, ovens and etc. From figure 2.11 below, it can be seen that the load can be reduced by shifting the load to other periods of time [86].

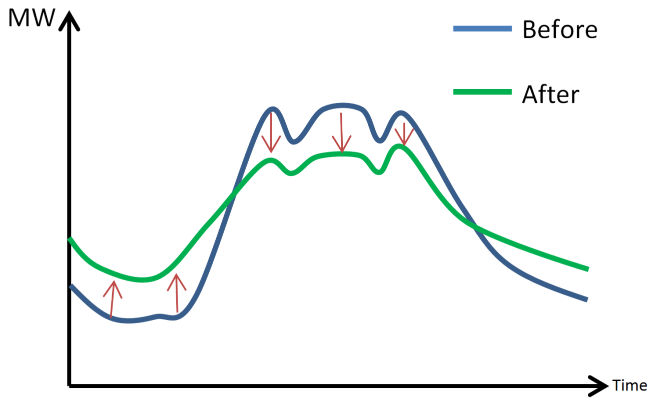

Figure 2.11: Load curves before and after load shifting.

2.4 Current Projects

2.4.1 Smart Region Pellworm

Smart Region Pellworm is a unique nationwide project for storing electricity on the Nordfieslan island of Pellworm. The island has approximately 1000 inhabitants and just over 600 houses. It has two sea cable connections to the main land, the total consumption over a year is approximately 7 GWh and the yearly generation of the island is 22 GWh (300 kWp Wind and 780 kWp PV).

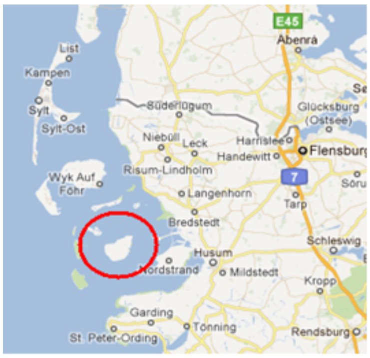

Figure 2.12: Geographical location of the island.

The project is launched in 2012 to build revolutionary solutions for optimal usage of renewable energy. The aim of the project is that the generation is carried out on site in order to reduce dependence on large-scale power transportations across Germany and Europe. The project is carried out by a broad-based innovation network of industry and science, and funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. On Pellworm a so-called hybrid storage system is set up to connect the electricity consumers and the generating facilities with modern data cables, so that the generation and consumption of electrical power are better coordinated. When large amounts of generated wind and sun power exist in the island, these can be stored in the future directly into powerful batteries and as well in heating systems for households. The project will provide valuable insights into the practical operation of smart grids and the on-site recycling of electricity from renewable sources.

Figure 2.13: Picture of the E.ON hybrid power plant.

The project is a completely new approach, because so far great power storage has not been integrated into regional networks. The concept of a mass storage system combines two of the currently most advanced battery technologies, Li-ion and redox flow batteries. The redox flow battery is used for long-term storage. The electrolytes are Vanadium salts with a storage capacity of 1.6 MWh and a maximum power of 200 kW, the battery can be fully charged or discharged in 8 hours and that is why it is used for long-term storage. The high performance Li-ion battery is used for short-term storage with a capacity of 560 kWh, a maximum discharge capacity of 1.1 MW and a loading capacity of 0.56 MW, it can be completely discharge and recharge within in about half an hour [96] [97].

Figure 2.14: Storage system of Pellworm.

2.4.2 M5BAT (Modular Multi-Megawatt Multi-Technology Medium-Voltage Battery Storage)

The goal of the cooperative project is the construction and operation of a stationary battery facility with a rated power of 5MW (installed power of 6.51 MW) in a specially adapted building at RWTH Aachen University in Aachen, Germany. The M5BAT project is backed by a 6.5 m€ funding from the German Federal Ministry for Economic Affairs and Energy as part of its "Energy Storage Funding Initiative" and its partners are E.ON, SMA, Exide, beta-motion and RWTH Aachen University. E.ON Technologies GmbH will be responsible for the modification and equipping of the building. The installation of the batteries will be carried out by Exide and beta-motion. The power electronics for the battery will be provided by SMA. RWTH Aachen will be responsible the researches, operation and testing. E.ON Global Commodities Capacities will trade up to 5 MW in the spot-market over a two year period. The battery system will be connected to the medium-voltage grid, close to a transformer-station (240 MW, 11 kV to 110 kV) in an old school building. The distance between the battery and the transformer is only 20 m. The surrounding area is a mix of an industry area and a residential area. The two battery technologies which are used in the system are Li-ion and Lead-acid. Each type has two strings; the Li-ion string has a power capacity of 1.25 MW and energy capacity of 0.7 MWh. The Lead-acid string has 1.25 MW power-capacity and 1.3 MWh energy-capacity. The system use same inverter for all the strings as it is modulated for both battery types [98].

“To achieve a 100% renewable power supply, adding large-scale storage systems to the utility grid is of vital importance. These systems back up the power from renewable sources and help stabilize utility grids. This research project will provide us with important data on how large-scale battery inverters can be used in the utility grid in the future. The goal is to develop a concept for modular and flexibly scalable battery inverter systems that can be used to supply all critical grid management services in the utility grid,” explained Volker Wachenfeld, Senior Vice President Hybrid & Storage at SMA [99].

Chapter 3

Simulations

The program that have been used for the simulation of the electrical grid is DIgSILENT PowerFactory. PowerFactory is a software created by the German company DIgSILENT. The program is graphically oriented and grid models are made by using the drawing tool of the software. With the DIgSILENT PowerFactory several simulation scenarios are possible. PowerFactory is the simulation program used in E.ON Technologies GmbH to investigate larger power plants. The study used for the simulation in the Thesis is the load flow study. The license for the software given from E.ON did only allow static simulations. The program was learned by studying the manual and completing the tutorial. The graphical interface makes it easy to implement the different measures. The grid model used for the simulations has been converted from PSSE, a simulation tool from Siemens.

Two different scenarios with different amount of installed power will be evaluated. These scenarios will be described in detail later on and are referred to as scenario 1 and scenario 2. The simulations for each scenario are based on four static simulation profiles with different load-demand and amount of power production. These four are moment simulations describing the load flow situation during a very short time. The four cases are summarized in table 3.1.

Profile	**Production**	**Load**
1	High	Low
2	High	High
3	Low	High
4	Low	Low

Table 3.1: Overview of the four static simulation profiles.

How big the power production and load is in the profiles, is depending on which scenario and profile the simulation is performed in. To get an overview and to see were critical points in time are, a simulation over 24 hours has been carried out. The measures carried out to balancing the active power in the grid is battery storage, load shifting and biomass power plants:

- The battery storage is dimensioned to prevent overloading of transformers, this is priority 1 and makes the charging power to a key parameter, profile 1 determine the battery capacity. It is also important for the batteries that they have enough storage capacity to help prevent overloading when it is necessary. The storage capacity is determined roughly from a 24 hour simulation of a sunny day, a margin of 50 % is also included. Battery storage is relevant for all the profiles due to their ability to both increase the load and also increase the production. In the simulation model the battery is implemented as generator.For a generator the input is possible to control the active power input. In PowerFactory it is possible to change the input on active power to negative values and this is done for when batteries are charging.

- Load shifting is the idea of controlling specific loads as combo cool-heat, wash machines, dishwashers and refrigerator. The maximum power of the devices is used to increase the loads during low load conditions. The power consumption of the devices has been taken from [69] and [51]. The simulation have been performed for different share of the households. In the result the case where 50 % used load shifting is presented and 50% of the household loads is increased with the average of the maximum power consumption for the devices used. It is also possible that load shifting reduces the load when the load peaks but it is hard to quantify those effects. For the implementation in the grid model the load shifting have been implemented by increasing the system load corresponding to the calculated average of the power consumption for the household devices and assumed that 50 % of the households use this increase.

- Biomass power plants are interesting for the profiles when production is low. They are often used when production of heat is necessary and therefore the operation of the power plants depends on the price difference between heat price and electricity price. Biomass power plants have only been used for profiles during the winter. Two different implementations of biomass power plant have been done. The first one to see how much installed power that is needed to compensate for high load peaks. The other one is an average biomass power plant around 10 MW.The heat demand is also investigated in order to see how big volumes that are realistic. The implementation of the biomass power plants in the grid model is done with synchronous machine. As the sizes of the implemented power plants are large it is connected in the medium voltage area.

3.1 System overview

The grid model has been received from internal source within E.ON and should be treated confidentially. That is why the grid model and grid data is not described in detail.

The area where the simulation-model is based on, is an area in south of Germany with a lot PV penetration. The DSO operating the area installs over 500 new PVs to grid connection every day all over their responsible region, which is a much larger area than the grid model represents. The model of the area is one of most extreme sights and therefore an interesting study case. The PV-modules are generating energy to the grid at 85% of their total installed power.

The grid model is medium-voltage to low-voltage model. In the model three of the low-voltage grids have detailed models, where every household is represented by a load. In figure 3.1 the detailed low-voltage grid is shown, the connection points to medium-voltage grids are marked with a red circle and the lines which separate the low-voltage grid, from each other, are marked with blue squares. Figure 3.2 is an enlarged part of a low-voltage are in the grid.

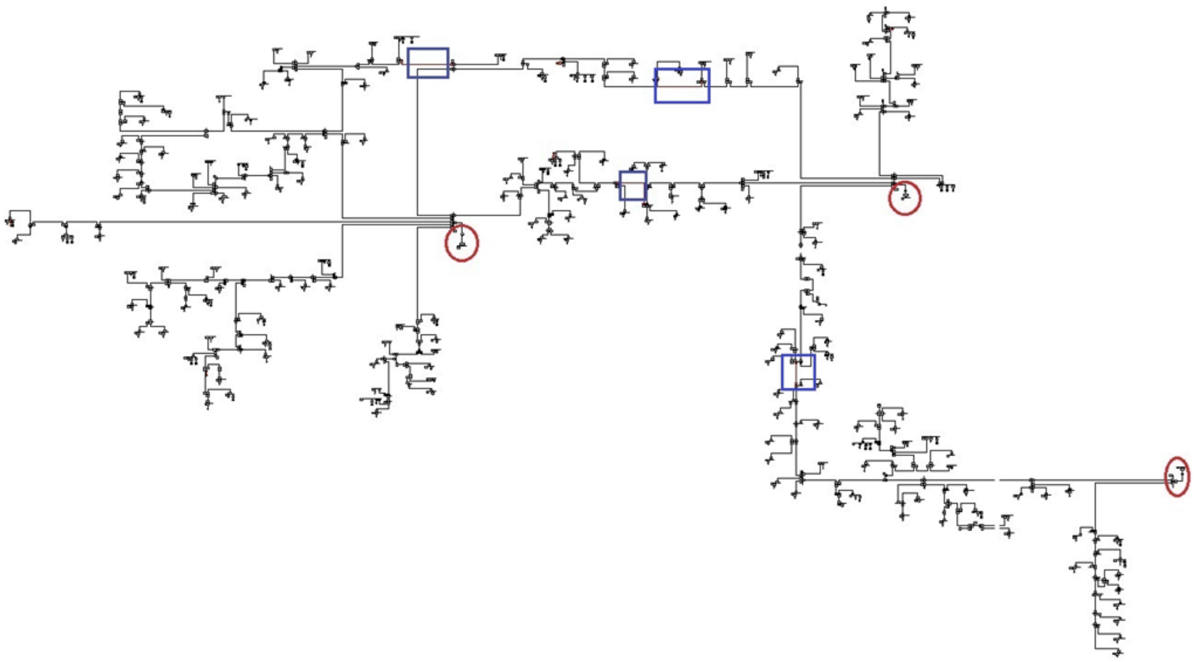

Figure 3.1: Low-voltage grid in Power Factory.

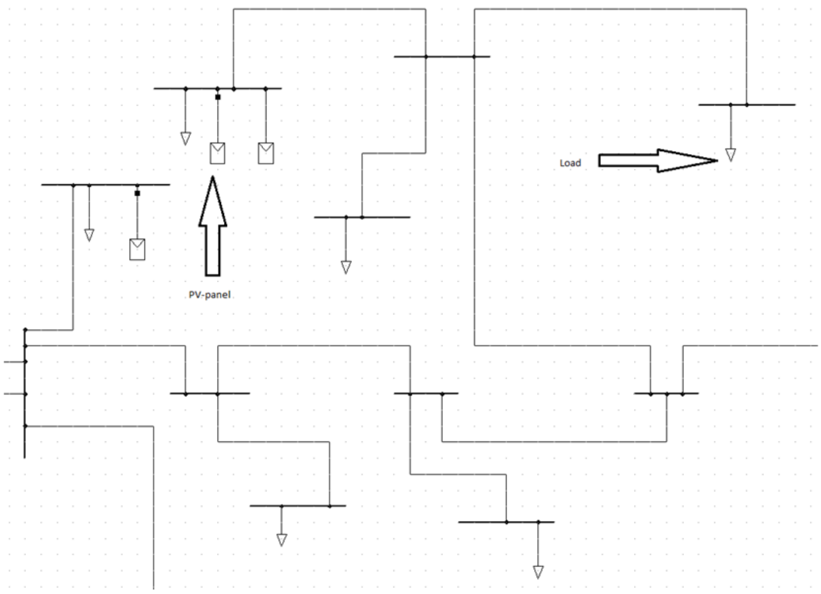

Figure 3.2: Enlarged part of the low-voltage the grid.

Figure 3.3 is the model of the medium-voltage grid. The connection points to the three detailed low-voltage grids are marked with red circles. The connection between medium-voltage grid and the transmission grid is marked with a green triangle and consists of two transformers.

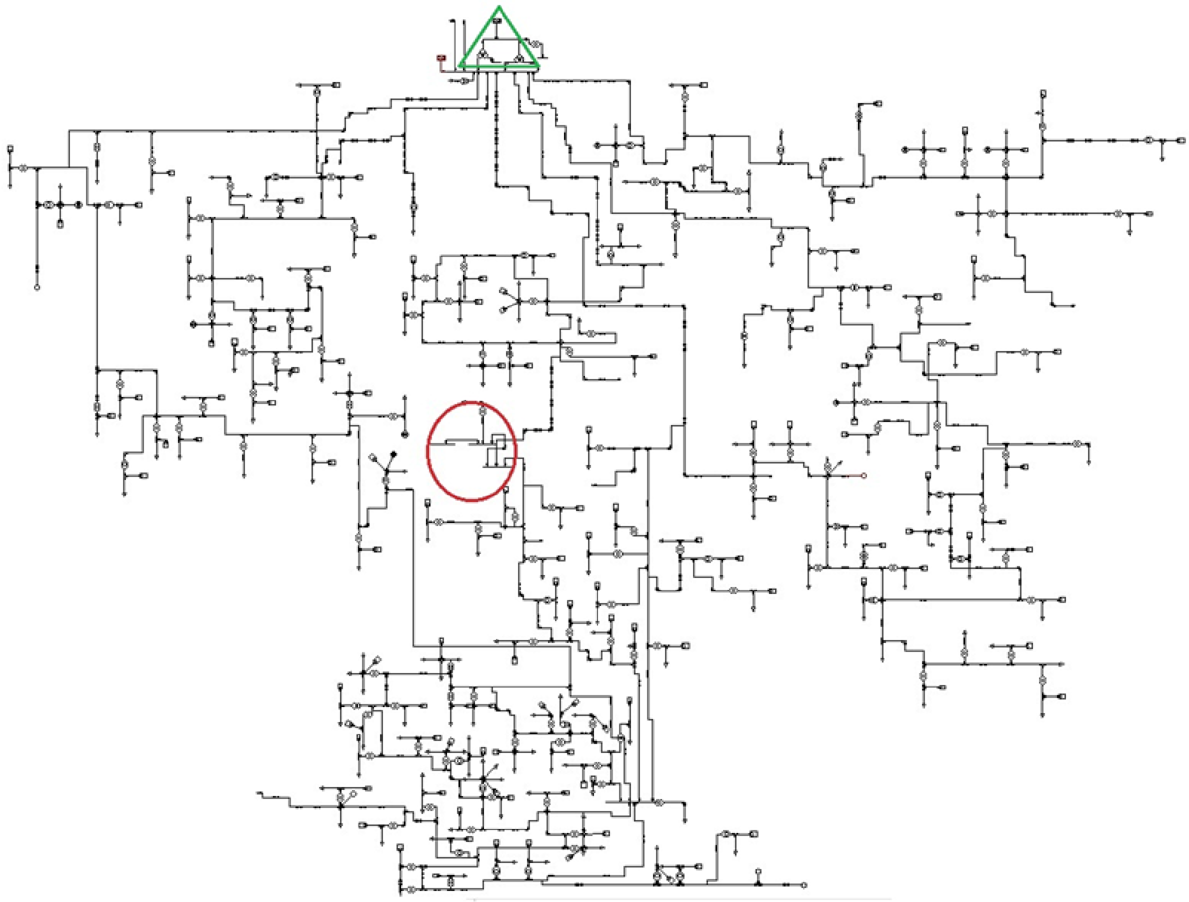

Figure 3.3: Medium-voltage grid in Power Factory.

Two 3-winding transformers where one of them have two connections to the medium-voltage side and one connection to high-voltage (transmission grid) and the other one have only one connection to medium voltage which makes it operate as a 2-winding transformer. The total transfer capacity at the primary substation transformers (connected between medium voltage and high voltage) is 75 MVA and the total sum of the secondary substation transformers (connected between low voltage and medium voltage) is around 45 MVA.

The other low voltage grids are represented by only a load or a load and a generator connected via a transformer to the medium voltage grid, as seen in figure 3.4 depending on if the low-voltage area has any infeed.

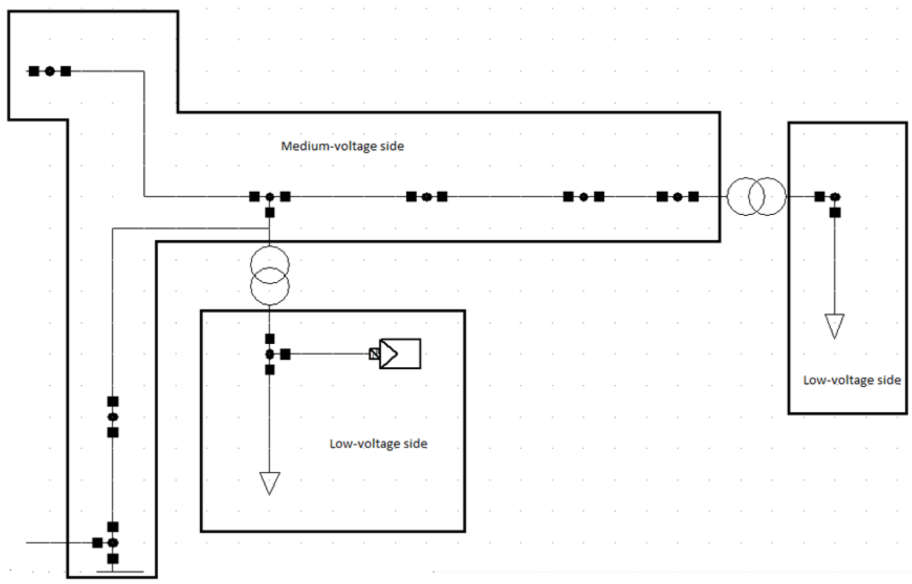

Figure 3.4: Description of the connections in the medium-voltage grid.

The load for the low voltage grids that are only represented as load or a load combined with a PV generator has been dimensioned after the size of the transformer that connect the low-voltage area to the medium-voltage. Since there have been three detailed low-voltage grid models available those have been used for the dimensioning. Every load in those models represents a household. By counting the loads and check the value for corresponding transformer and then made some simple calculations.

$$\frac{\text{Transformer capacity}}{\text{Number of loads}} = \text{capacity/household}$$

The reverse calculation was then done for the low voltage grids only represented by a load. To validate this method a simulation with a high load profile was executed to see if the sizing was sensible. Some smaller corrections were then done. The power factor for the household loads was already set to 0.9 and the loads representing a whole low voltage grid has a power factor of 0.98.The number of low-voltage areas in the grid model is 159. 131 of these areas have production from PV. The total sum of households in the grid model is around 10 000 households. There are also seven loads connected directly to the medium voltage network which represent SME:s [1].

Nominal voltage at medium voltage level is 20 kV and the low voltage is 0.4 kV. The medium-voltage grid model is treated as an isolated part of the medium voltage grid with only one connection point to the transmission grid. A summary of the components in the grid is presented in table 3.2.

[1]Small and Medium industries and enterprises

Component	Number	Connected in
Transformer	2	Between MV-HV
Transformer	159	Between LV-MV
Overhead lines	166	MV
Cables	311	LV
Cables	257	MV

Table 3.2: A summary of the components in the grid.

The parameters taken into account for the transformers in the grid model are the following:

- Rated power (MVA)
- Rated Voltage low voltage and high voltage side (kV)
- Positive sequence impedance (%)
- Zero sequence impedance (%)
- Vector group (D/YN)
- No load losses (kW)
- No load current (kA)
- Distribution of leakage Reactances (p.u)
- Distribution of leakage Resistances (p.u)

For the cables and overhead lines this parameters has been taken into account:

- Length of Line (km)
- Rated voltage (kV)
- Rated current (kA)
- Parameters per length 0, 1 and 2 – sequences (ohm/km)
- Parameters per length 0, 1 and 2 – sequences (μS/km)

The transmission grid is modeled as infinite voltage source. To be able to see how the busbar connected to the transmission grid is affected, it is connected with an impedance between the voltage source (transmission grid) and the busbar. This impedance is calculated automatically in the simulation program by inserting the short circuit power for the connection point to the transmission grid and the X to R ratio for the grid. The value for the short circuit power of the connection point is 1000 MVA and X to R ratio for the grid is 10.How the calculation of the impedance is done is described by equations 3.1,3.2 and 3.3. The short circuit power need to be transformed to per unit and then the impedance is given by the inverse of the short circuit power as showed in the 3.1.

$$Z = \frac{1}{s''_k} \tag{3.1}$$

$$s''_k = \text{Short circuit power}$$

How the impedance is divided between resistive part and reactance part is given by the X to R ratio and is calculated with the equations 3.2 and 3.3.

$$X = \sin\left(\arctan\left(\frac{X}{R}\right)\right) \cdot |Z| \tag{3.2}$$

$$R = \cos\left(\arctan\left(\frac{X}{R}\right)\right) \cdot |Z| \tag{3.3}$$

The impedance is dominated by the imaginary part. In Figure 3.5 the connection to the transmission grid is enlarged.

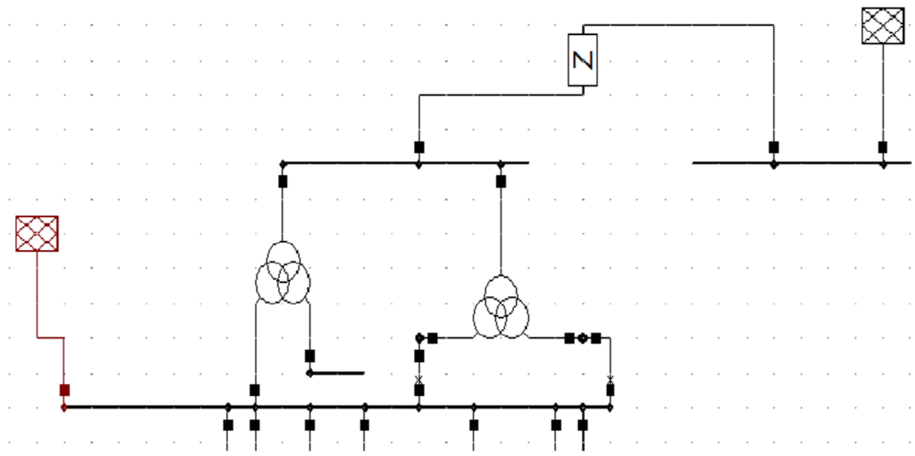

Figure 3.5: Impedance between the transmission grid and the transformers to the medium-voltage grid.

Figure 3.5 shows how the impedance between the transmission grid and the busbar connected to the transmission grid is arranged. In this figure it is also shown how the transformers are connected where one of them have one winding connected to a single busbar. The data for cables, transformers and generators have been checked so their values seemed reasonable.

The simulation study that were done was the load flow simulation.

3.2 Load flow study

Load flow study is often referred to as power flow study and is a method for analyzing the movement of power in a steady-state power system. By calculating the voltage magnitudes and phase angles at each busbar and node in a power system the active and reactive power flow, through the components of the system, are also given.

For a power system to work in normal three-phase steady-state conditions, four requirements need to be fulfilled.

1. The generations of power need to be the same as the demanded power of the system.

   By having a connection point to a transmission grid, in the model, the balance between the produced power and consumed power is secured. With this connection it is possible to see how much power goes out from grid model or comes in to the grid under certain circumstances.

2. The nodal voltages need to be close to the rated voltage of the node.

   The goal of the simulations is to, with help of implemented measures, be able to not exceed the voltage limits set by grid codes. Since the measures carried out are measures concerning active power and the voltage magnitudes also are affected by the reactive power balancing this might also be solved by other measures as capacity bank, controllable inverters or tap changing transformer.

3. The generators of the system have to work within the established limits for active and reactive power.

   The active power and reactive power production of the generators are given by the creator of the grid model. They are in between the established limits. As explained in section 1.3, PVs are manufactured to have a high power factor as possible and for the study case all the PVs have a power factor of 1.

4. Transmission lines and transformers of the system must not be overloaded.

   As the active power is the largest part of the apparent power during normal condition of power system, the measures carried out for the active power balancing have great effect on preventing overloading on transformers and lines. It is also possible to replace concerned transformers and lines to components with higher transfer capacity or install parallel lines and transformers.

As the inputs to a power system often are given in power the voltages sources are considered as power sources and the load flow problem is formulated as non-linear equations which are often solved with iterative methods. The iterative methods fits computational calculations very well [91].

The setup of the load-flow problem arose from a single-line diagram of the grid. The input data for this diagram is information about the buses, lines and transformers in the system.

The grid can be modeled as a matrix which contains the equivalent admittance between the buses in the system. With this matrix available, the following equation can be written for the load flow problem.

$$P_k + jQ_k = V_k \cdot \sum_{n=1}^{n} Y_k n \cdot V_n \cdot e^{j \cdot (\delta_k - \delta_n - \theta_k n)} \tag{3.4}$$

Where
P_k = Active power delivered from or to bus k
Q_k = Reactive power delivered from or to bus k
N = Number of buses connected to bus k
$Y_k n$ = Element kn from the bus admittance
V_k = Voltage magnitude at bus k
V_n = Voltage magnitude at bus N
δ_k = Voltage angle at bus k
δ_n = Voltage angle at bus n
$\theta_k n$ = Argument of element $Y_k n$ [91]

Using equation 3.4 for every bus in the system, a system of equations is obtained. This system can then be solved with iteration methods.

3.3 Production profile

The production units in the grid is controlled by active power input and $\cos(\varphi)$. This inputs were given from the grid creator. The active power input was the total installed power. The grid model representing a area with a lot of PV penetration and as the production from solar power is dependent on the irradiation from the sun, a sun profile for the area was retrieved from [95]. The curve in figure 3.6 represents the irradiation during the sunniest day of the year. The sun irradiation characteristics are dependent on longitude of the area and day of year.

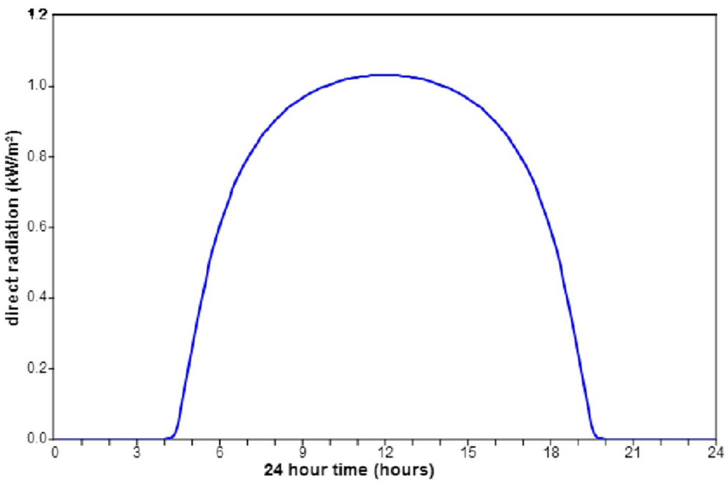

Figure 3.6: The irradiation during the sunniest day of the year for the area.

The figure 3.6 is solar irradiance as a function of time during a sunny day. The solar irradiance is given in kW/m^2. The PVs produce electricity according to equation 3.5.

$$P_e = I * \eta * A \tag{3.5}$$

P_e=Electricity output from PV (W)
η=Efficiency of PV
I=Solar irradiation (W/m^2)
A=Area of the installed solar panels (m^2)

As an example, if the PVs has efficiency is 20 % ,the irradiance is 1000 kW/m^2 and the size of the installed PVs are 10 m^2. The produced electricity during this time is:

1000*0.2*10=2 kW

The production varies with time depending on the irradiance which depends on what time of year it is, time of day, the circumstances with clouds and heat.

As the maximum output from the PV modules is for a very short time(when it is maximum sun irradiance) the DSO have decided to use them at 85 % of their total installed power. This is to avoid the need of cables with larger transfer capacity. Because only 85 % of the installed power is used by the grid operator (the DSO) the production curve of electricity to the grid gets another appearance than the irradiation curve. If the solar modules would produce 100 % of the installed power the production curve would look much like the irradiance curve. By only using 85 % the appearance looks like the curve in figure 3.7. This production curve represent a the same day as for the irradiance curve in figure 3.6.

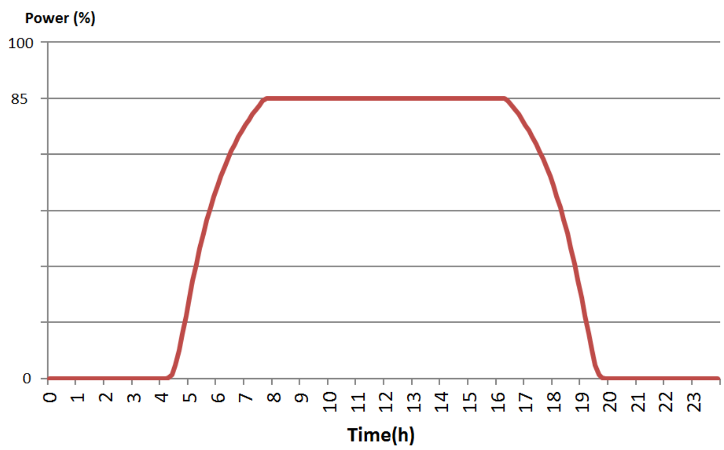

Figure 3.7: Production curve in percentage of installed power for grid operation point.

The appearance of the production curve uniform output during a longer time compared to the curve of the irradiance. In reality the day with low cloud can give the same production as a clear day due to the cooling of the PV devices, the efficiency drops when the modules become warm. This has not been taking under consideration for the simulations. For low production winter time and cloudy is assumed. The power output is reduced with 50 % by the clouds [52]. To identify the power output the time for the profile is relevant. By checking corresponding value in figure 3.6. The value(in percentage) is then multiplied with the installed solar power.

3.4 Load profile identification

Excel tables with data from a study about the energy consumption in German households with an average of four persons were provided from an internal source within E.ON. The data is from 2002 but according to the source, there are no big differences between the data then and now. The data in the tables are weighted averages of the energy demand for every minute during a day in form of electricity, heat and hot water heating. The weighted average for the electricity consumption is the most interesting for the simulations. The day scenarios consist of two different seasons (winter, summer). Every season has four different categories which were based on the weather (sunny, cloudy or neither) and the type of day (workday or Sunday). For the summer, the weather was assumed as sunny during the measurements by the source. For every table-profile, three total-weights (minimum, middle and maximum) for the electricity consumption are given. An overview of the investigated profiles are given in table 3.3 below: The reasons are based on whether the persons in the household are at home or

Table-profile	**Reason**	**Total-weight (kWh)**
Summer-Workday-Sunny	Low consumption and high PV production. Minimum total-weight	10.21
Summer-Sunday-Sunny	High consumption and high PV production. Maximum total-weight	18.3
Winter-Sunday-Cloudy	High consumption and low PV production. Maximum total-weight	30.77
Winter-Workday-Cloudy	Low consumption and low PV production. Minimum total-weight	13.05

Table 3.3: Overview of the chosen table-profiles.

not (work day or Sunday) and if it is sunny outside or not. If the persons in the household are at home, it will result in an increment of the power consumption and the other way around. If it's sunny outside, the production from the PVs will increase and vice versa.

The total-weight for each table-profile in 3.3 is the total electricity consumption during a day for a household. How the electricity consumption was divided on a minute basis during the day was also given from the study.To get the power consumption, the energy consumption for every minute were divided with 60 and plotted. An example of that is shown in figure 3.8 below. The graph in 3.8 is describing the power consumption during a day.

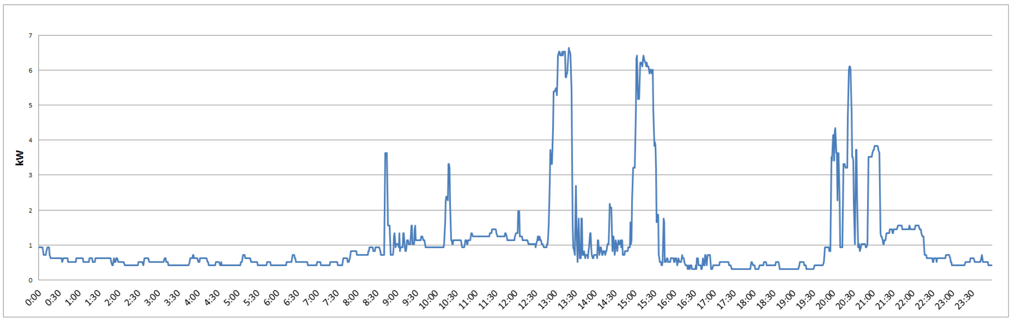

Figure 3.8: Load curve for the "Winter-Sunday-Cloudy" table profile, load in kW as function time on minute basis.

From every plot, different time intervals were chosen dependently regarding the peaks (for high power consumption) and valleys (for low power consumption) for each table-profile. Power consumption over a time interval is more realistic because it is unlikely that a peak occurs in all houses at the same time. An average power consumption value (P_{avg}) over a time interval was calculated as below:

$$P_{avg} = \frac{\sum_n^m P_n}{m - n} \tag{3.6}$$

Where P_n is the power consumption from time n to m.

The chosen time intervals with corresponding power consumption for every load profile are listed in the tables below.

Time interval	**Power consumption (kW)**
08:00-08:30	0.3235
10:00-10:30	0.09461
12:30-13:00	0.3311
16:30-17:00	0.28382

Table 3.4: Power consumption for chosen time intervals for load profile: Summer-Workday-Sunny (Profile 1).

Time interval	**Power consumption (kW)**
07:15-08:45	1.5909
11:30-12:00	2.3931
14:30-15:00	2.4317
16:00-16:30	2.3445

Table 3.5: Power consumption for chosen time intervals for load profile: Summer-Sunday-Sunny (Profile 2).

Time interval	Power consumption (kW)
08:00-09:30	1.0721
11:00-11:30	1.1393
12:30-13:30	3.6674

Table 3.6: Power consumption for chosen time intervals for load profile: Winter-Workday-Cloudy (Profile 3)

Time interval	Power consumption (kW)
05:30-06:30	0.7716
08:00-08:30	1.0348
10:00-10:45	0.7136
12:00-12:30	0.1319
15:30-16:45	0.4632

Table 3.7: Power consumption for chosen time intervals for load profile: Winter-Workday-Cloudy (Profile 4)

A load curve over the average power consumption for every hour gives a better view of the consumption. An hourly power consumption is calculated with equation 3.6 ,where m=60 and n=0, and then plotted, see figure 3.9 below. Note that the power was caluclated using the middle total-weight for a better average value. The hourly power consumption is only used for the time sweep simulations. More curves can be found in appendix B. The industrial nodes in

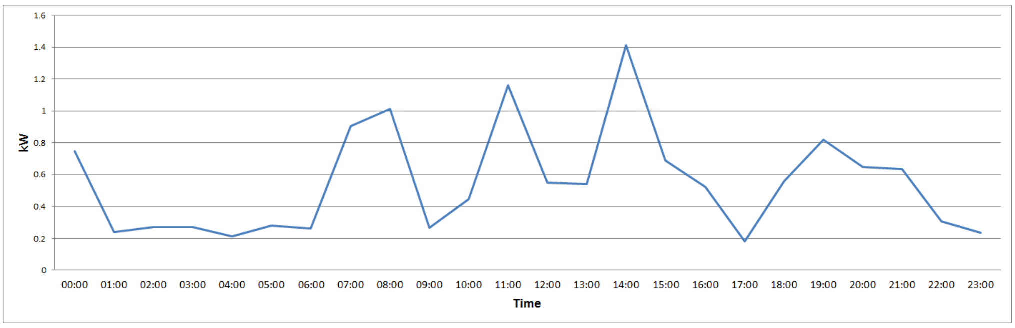

Figure 3.9: Exmaple of a average hourly load curve for a household.

the grid were assumed to be SME:s. The yearly energy consumption of an SME (E_{SME}) is 1500000 kWh [101]. The SME is assumed to be running for 15 h (t) per day in 312 days/year (D). This leads to an hourly power consumption of:

$$\frac{E}{t \cdot D} = \frac{1500000}{15 \cdot 312} \approx 320kW$$

3.5 Scenario 1 & Scenario 2 installed power

The installed power for scenario 1 is shown in 3.8. Scenario 1 describe the current situation for the area of the grid model. A lot of PV is connected to the low voltage and some to the medium voltage grid. A few combined heat and power plants (CHP) are in grid with very small installed power. Worth mentioning is that the CHPs are only active for profiles during winter time. This installed power is the installed power for the base case of the simulations. When biomass power plants are used, as an measure, the total installed power is changed.

Energy Source	**Connected to (LV or MV)**	**Amount (MW)**
Photovoltaics	LV	19.78
Photovoltaics	MV	6.54
CHP, Biomass	LV	0.588
CHP	LV	0.053
CHP	MV	0.225

Table 3.8: The summation of the installed power in scenario 1 for the base case.

For scenario 2 an increase of the sun power has been investigated.It is not realistic that areas with high penetration of PV increase their sun production furthermore the increased PV production has been located for nodes with low PV production. An average production per household was calculated and areas with lower production than the average were raised to the average level. This raise corresponds to around a 30% increase in total installed power. Only the sun production in the low voltage areas were changed.

3.6 Structure of production-load profiles

To investigate were the most critical times are, a simulation over 24 hour was done. Figure 3.10 the result of the 24 hour simulation. The figure shows the power delivered to the transmission grid as function of time, negative values if the transmission grid is supplying the area. For every hour of the day an average value for sun production and an average value for the load were calculated and then simulated. From the 24 hour simulation it is possible to see where critical times concerning the power flow are.The load for the profiles is not hourly average only half hour averages to get clearer peaks and lows as they describe worst case scenarios.

The load values stated in section "Load profile identification" are matched with corresponding value of production in figure 3.7, the production value in percentage is multiplied with the installed power for the PVs in the grid model. For low production profiles the values are taken for corresponding graphs for a winter day with clouds. The production has been reduced with 50 % due to the clouds. For the implementation of the measures, batteries are assumed to be able to charge for high production profiles and to deliver full power during low production profiles this means that the batteries need to be charged before this point. Because the profiles describes worst case during a short time, the assumption of high delivery from batteries is possible. The loads from values in

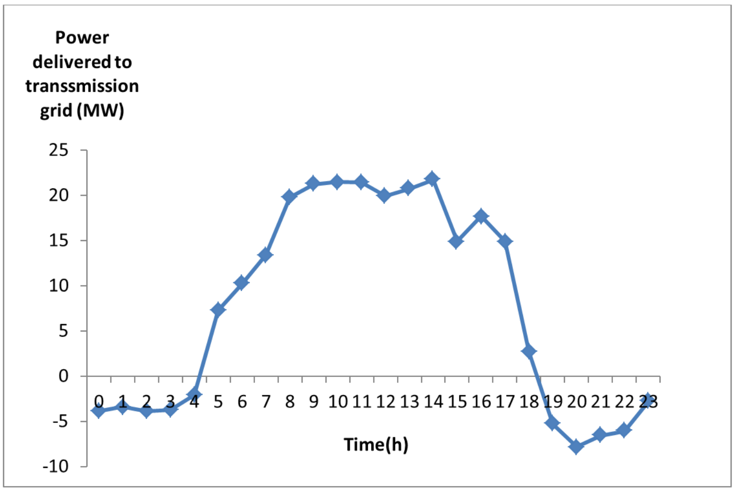

Figure 3.10: Power delivered to the transmission grid as function of time during 24 h.

"Load profile identification" are generalized for all the loads in the grid. In reality areas also have schools, commercials and other places that have a different energy consumption profile but since the profiles describes a worst case it have not been considered. All the different points of load have been simulated and one point for each profile, with most problem, have been chosen as base case for the profile. The system load and production is summarized in table 3.6,3.6,3.6 and 3.6 for Profile 1-4 and for the different implementation of measures. when batteries are delivering power it counts as power generation and when charging it counts as load. The system load is referring to the total load in the grid model.

Profile 1	**Power generation(MW)**	**System load(MW)**
Base case	26.3	2.9
Battery	26.3	5.2
Load shifting	26.3	8.0

Table 3.9: Power generation and system load for Profile 1.

Profile 2	**Power generation(MW)**	**System load(MW)**
Base case	27.5	18.1
Battery	27.5	20.5

Table 3.10: Power generation and system load for Profile 2.

Profile 3	Power generation(MW)	System load(MW)
Base case	10.1	39.1
Battery	12.5	39.1
Biomass 1	41.1	39.1
Biomass 2	20.1	39.1

Table 3.11: Power generation and system load for Profile 3.

Profile 4	Power generation(MW)	System load(MW)
Base case	9.2	9.2

Table 3.12: Power generation and system load for Profile 4.

The results from these profile simulations will be presented in the next chapter.

To sum up the simulation a 24 hour simulation with a combination of the different measures were performed. Two of these 24 hour simulations have been done, one in summer time when sun production produces maximum power and one cloudy winter day when load is high and the sun production is low.

For the summer day simulation the batteries have been used to prevent overloading of transformers. An important issue is also that the battery need free storage capacity to be able to charge when it is needed. Load shifting has been used two times during the day and an assumption of 25% of the loads is possible to control for each of those times. An assumption that if controllable loads are used during low load times the high load times might be reduced with 10% of the average power of the controllable loads. No biomass power plants are used during the summer day simulation as there is no use for the heat that is produced.

During the winter day, a biomass power plant with an installed power of 10 MW is implemented and in operation during the 24 hours. Batteries are charging when there is surplus power in the grid and deliver power during load peaks.

3.7 Chapter summary

As described in the different parts of this chapter the simulation work is based on four different cases describing worst case scenarios. The profile 3 with low production and low load is not that relevant from an active power point of view.

To identify the loads and the production for the profiles a study about energy consumption in German households have been used and also the sun irradiance for the concerned area. The installed power for the grid model was already implemented in the grid model. By matching the identified load and production according to the different profiles the profiles were implemented in the grid model and then simulated.

The measures used is also depending on which profile that was simulated. For profile 1 the battery and load shifting was implemented, for profile 2 the battery was the only measured implemented and profile 4, battery and biomass was implemented. For profile 1 a combination load shifting and battery storage was also investigated to see how it could reduce the battery capacity needed.

For the biomass implementation two different cases have been investigated, one average biomass power plant of the larger ones in Germany and one to cover the load peak totally. The study used for identifying the electrical load was also used to identify heating demand for the households. The maximum demand for heating and domestic water was 162 kWh for a day. If all the households have the same heat consumption a total consumption for day is 1620 MWh. A biomass power plant electrical efficiency is around 30 % which means that the electricity produced to cover the heat demand is 28.9 MWh as an average per hour.

To get an overview of the simulations two simulation over 24 hours was done. One for a summer day and for a winter day. These days are especially interesting concerning the active power because summer day have surplus of energy and a cloudy winter day have deficit of energy.

The interesting results from the simulations will be presented in the next chapter. As was mentioned earlier the results from profile 3 had no interesting results concerning the active power but the simualtion results can be found in appendix C.

Chapter 4

Results

The key parameters for the simulation results are here described.

Delivery to transmission grid

The main issue for the load flow is the active power flow in and out from the grid. Therefore the delivery to the transmission grid is a main parameter. For the critical times the power to the transmission grid will presented in MW, negative values for times when the transmission grid support the local production.

Loading of transformers connected to the transmission grid

In the table with results the name of the transformers are T1 and T2. The loading will be presented in percentage of their transfer capacity.

Voltage of MV busbar connected to transmission grid busbar

The transformers from the transmission grid are connected to one busbar on the medium voltage side. This parameter is presented in per unit (p.u).

Voltage of transmission grid busbar

This is the busbar connected before the impedance seen from transformer side. This parameter is presented in per unit (p.u).

Highest Voltage

The highest voltage in the grid given in p.u and also percentages of how many busbars and nodes that has a higher voltage than 1.1 p.u if there is any.

Lowest Voltage

The lowest voltage in the grid given in p.u and also percentages of how many busbars and nodes that has a lower voltage than 0.9 p.u if there is any.

Average Voltage

The average of the busbars and nodes in the network. The parameter is given in p.u and the standard deviation is also denoted.

Grid losses

Grid losses concerns only the losses related to the grid(low voltage and medium voltage) as losses in transformers and cables. Only three datailed low voltage grid are in the model so losses are lower than it would be with full model. The grid losses are presented in percentage.

All these parameters are summarized in tables. Other results are the voltages for every single busbar and node in the grid. This gives a good overview of the variation of voltages in the network. Transformers loading are also presented in histograms. In appendix all the graphs and histograms are presented. Only the interesting and relevant curves and figures will be shown in this part. This structure will be followed for all the load-production profiles. For the low production low load profile there were no interesting results concerning the active power but the results are documented in appendix. As said before all measures are not implemented for all profiles.

It is Profile 1 that dimensioning the battery capacity. As explained in the chapter 3, the battery capacity is dimensioned to prevent overloaded transformers and cables. The battery energy capacity is dimensioned by a 24 hour simulation where the main issue is that the batteries implemented need to be able to charge during the time when transformers and cables are overloaded. Load shifting is only used for profile 1 to increase the load. The results show the case where 50 % of the households have the possibility to control one of the controllable loads. The biomass implementation is done for profile 3 and two different sizes of power plants are implemented. One to cover the load peak and one average sized power plant of 10 MW installed power. These two implementations changes the installed power in the grid. The results for the different profiles for scenario 1 are presented in this section

4.1 Scenario 1

In this section, the results from simulations of scenario 1 are presented.

4.1.1 Profile 1

In table 4.1 the result from the first simulation for the base case, for implementation with batteries and for implementation of load shifting is shown.

Key parameters	Base Case	Battery	Load shifting
Delivery to transmission grid (MW)	22.3	20.1	15.2
Loading of T1 (%)	46	43	34
Loading of T2 (%)	33	30	24
Busbar MV to transmission (p.u)	1.038	1.032	1.028
Busbar transmission grid (p.u)	1.004	1.003	1.002
Highest Voltage (p.u)	1.108 (0.65%)	1.094	1.092
Lowest Voltage (p.u)	0.995	0.995	0.985
Average voltage(p.u)	1.047±0.020	1.046±0,019	1.035±0,019
Grid-losses (%)	4.4	3.7	2.7

Table 4.1: Results for profile 1.

As the table 4.1 show a lot of power is going in to the transmission grid due to the high production while the load is low. The load shifting and battery implementation reduce the power to the transmission grid because the loads are higher with load shifting and the batteries implemented are charging, therefore also the loading of T1 and T2 are decreased. The voltages at the busbar at primary station are not affected that much for the different cases. The average voltage is decreased notably by the load shifting implementation. The grid losses are reduced for battery and load shifting. The battery efficiency is not 100 %, if it is assumed that the losses for the batteries are related with the charging of the batteries the total losses for this case is 4.6 -6.4 %. It is seen that even with the best efficiency the losses are higher than the base case. Notice that this battery capacity is necessary to prevent overloading for this scenario and profile, the smallest capacity possible for this purpose.

Figure 4.1 shows the variation of voltages in the network for the busbars and nodes. All of the busbars with an overvoltage are located in the low voltage areas. Both in the battery case and load shifting case the high voltages are reduced, more for load shifting than for the batteries.

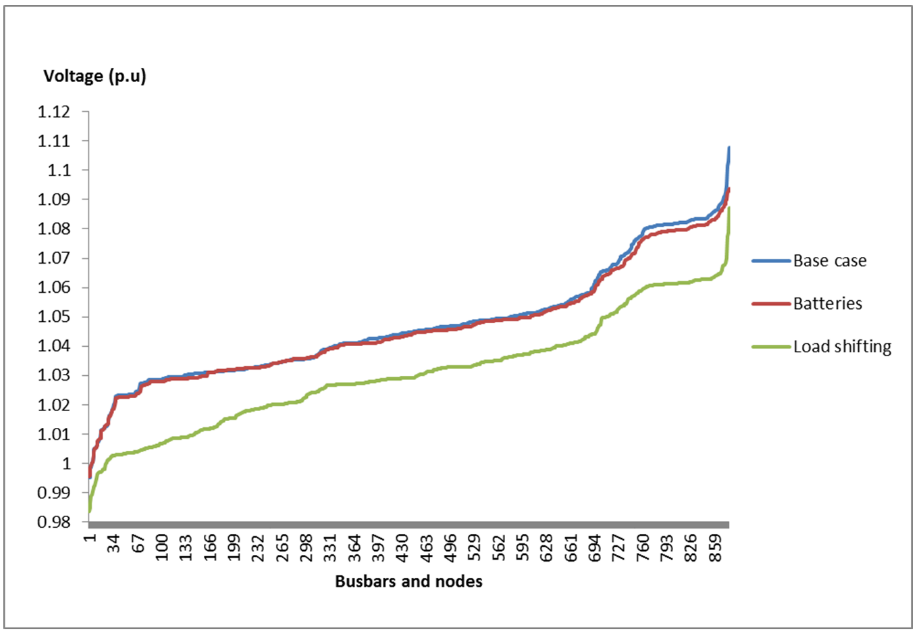

Figure 4.1: Voltage for the busbars and nodes in the grid.

14 of the transformers are overloaded (loading more than 100% in the base case). As the batteries are dimensioned to prevent overloading,the transformer loading is reduced for all the overloaded transformers by the batteries. Load shifting reduces half of the overloaded transformers but not all of them, despite the large part of adjustable loads. How the loading is reduced by the different measures is shown in figure 4.2. To get more detailed view histograms for each measure and base case can be found in appendix C.

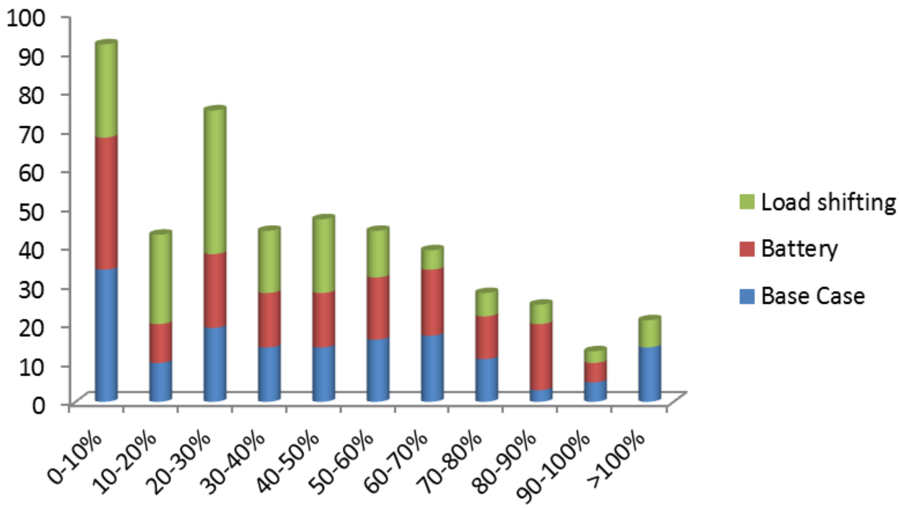

Figure 4.2: The loading of the transformers at secondary substation.

Only one cable in the grid is overloaded. The line loading is reduced by both load shifting and batteries. Only 20% of the households is needed to prevent the overloading in the load shifting implementation. The overloaded line is an overhead line. In figure 4.3 the overloaded line position is shown. The red line is the critical line; the red circle is the solar park. Overall the loading of the cables and lines are very low and histograms for cables and lines are shown in appendix C.

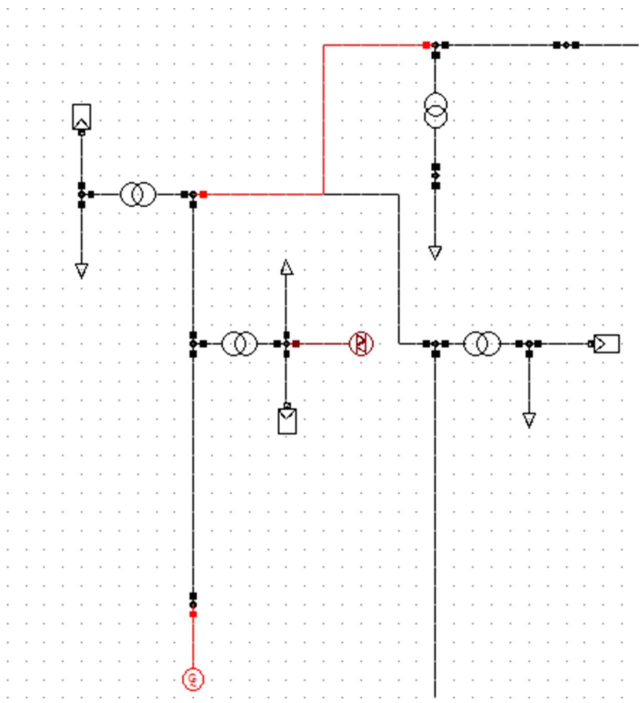

Figure 4.3: The overloaded line (red) in the grid.

Relevant result for this section is the battery capacity. It is this profile that defines the battery capacity. 15 battery storages are implemented in the model, 14 for the overloaded transformer and 1 to prevent the overloaded line. The storage capacity for the batteries are a roughly estimation based on the 24 hour simulation. The batteries charging capacity and storage capacity are summed up in table 4.2. A total charging capacity of 2.345 MW for all the batteries is implemented. Table 4.2 above shows also the prices of different battery technologies based on power installation cost for the battery-power capacities used for this scenario. The price for each battery is given by:

$$c_j = P \cdot C_P \tag{4.1}$$

The price rates for the power capacity (Cp) is given by table 2.2, 2.3 and 2.4. Battery 15 is installed close to a power plant with a maximum output power of 2500 kW and has the highest amount of power and energy capacity, the reason

Battery	Power Capacity (kW)	Energy Capacity (kWh)	Cost for Li-ion based on €/kW	Cost for Lead-acid based on €/kW	Cost for Vanadium redox flow based on €/kW
			$C_{j,Li-ion}$ (€)	$C_{j,Lead-acid}$ (€)	$C_{j,VRF}$ (€)
1	130	2070	52,000	39,000	208,000
2	125	1890	50,000	37,500	200,000
3	300	4350	120,000	90,000	480,000
4	120	1650	48,000	36,000	192,000
5	120	1650	48,000	36,000	192,000
6	70	1005	28,000	21,000	112,000
7	50	585	20,000	15,000	80,000
8	70	675	28,000	21,000	112,000
9	30	300	12,000	9,000	48,000
10	60	540	24,000	18,000	96,000
11	20	240	8,000	6,000	32,000
12	50	420	20,000	15,000	80,000
13	70	480	28,000	21,000	112,000
14	30	225	12,000	9,000	48,000
15	1100	6750	440,000	330,000	1,760,000
		Total	938,000	703,500	3,752,000

Table 4.2: Charging-, storage capacity and prices of the different battery technologies depending on the cost of €/kW.

for that is to decrease the load on one of the lines nearby which otherwise is very heavily loaded. The price calculation of a battery is calculated for the most cases after the energy capacity and not the power capacity [100], but in this case the calculation is calculated after the power capacity. The reason is the batteries are used to avoid overloadings of the transformers and the lines and in that way, the power capacity is the critical parameter. It is also important that the batteries absorbs the required power during the time interval when the transformer otherwise would be overloaded.

Each battery is compared for each price of the three different battery types. The colors indicate the price ratio between the three different prices. Green is cheapest and red is the most expensive.

The total cost (C_{TOT}) for every technology is given below:

$$C_{TOT} = \sum_{j=1}^{j} cj \tag{4.2}$$

From table 4.2, the cost for the Lead-Acid technology is lowest due to the green colour which means it is the lowest price for every battery, except battery 7 due to the high power capacity. The total cost for the batteries in the grid for every technology is given by:

$$C_{TOT,Lead-acid} = \sum_{j=1}^{15} c_{j,Lead-acid} = 938\ 000\,€$$

$$C_{TOT,Li-ion} = \sum_{j=1}^{15} c_{j,Li-ion} = 703\ 500\,€$$

$$C_{TOT,VRF} = \sum_{j=1}^{15} c_{j,VRF} = 3\ 752\ 000\,€$$

Battery	Power Capacity (kW)	Energy Capacity (kWh)	Cost for Li-ion based on €/kWh	Cost for Lead-acid based on €/kWh	Cost for Vanadium redox flow based on €/kWh
			$C_{e,Li-ion}$ (€)	$C_{e,Lead-acid}$ (€)	$C_{e,VRF}$ (€)
1	130	2070	2,070,000	828,000	828,000
2	125	1890	1,890,000	756,000	756,000
3	300	4350	4,350,000	1,740,000	1,740,000
4	120	1650	1,650,000	660,000	660,000
5	120	1650	1,650,000	660,000	660,000
6	70	1005	1,005,000	402,000	402,000
7	50	585	585,000	234,000	234,000
8	70	675	675,000	270,000	270,000
9	30	300	300,000	120,000	120,000
10	60	540	540,000	216,000	216,000
11	20	240	240,000	96,000	96,000
12	50	420	420,000	168,000	168,000
13	70	480	480,000	192,000	192,000
14	30	225	225,000	90,000	90,000
15	1100	6750	6,750,000	2,700,000	2,700,000
		Total	22,830,000	9,132,000	9,132,000

Table 4.3: Charging-, storage capacity and prices of the different battery technologies depending on the cost of €/kWh

In table 4.3, prices for the batteries depending on the price per kWh are shown. To calculate the total cost for every technology, equation 4.2 is used for every technology.

$$C_{TOT,Lead-acid} = \sum_{j=1}^{15} c_{e,Lead-acid} = 6{,}750{,}000\,€$$

$$C_{TOT,Li-ion} = \sum_{j=1}^{15} c_{e,Li-ion} = 2{,}700{,}000\,€$$

$$C_{TOT,VRF} = \sum_{j=1}^{15} c_{e,VRF} = 2{,}700{,}000\,€$$

It is very important to notice that the costs calculated for the batteries do not include the costs for the power electronics needed for connection with the electrical grid. The costs calculated are bigger in reality if power electronics are included.

From [102] it is possible to see how big the cost for grid strengthen will be if that is done to solve the overloaded transformers and cable. The transfer capacity needed for the transformers are the same as the charging power for the batteries. The cost for a net station and installation of a transformer with transfer capacity 315 KVA(enough for all the overloaded transformers) is around 22 000 €. This is less than the cost for batteries where the cost for power electronics and installation not is included. The overloaded line is a one km long aluminium overhead line and it is connected in the medium voltage area. For the grid extension with one new cable the cost is also much lower than the battery needed to prevent overloading.

For a combination of load shifting with 50 % of the households and battery storage the result shown that the needed battery capcity could be reduced to 0.59 MW for the this profile.

4.1.2 Profile 2

In table 4.4 the key parameters for the simulation are shown. The production

Key parameters	Base case	Battery
Delivery to transmission grid (MW)	8	5.8
Loading of T1 (%)	27	26
Loading of T2 (%)	13	10
Busbar MV to transmission (p.u)	1.034	1.032
Busbar transmission grid (p.u)	1.003	1.003
Highest Voltage (p.u)	1.096	1.094
Lowest Voltage (p.u)	0.984	0.995
Average Voltage (p.u)	1.032±0.020	1.030±0.019
Grid-losses (%)	1.6	1.2

Table 4.4: Results for Profile 2.

is still higher during this load peak. The voltages of the relevant busbars are unchanged compared to Profile 1. The transformer loading are reduced by the batteries.

The graphs in figure 4.4 have a similar appearance as profile 1 but overall with lower voltage. It can be seen from table 4.4 that the highest voltage on a busbar is lower than 1.1 p.u. The voltages are slightly reduced by the battery implementation.

Figure 4.5 shows the loading of the transformers at secondary substation in the grid.

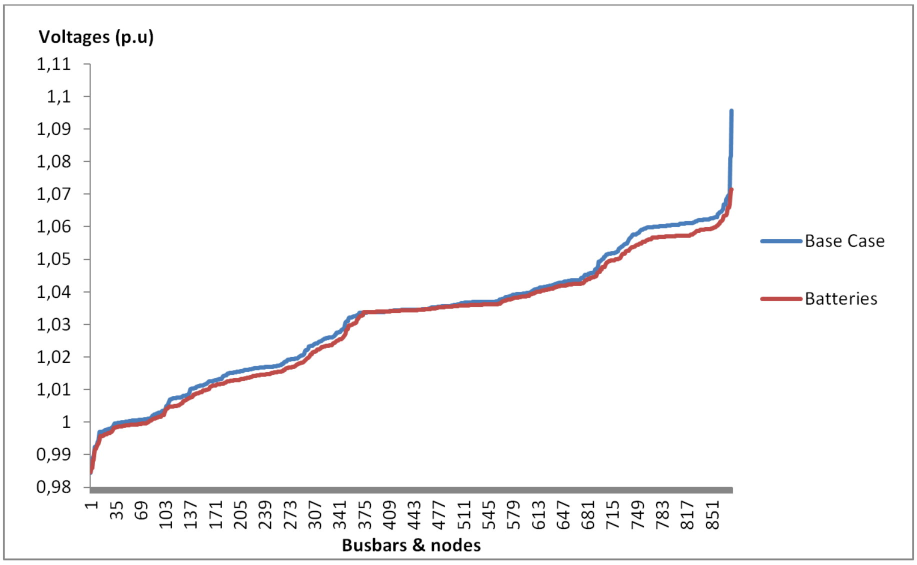

Figure 4.4: The voltage over the busbars and nodes

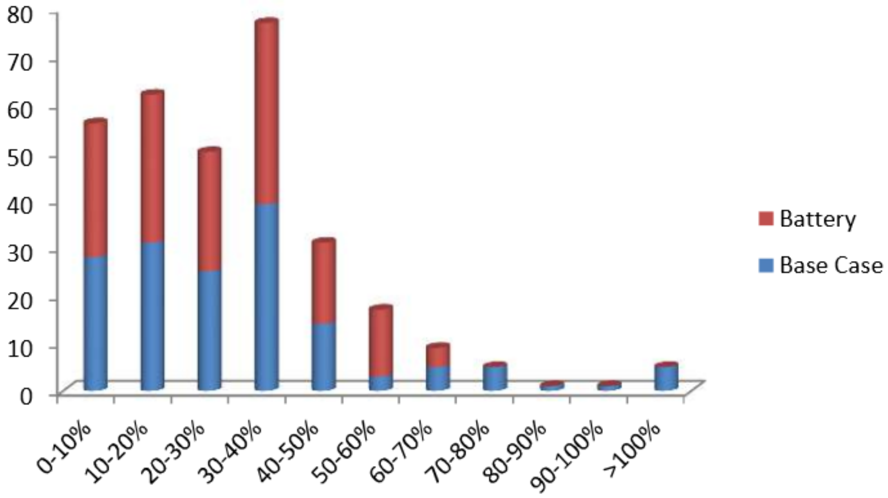

Figure 4.5: The loading of the transformers for base case and with batteries implemented.

Despite the high load, five transformers are still overloaded. They are all reduced by the battery implementation. The batteries reduce the loading of the transformers such that none are more loaded than 70% because the batteries are charging with full capacity.

Key parameters	Base case	Battery	Biomass 1	Biomass 2
Delivery to transmission grid (MW)	-30.9	-28.5	0	-20.7
Loading of T1 (%)	57	52	21	39
Loading of T2 (%)	50	46	8	34
Busbar MV to transmission (p.u)	0.995	0.996	0.993	1.030
Busbar transmission grid (p.u)	0.988	0.989	1.007	1.002
Highest Voltage	0.995	0.996	1.007	1.030
Lowest Voltage	0.859(34.58%)	0.863(30.72%)	0.897(4.89%)	0.873 (26.39%)
Average Voltage (p.u)	0.925±0.042	0.930±0,041	0.962±0.062	0.939±0.042
Grid-losses (%)	4.6	4.1	3.9	4.2

Table 4.5: Results for Profile 3.

4.1.3 Profile 3

Notice that the delivery to transmission grid is negative which means that the transmission grid is supporting the network. For this profile the transformers are highly loaded due to the high load and low local production.Many voltages in the grid are low during this load profile but the high load peaks do not last for long normally. These graphs and figures are to be found in appendix.
To cover the load peaks with own resources (without the need of transmission grid) a very big biomass power plant is needed. The other scenario is an average biomass power plant (of the bigger ones in Germany) which is a more realistic implementation. It can vary between 2 500 000 and 3 200 000€, for the 10 MW between 77 500 000 and 99 200 000 €for the one that covers to load peak. To this price a fuel price is added for the produced electricity. The price for the biomass power plants are calculated from the price data in the section 2.2.3.

4.1.4 Profile 4

This profile did not show any interesting results concerning active power balancing. The graphs and figures are documented in appendix.

4.1.5 Time sweep

Following figures shows a 24 hour simulation with the base case (red) and a case with a combination of all the measures used (blue). Figure 4.6 is a sunny day and figure 4.7 is for a cloudy winter day. In the figure 4.6 the arrows illustrate which measures that create the difference in power delivery between the base case and the mixed combination case are used.

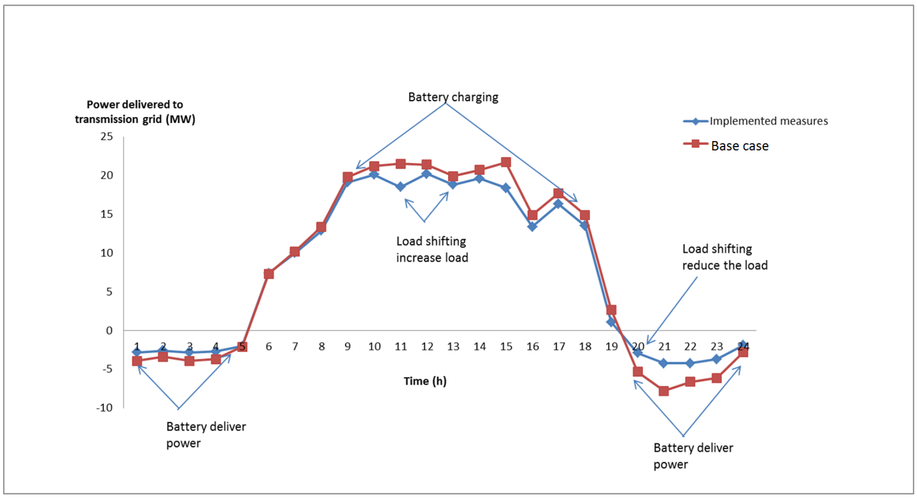

Figure 4.6: 24 hour simulation for a sunny day with combination of different measures

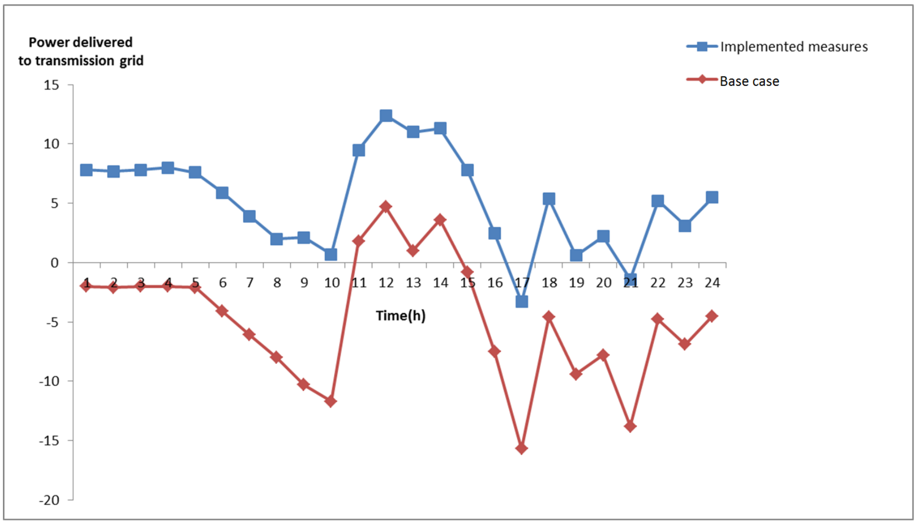

Figure 4.7: 24 hour simulation for a winter day with combination of different measures

For the summer day there are no bigger differences between the two graphs. But it is enough to prevent the transformers to not be overloaded. The load shifting also reduces the highest production peaks. The simulation also showed that transformers were overloaded for long time during the production peaks, even if the loads were hourly average. The detailed operation of the batteries is shown in appendix C.

The main difference between the two graphs in figure 4.7 is that the blue, with implemented measures (battery and biomass), are 10 MW higher due to the output of the biomass power plant. Batteries are also implemented. With a surplus production, because of the biomass power plant, it is possible to charge the batteries when the total production is high and deliver energy back during load peaks. The implementation of the batteries has the same capacity as the batteries used for the high production-low load profile. How they are used is shown in appendix. The heat produced by the biomass power plant is 50 % of the heat demand during the coldest day. It is possible that a day with low production not coincide with a cold day and the heat production would then be a larger share or needed to be reduced.

From 4.6 and 4.7 it is possible to see that the grid model areal is a net exporter of energy during a day with the implemented measures, more energy is delivered to the transmission grid than received. Calculations comparing the hourly average of the production of and the hourly average of the load and sum up the difference results in, for the sunny day the net export to the transmission grid is around 180 MWh (182 MWh for base case) and for the winter day 125 MWh (-115 MWh for base case). The grid model area is still dependent on transmission grid to deliver power because that the consumption is not at the same time as the production. To be able to be independent of the transmission grid delivery more storages are needed. How much storage that is needed on an hourly base is for the summer day is 4.2 MW more than the already installed capacity and for the winter day 3.3 MW. This is to cover the load peak average over an hour. To cover maximum load peaks more storage capacity is probably needed.

4.2 Scenario 2

In this section, the results from simulations of scenario 2 are presented.

4.2.1 Profile 1

For the results of scenario 2, it is interesting to compare it to scenario 1 to see how an increased production from PV to an already highly PV penetrated grid segment. The higher solar production makes the biggest differences in the high production low load profile. Table 4.6 shows a summation of the key parameters for the implementations and base case.The delivery to the transmission grid has increased with 31% compared to the base case in scenario 1.

A comparison between scenario 1 and scenario 2 is investigated for the voltages in the grid.

Figure 4.8 shows the voltages in the network for the busbars and nodes for scenario 1, scenario 2 and the different measures used in the same figure.
2.5% of the busbars and nodes in scenario 2 base case have a voltage over 1.1 p.u, this is six times more busbars and than in scenario 1 base case.. As seen in figure 4.8 the lowest voltages for scenario 2 is lower than the lowest voltages for scenario 1. It is hard to see in the graphs but the batteries reduce some of the voltages, but some are still too high. Load shifting reduces all of them. For

Key parameters	Base case	Battery	Load shifting
Delivery to transmission grid (MW)	29.2	26	22.7
Loading of T1 (%)	57	52	46
Loading of T2 (%)	42	38	34
Busbar MV to transmission (p.u)	1.028	1.030	1.026
Busbar transmission grid (p.u)	1.002	1.002	1.001
Highest Voltage (p.u)	1.115(2.5%)	1.106 (1.82%)	1.100
Lowest Voltage(p.u)	0.994	0.995	0.985
Grid-losses (%)	5.4	4.6	3.7

Table 4.6: Results for the High production-low load profile

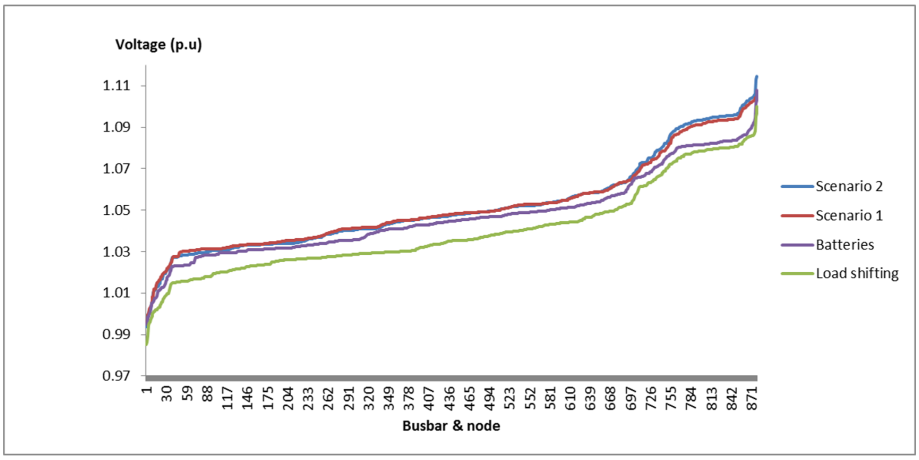

Figure 4.8: The voltage over the busbars and nodes

scenario 1 the voltages that exceeded the voltage limit was all in the low voltage area. In Scernario 2 some of the high voltages are in the medium voltage area.

For transformer loading concerning scenario 2, the loading overall was raised for the transformers. The transformers that were overloaded in scenario 2 are the same as the ones in scenario 1 because of the increase in solar production was implemented for areas with already relatively low production.The overloaded cable became more congested which needed to be solved with a raise of charging capacity for the concerned battery with 1 MW. All curves and histograms for scenario 2 can be found in appendix.

4.3 Chapter summary

The results from profile 1 shows that some voltages in the low voltage area exceed the limits and 14 transformers in the grid model are overloaded. The battery dimensioning is done to prevent overloading and therefore all the overloaded transformers loading were reduced. 2.345 MW charging capacity was needed to prevent overloading were a 1 MW battery was implemented to prevent a overloaded line.

From profile 2 the results shown that even under a load peak during high production times some transformers were overloaded and a lot of power was delivered to transmission grid.

The results from profile 3 showe that a bio mass power plant of 31 MW installed power was needed to cover the load peaks. The voltages in the grid was overall low during load peaks and increased some by the biomass implementation. The battery implementation had the same capacity as for profile 1 and that was too small to affect anything notably. The overloaded line in scenario 1 became more overloaded and more battery capacity was needed to reduce the loading.

The 24 hour simulations the summer day showed that the transformers were overloaded for a longer time of the day assumed that the power from the PV had constant delivering to the grid. For the winter day a implementation of a 10 MW biomass power plant made the grid model to net exporter instead of net importer. If the concerned day would be the same day as the coldest day, when most heating is needed, the biomass power plant would account for 35 % of the heating needed during a day with the assumption of electrical efficiency of 30 %.

For the results from scenario 2 was focused on profile 1 to see how an increased PV penetration in the low voltages grid affect the grid segment. The voltages in the grid become higher and even some of the busbars and nodes in medium voltage area exceeded the voltage limits. As the increase in production was done in areas with low PV production no other transformers were overloaded compared to scenario 1.

Chapter 5

Discussion

The simulation software, PowerFactory is a powerful tool, even if the use of the Thesis was restricted by the license that have been given, many aspects and results could be investigated. For the aim of this Master Thesis, balancing active power, the software was easy to learn. Simulations of many different load and productions profiles have been performed and although the simulations have taken a lot of time the changes between different profiles is quite easy. The grid model was provided from a grid operator within E.ON and was converted from PSSE, a software from Siemens, and the need of validation of the model was important. As the grid model had a lot of busbars, nodes,transformers, cables ,lines, loads and generators it is difficult to get a full overview. The benefits of building our own model was realized, but this was just too time consuming within the framework of this Thesis.

The measures investigated and implemented in the simulation tool was battery storage, load shifting and biomass power plant. Although simulations were performed on four different load and production profiles the most interesting one was, as expected, the high production low load profile. It came clear that with the current situation, some problems occur concerning the active power flow. Overloaded transformers are the main issue during production peaks; also high grid losses are experienced when huge amount of power travel from the distribution grid to the transmission grid. Although a solution to avoid overloading on transformers and cables is to strengthen the grid by grid extensions which means that cables and transformers should be changed or adding parallel cables and transformers to the overloaded areas. One great example can be seen in the medium-voltage grid where a big solar power plant connected to an overloaded line. To avoid overloading, a battery with very high charging and energy capacity was added close to the solar power plant. But a more cost effective solution would have been if the line was changed or a new line was added in parallel to share the loading, this also applies to the transformers where a change of transformers is related to lower cost, but the other benefits with batteries are then missed out.

Storing energy is the most effective measure for balancing the active power because of the valuable property to store energy and use when it is needed. At present, batteries are the most mature technology for short-term and medium-term energy storage and it was stated from several interviews with experts in the energy storage business. In the future, other technologies may be useful like flywheels and supercapacitors. An important point is that the batteries are especially good for short term storage which fits perfect as a balancing measure. For long term, other storage possibilities as pumped hydro storages and compressed air storage should be considered. Main disadvantages of the batteries are their high costs and relatively low efficiency. Although the simulations show that grid losses are reduced with implementation of battery storage, it is not the case for the total losses due to the relatively low battery efficiency. Even with batteries with the best efficiency the total losses become higher with batteries implemented in the grid. When using batteries for balancing active power it is important to have enough storage capacity so they can charge when it is needed. Concerning solar power it is very easy to predict when the production from solar will reach its peak and therefore the battery needs to discharge before the peak occurs in order to utilize the free capacity. Even the production of wind power can be forecast but not definitely and this might lead to larger margins regarding the battery capacities.Wind power is usually not connected to low voltage side and might not cause the same problem. When controlling the battery operation, one must take in to account several parameters as transformer loading, electricity prices, state of charge (for battery) and also predictions for expected production. As the batteries are implemented on the low-voltage side in the grid, they will for some circumstances while delivering power to the grid in combination with low load, increase the loading of the transformers.

Mr. Ulrich Spaetling, an expert in the field of energy storage stated in a mail conversation "From utility perspective it seems a more promising business model to use larger storage systems ($\approx$ 50-250kWh) at selected positions in the distribution network, rather than to aggregate residential storage systems and to operate them in a beneficial way to solve voltage/frequency problems in the LV grid. However, we test both ways in our T&I projects (Pellworm, Distribat). It is also not yet understood what will bring more value for E.ON as distribution network operator: Either more capacity based storage technologies or storage devices with more power capabilities, so there is no simple answer to this question". That was the main point on why the battery storages were implemented on the secondary substation on the low-voltage side.

As it can be seen in table 4.2 and 4.3, the costs for the batteries differs a lot depending on which price the calculations have been based on. As a the project leader of the M5BAT mentioned in the interview [100], the cost for battery-storage should in most cases be based on the price per kWh, which means that the lowest costs for the batteries in the grid would be 9,132,000 €. The lowest cost will result in implementation of Vanadium redox flow batteries or Lead-acid batteries because of the same energy capacity price. But comparing the prices for the charging capacity between Vanadium redox flow (1600 €/kW) and Lead-acid (400 €/kW), the lowest system cost would then be if the battery-storages are implemented with the Lead-acid technology. But as mentioned before, the Lead-acid have several disadvantages concerning electricity storage in the grid which makes it harder to realize on big energy capacities. From an economical perspective, the Lead-acid batteries would be ideal in this case but from a technical perspective, either the Vanadium redox flow or the

Li-ion suite well. The third and maybe the best solution are to combine the technologies. The batteries with highest energy capacity should be Vanadium redox flow and batteries with less required energy capacity should be either Li-ion or Lead-acid. It is very important to notice that the costs calculated for the batteries do not include the costs for the power electronics needed for connection with the electrical grid. The costs calculated are bigger in reality if power electronics are included.

One way to implement battery storage is to use the battery capacity of vehicles. For this the controll need to acess the vehicles battery control and this opposes the manufactures so far.

The load shifting measures is mostly useful when production is high in combination with low load. Although a large share of controllable loads was used in the simulations, load shifting could not solve all problems. Even if the consumption and the maximum power of the controllable loads are high they do not last for a long time, which would be necessary for balancing the power. Implementing more loads as cooling equipment would also lead to higher total electricity consumption, which is not desirable. The main benefit for using load shifting is the reduced grid losses, due to that the consumption of energy is closer to the production units in areas with distributed generation. Another benefit is that if the controllable loads are used during production peaks and they will probably not be used during other times when production might be lower, this benefit is hard to quantify since the high load peaks might depend on other loads than the controllable ones. The costs for load shifting are not very high, but the main problem is that the controllable loads need a controlling device implemented or implementation of demand response management programs. The easiest way is to implement the controlling devices in the construction stages of the household equipment. Load shifting is a measure for the future. Depending on how big capacity of loads that are possible to control, it can be a very valuable asset for balancing the active power. The load shifting requires customer awareness or automatic control and it might need sufficient incitement to get customers using it.

Biomass power plants should ideally be used as regulating power from perspective of balancing the active power in the electrical grid, especially when load is higher than production. Biomass power plants are often driven as combined heat and power, so when the price differences between electricity and heat is relatively high, there is a possibility to run those as condensing power, and then cooling systems are required to take care of excess heat. In Germany the price difference between heat and electricity is very high. The price difference initiates that biomass power plants might be used as condensing power, but Germany has a lot of coal fired power plants, which creates a surplus of heat that results in lower heat prices. Coal is the cheapest fuel on the market and that means that the situation might not look the same with biomass used as larger parts in the energy system, even if biomass fuels are cheaper than both oil and natural gas. The average power production of biomass power plants in Germany is 10MW electricity when in full operation. An implementation of 10 MW power plants in the simulation model makes the grid for the case study to be a net exporter instead of a net importer during a day with low solar power production and high load. As noted before, the biomass power plants will be cheaper in the future much because of the small carbon capture, which makes path for increasing integration of the biomass power plants in the energy system. One of the biggest advantages of the biomass power plants is their ability to produce electricity at any time which makes it superior to the other renewables as wind and solar. It's ideal in the simulation case where it is assumed that a feed in of 10 MW can be maintained all time. The main disadvantage addressed in the report was that the biomass power plants were located in rural areas where the grid connections are weak relatively to the urban areas. That results in high voltages in the grid especially on the low-voltage side. This effect was also noticed in the simulations where one of the biomass power plants connected in the low-voltage side led to high loadings on the connected transformer.

Some concerns for the simulation results are that the load profiles are generalized for all the loads in the grid and are based on data from 2002. Data from recent studies were not available due to confidential reasons. Even if it is not likely that 10 000 households have have same electricity consumption as each other, the load profiles give a good overview over how low and how big loads might be. The load profile study does not take in concern of schools, commercial stores and households with different consumption behaviour located in the area that might increase or decrease the load during different times in a day.

The grid model has been given from a German DSO and been converted from another simulation tool. That might lead to some uncertainty especially as big grid models are hard to get a full overview off. The grid model contained only three detailed low-voltage grids and only one medium-voltage grid. For more general conclusions the simulations should be done on more grids to get a better significance.

Chapter 6

Conclusions and Future Work

The main conclusions and future work for the report are mentioned in the next sections.

6.1 Conclusions

Large integration of PV into the distribution network will lead to high voltages and overloading, especially in the low-voltage side and the secondary station. At the primary station, the results from the case study, showed no signs of problems related to grid capacity issues.

From a DSO's point of view, the easiest and most profitable to implement larger energy storages close to the transformers and to be able to avoid over loadings, it should be done at the low-voltage side. It is difficult to compare the cost of battery storage and load shifting where there are no costs for implementation of load shifting available yet. Battery storages and load shifting does not fill the same purpose. With a 30% increase of PV, the voltages may increase in the grid and then also in the medium-voltage areas. If the increment is carried out in areas that already have a high PV integration, then over loadings will also arise for more transformers. Either the increment of PV should be limited, grid strengthening carried out or battery storage should be implemented to utilize the produced electricity. Battery layer provides unlike from grid reinforcement effect on voltages but may be needed in large capacities. How battery storages should be dimensioned, economical aspects should also be taken into account and that have been outside the scope of the Thesis.

The current price situation for battery storage is very high. Thus, it is much more expensive to implement batteries than grid strengthening. The recommendation is to limit the development of PV integration in areas where congestions occurs otherwise grid strengthening should be considered. For the long term, battery storages will fulfill an important function in the grid that cannot be met by grid strengthening and that is why the DSO is recommended to wait until the price trend for the battery storages begin to decrease before considering grid strengthening. Load shifting should be implemented as much as possible to be able to use the energy from the intermittent renewable energy sources. Biomass power plants will be needed to cover up for loss of nuclear power plants and coal power plants in the future. We think it will be more common to implement battery storages in the grid in the future specially when most of the energy in the energy system coming from renewable sources. Battery prices will drop and it will be more profitable to implement batteries for grid applications. About 30 years, load shifting and batteries will overlap each other in a very smooth and organized way. Energy consumption will be reduced by using "smarter" home appliances and emissions will be reduced because of the increased integration of renewable sources in the system. The shutdown of the nuclear power plants will open the path for the integration of large scale biomass power plants in the near future and this will lead to a more reliable renewable energy source.

Next follows some advantages and disadvantages regarding each technique based on simulations, interviews and literature studies:

Battery Storage

- Efficient for power balancing purposes
- Implementation of battery storage has higher costs than to strengthen the electrical grid.
- Might lead to higher revenues in the spot market.
- High capital costs.
- Even with batteries with the best efficiency the total losses become higher with batteries implemented in the grid.

Load shifting

- Works to partially reduce the problems of overloading.
- Low capital costs assumed it is only a matter of integration of microchips in household devices or installation of demand response programs.
- Low grid losses assumed that the electricity is produced close to the loads.
- Uncertainty about how the financing and the implementation should be realized.
- Unproven
- Since production is not controlled by load, load should be controlled by the production as good as possible.

Biomass power plant

- Possibility of controllable power generation
- High capital costs
- Can be controlled by the heat demand

The studied potential for the renewables in Germany can be used to investigate the different areas more in detail to get a better overview where exactly the problems in the grid will occur in the future. The evaluated measures for balancing the active power can be used for other grid with other renewable sources as distributed wind power integration. It is then interesting to see if the results are the same as in this case. The method used to investigate a grid model can be used for general basis to other grid models.

6.2 Future work

Proposal for future work in this field are:

- Investigate more grids with other mixtures of power production especially wind power. The approach can be the same as in this report but other production curves and worst case scenarios.
- An investigation of the faster processes in the electrical grid caused by a larger integration of renewable energy sources (dynamic simulations). As example when clouds shadows the solar panels or wind power plants goes from full production to none due to reaching the cut off wind.
- The controlling of how batteries operation should be done if they are implemented in the grid as balancing measure is an interesting task. There are many factors to consider making it advantageous from both an economical and technical point of view. This should be evaluated to get better conclusion concerning the batteries benefits. In this report the battery operation are based on rough estimation during the worst case days.
- Investigate how the placement of the battery storage can be more efficient and the capacity in kW/kWh at each placement. Evaluate the strategy, instructions and the dimensioning of the battery storages.
- Investigate how the communication of load shifting should be realized.
- More accurate analysis of the different measures; biomass power plants, storage and load shifting.

Appendix A

Interviews

The following chapter is about the interviews with the different experts within E.ON.

A.1 Interview Mr. Gerbert van der Weijde, storage expert. 2014-02-27

- Which technology (s) do you think that I should focus on?
Batteries: Vanadium flow batteries, Lead-Acid and Li-ion batteries.

More details about Lead-acid, Li-ion and Vanadium Redox flow?
Lead-acid: There are many different manufactures, not produced in large quantities. But by mass-producing the Lead-acid could result to lower costs, even more reduced by optimization of the cell design.
Li-ion: Medium-term storage, more expensive than Lead-acid, higher daily self-discharge
Vanadium Redox flow: Expensive because it is limited, higher maintenance costs due to leakage.

Technology	Does E.ON use it? If yes, then where?	Long- or short term?	Suitable for PV, Wind or Biofuel etc.?	Company providing this technology	Comments (specifications, special requirements, economical? etc.)
Power to Gas	Yes, in Falkhagen and Reitbrook	Long term	Uses most Wind, but it works also for PV and Biofuel	- Hydrogenics - AEG	- Not suitable for small areas i.e. not for distribution storage. - Very expensive - The main point is to feed in the produced gas in the gas pipelines and not to reproduce the electricity - More a business case than a stabilization case. E.ON uses the Power to Gas storage whenever the electricity price is low and sells the gas. - Not very efficient
Pumped Hydro Storage	Yes, there are a lot of sites, most of them in southern Germany i.e. Erzhousen, Glems. E.ON is thinking of using the old mines for this purpose	Long term	Suitable for most generation units; Wind, biofuel, power plants etc.		- Most of them are located in southern Germany because of the geographical conditions. - Slow "charging" time - Expensive - Not flexible i.e. high potential are vital. Mountain areas. - 80% efficiency - Suitable for larger grids and not for distribution grids. - Seasonal storage - High energy density - Long construction time
Flow batteries/ Chemical batteries	Yes, in households, project called Pellworm. M5BAT	Long term	For all	- A123 Systems - EaglePicher Technologies - ABB - EOS - Younicos	- Mature technology (Lead-acid) - Cheap- (Lead Acid) - Effective - Flexible - Good re- and discharge time - Good capacity - Well used in distribution systems (lead-acid) - Different technologies - High temperature of work (Lead-acid)
Compressed Air Energy Storage	Yes, in Huntorf	Long term	Nuclear or "big" power plants		- Slow "charging" time - Expensive - Suitable for larger grids and not for distribution grids. - Very efficient - Seasonal storage - High energy density -Requires fuel input - Long construction time
Thermal Energy storage		Long term			- Expensive - Suitable for larger grids and not for distribution grids. - Seasonal storage - High energy density - Long construction time
Superconducting Magnet Energy Storage (SMES)	Not focused on it	Short term			- SMES are currently only used for power quality/frequency regulation applications. - Expensive
Supercapacitors	Not focused on it	Short term			- Expensive - Low energy density - Very fast recharge

A.2 Interview Mr. Tobias Blank, involved in project of Pellworm. 2014-03-10

Could you tell me some general details about the island? (Geographical, inhabitants, grid connections etc.)
The area of Pellworm is 37,144 km2. Number of inhabitants is over 1000 with approx. 600 households. The name of the district is Nordfriesland. There are 2 sea cables to the mainland and there are approx. 50 substations with 20kV and 400 V cables on the island.

How much is the average power consumption and generation in Pellworm? How much is the average power consumption in every household?
Average consumption: 7 GWh/ year Average generation: 22 GWh/ year

Details about the power plant in Pellworm?
E.ON Hybrid Power Plant. 300 kW Wind, 780 kWp PV. There is additional a big wind park. In total 5.725 MW wind, 2.74 MW PV and 530 kW biomass on the island. First PV installation in 1983

I know that you use storage heaters, flow- batteries and Li- ion batteries to store the energy, but do you use other kind of storages?
Yes, residential batteries.

When is it better to use flow batteries rather than Li- ion?
Different storage technologies have to be used for "minutes-to-hours" – storage than "hours-to-days" – storage. Vanadium Redox-Flow battery is used as "hours-to-days" - storage. This is because the high energy density and the long discharge time. Li-Ion batteries are used as "minutes-to-hours" – storage. Fast charge and discharge time.

Details about the storage heating. Is it only in households you have storage heating system in the distribution system?
Electrical Storage Heaters are used for load flexibilities as "hours" – storage. Average energy capacity per household is 135 kWh and average power in 17 kW. Average number of units in every household is 4. Yes only in the households.

Details of the storage batteries?

Vanadium Redox-Flow	
Continuous power	200 kW
Energy capacity	1600 kWh
AC-AC roundtrip efficiency	60%
Cycle-life time	>20.000
Calendar life time	25 years

Table A.1: Specification of the Vanadium redox flow battery

Where in the grid do you put the storages? Are there any special

Li-ion	
Continuous charging power	560 kW
Continuous discharging power	1,1 MW
Energy capacity	560 kWh
AC-AC roundtrip efficiency	85%
Cycle-life time	>4500 (80% DD)
Calendar life time	20 years

Table A.2: Specification of the Li-ion battery

requirements the geographical place need to maintain?
The battery storage is placed in the middle of the island and is connected to the sea cables. There are no special requirements just that the air is very "salty" and it can lead to corrosion on the batteries. For that, the solution is to have a very high quality of stainless steel.

Is it better to have one storage with very high capacity or several low capacity storages clustered in the grid?
There is no good answer because Pellworm have just started with house battery storage and there is no overview of the potential, dis- and advantages.

How often are you forced to provide Pellworm with "external" power from the submarine cable? On which circumstances are you forced to do it?
The purpose of the project is NOT to convert Pellworm to an Energy independent island. On circumstances where there is no sun and no wind, power from the sea cables is used.

Does it happen that you are forced to feed in the surplus power in the submarine cable because of the storage capacity is full?
Yes

Do you use load shifting? If yes, how do you use it? If no, do you know anything about the potential?
Yes, with the storage heaters only.

Where you forced to upgrade the grid before the smart grid implementation? If yes, in which way?
No, everything is the same as before.

Is there any simulation data of PowerFactory for Pellworm?
N/A

How do you disconnect the PV from the grid on the night?
No.

A.3 Interview with Expert, involved in M5BAT project. 24-04-2014

I have only read about the M5BAT on a few articles because I couldn't find much more I know that the battery system is a combination of Li-ion (for short-term demand) and Lead-Acid, 5 MW. E.ON Research Center corporation with Aachen University.

1. What is the main purpose of the storage system? (Stabilization of the grid, economical, science...?)
BBackground: The storage project is not yet commissioned. At the moment the basic engineering is undergoing and within the next months the building permit is expected to be given by the local authorities. It is expected, that the storage will run in the late of 2015. E.ON is responsible for the civil modification, high voltage equipment and several minor rearrangements.

Since The main purpose is for research activities; a profitable business case is not expected. Nevertheless, E.ON is expecting to learn from the market integration Work package, which is part of the project. To investigate how a grid scales battery storage can be applied in the future. The main benefit for E.ON will be to see how we can integrated for the benefits of the power plants

2. Where does the stored power come from? (Wind, power plants?)
From the grid, it is not connected directly to a power plant, wind farms and so on.

3. What is the energy capacity, efficiency, cycle and calendar lifetime of the system?
Most of the values are not yet evaluated due to the early state of the project; we expect a round trip efficiency of 80%. Energy capacity depends on the outcome of running tenders and is likely to be 4 MWh. The whole system consists of five independent battery string with 1.26 MVA each. This gives a power of 5 MW-guaranteed or 6.5 MW gross. Cycle and calendar lifetime are not yet evaluated.

4. What are the main problems you have experienced with the storage system?
Since the storage system is not in operation, this question cannot be answered.

5. How did you solve the problems?
N/A

6. Why didn't you use Vanadium Redox Flow batteries?
Using a VRF battery is out of the projects scope.

7. Where in the medium- voltage grid is the system placed? (Close to a power plant, close to transformers, close to the loads?)
It is placed in the medium-voltage grid close to a transformer-station (approx. 2x40 MVA, 11 kV to 110 kV). The battery is placed in an old school building.

Required only 20 m of lines and the area is a mix of an industry area and a residential area.

8. Which are the main costs of the system?
We don't know the cost split exactly because it is not our responsibility but the whole cost for the project is 12.5 m€

9. What are the maintenance costs?
N/A

10. How big is the price difference between the Li-ion and the Lead-acid batteries?
N/A

11. How much does the power electronics cost and how much does only the batteries cost?
SMA is a funded project partner and will bring in the inverters as a contribution. Therefore, the project prices are not meaningful.

12. Do you think this storage system will be installed more often in the future? Why?
It is very hard to answer without any major operational experiences. I see some hurdles from the regulations in Germany.

13. Does is happened that you inject some of the stored energy in to the transmission grid?
Physically it is hard to determine if the energy is injected into the transmission grid, because the system is not connected directly to the 380 kV system. At least, it is not the goal of the project to do so.

14. Have you noticed any difference on the grid equipment (feeders, transformers and etc.)?
No, as said before the transformer is on 2x40 MVA so there is no problems on the transformer regarding feed in capacities.

It is expected that the DSO limits the maximum ramp rate to maintain grid security. The ramp rate right now is up to 3 GW/min. However, the negotiations between the DSO and the University regarding this topic are still underway and the outcome is not clear.

A.4 Telephone interview with project leader of M5BAT. 2014-04-29

1. How many MW & MWh is the Li-Ion part and how many MW MWh is the Lead-Acid part? Why this proportions?
2 battery strings for every type:
- Li-ion: 1.25 MW & 0.7 MWh
- Lead Acid: 1.25 MW & 1.3 MWh

The proportions comes from the project RH, it is not optimal properties, the project is founded by the public sector and the main aim is science, investigate how every battery type operates in the grid.

2. Do you use different power electronics for the Li-Ion and the Lead-Acid?
No, one type of inverter, same for each battery string. The inverter is modulated so you can connect to both battery types

3. How big is the medium-voltage grid that the battery is connected to? (Approx. how many nodes?)
No I don't know, not lot knowledge about the grid. All I know that it is 10 kV. Total installed power in the grid is 20 MW. Mainly industry nodes (Continental & Philips are the biggest energy consumers). I don't think it is a lot of nodes. I don't know if the residential area is connected to this medium-voltage grid.

4. Which are the main costs of the system?
First the Batteries and then the system integration: - Cost of building - Inverter - Development of energy management system

5. A general question about designing a battery:
The energy cost of a battery is not the same as the power cost of a battery. So when you calculate the cost of a battery, do you base it on €/kW or €/kWh?
Most cases states the costs for €/kWh. And if you want to know the power, then you should look at the C-rate of the battery. 1C-rate means that the discharge current will discharge the entire battery in 1 hour.

A.5 Mail conversation with Mr.Ulrich Spaetling, storage expert. 2015-05-06

When is it better to have one big capacity storage connected to the distribution grid rather than to have several low capacity storages clustered in the grid (house storages)?
From utility perspective it seems a more promising business model to use larger storage systems ($\approx$ 50-250kWh) at selected positions in the distribution network, rather than to aggregate residential storage systems and to operate them in a benefitial way to solve voltage/frequency problems in the LV grid. However, we test both ways in our T&I projects (Pellworm, Distribat). It is also not yet understood what will bring more value for E.ON as distribution network operator: Either more capacity based storage technologies or storage devices with more power capabilities, so there is no simple answer to this question.

When is it better to use Vanadium Redox flow batteries rather than Li-Ion batteries?
As a tendency, lithium-ion is more suitable for power related services/products (balancing energy, frequency control), and vanadium redox flow more for capacity related products/services (arbitrage, voltage control). Lithium-ion has

higher specific capacity cost (≈ 800 €/kW), but lower specific power cost (≈ 300 €/kW). For vanadium redox flow it's the other way round: Specific power cost are high (≈ 2000 €/kW), but capacity cost are low (≈ 400 €/kWh). Therefore typical power-to-energy ratios of lithium-ion are 2:1 or as a minimum 1:1. For vanadium redox flow typical power-to-energy ratios are 1:4 or 1:6. Again, this questions cannot be generally answered in a few sentences. You have to consider also other battery systems or competing storage technologies, and not only the cost side (investment cost, O&M cost) but also the revenue side.
Please see my best guess in the table below (marked in red) !

Technology	€/kW	€/kWh
Li-Ion	400	1000
Lead-Acid	300	400
Van.red.flow.	1600	400

Appendix B

Load Curves

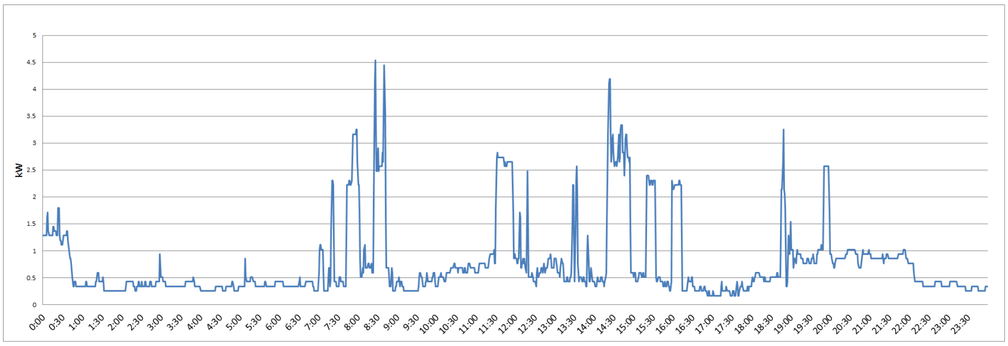

Figure B.1: Load curve for the "Summer-Sunday-Cloudy" table profile

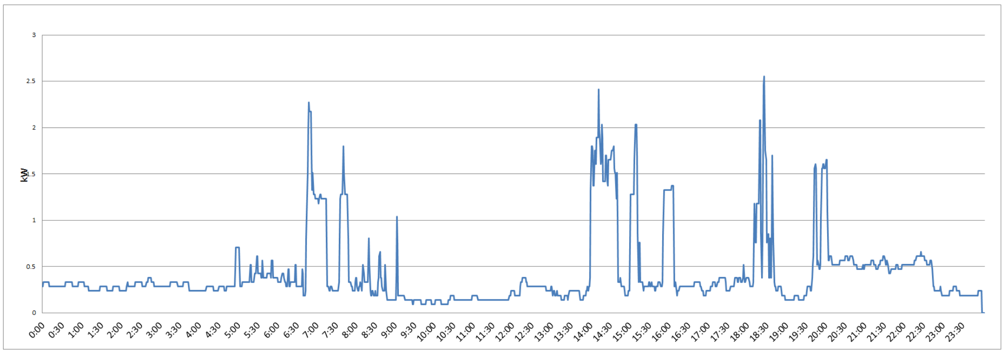

Figure B.2: Load curve for the "Summer-Workday-Neither" table profile

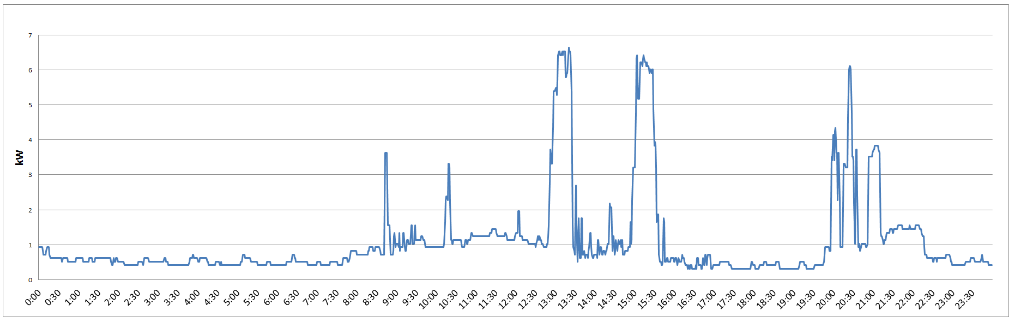

Figure B.3: Load curve for the "Winter-Sunday-Cloudy" table profile

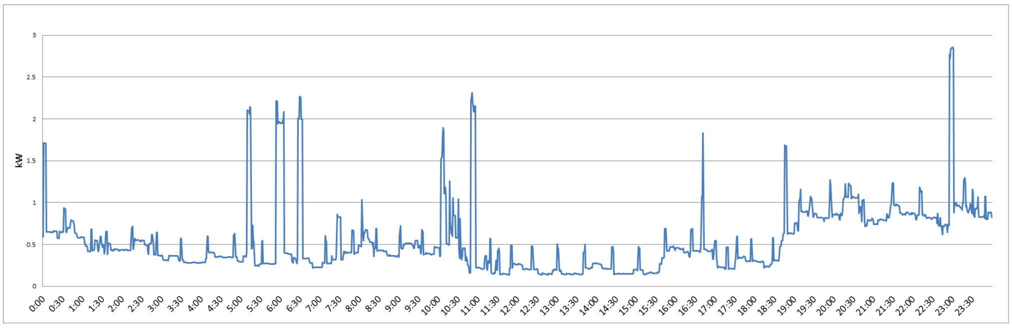

Figure B.4: Load curve for the "Winter-Workday-Cloudy" table profile

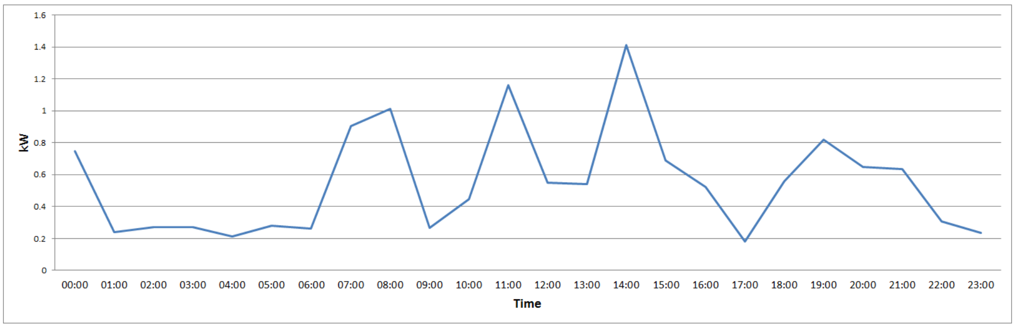

Figure B.5: Average hourly load curve for the "Summer-Sunday-Neither" table profile

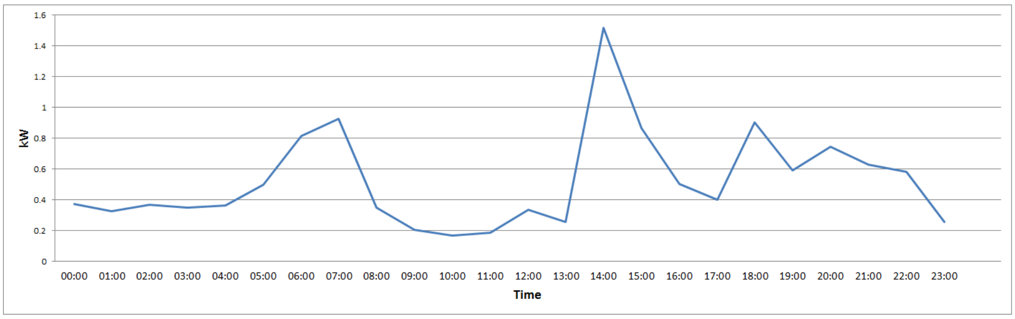

Figure B.6: Average hourly load curve for the "Summer-Workday-Neither" table profile

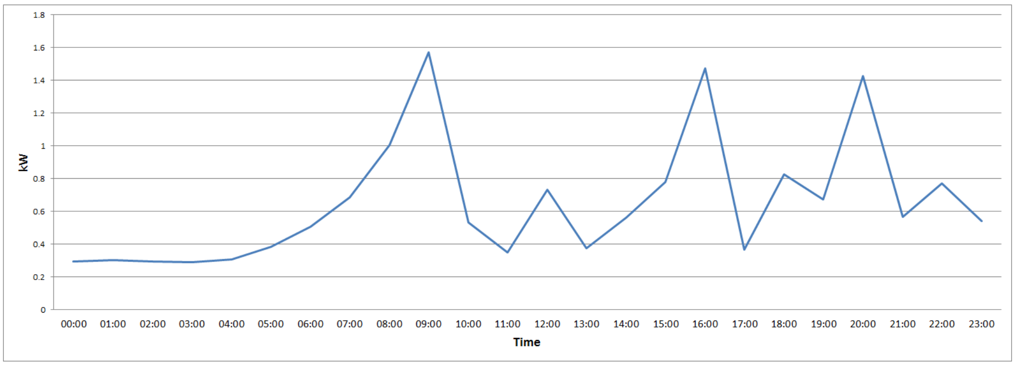

Figure B.7: Average hourly load curve for the "Winter-Workday-Sunny" table profile

Appendix C

Results

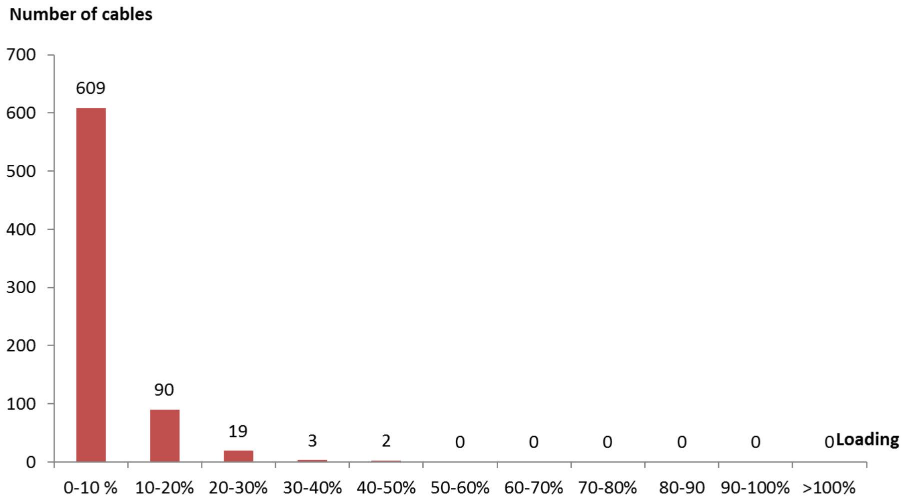

Figure C.1: High production - high load, loading of cables with batteries implemented for scenario 1

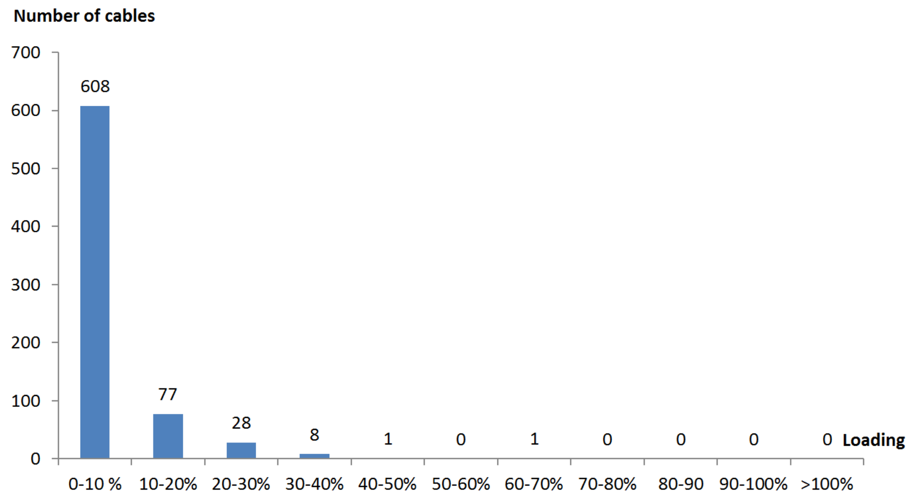

Figure C.2: High production - high load, loading of cables for the base case for scenario 1

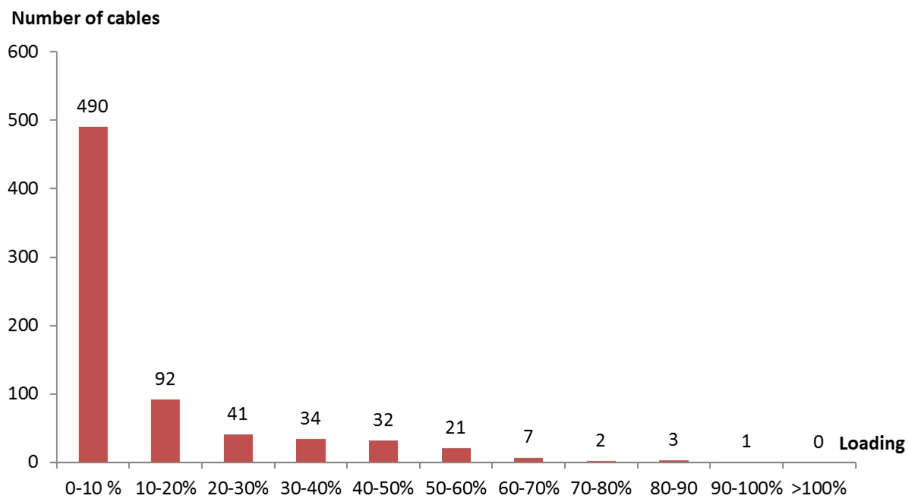

Figure C.3: High production - low load, loading of cables with batteries implemented for scenario 2

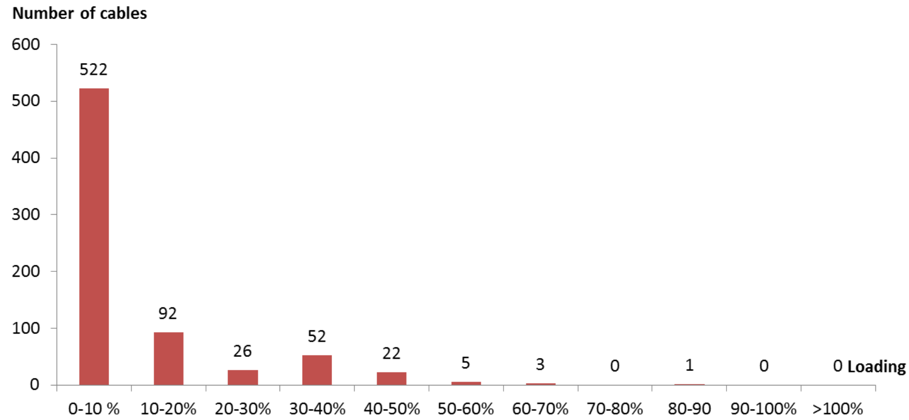

Figure C.4: High production - low load, loading of cables with batteries implemented for scenario 1

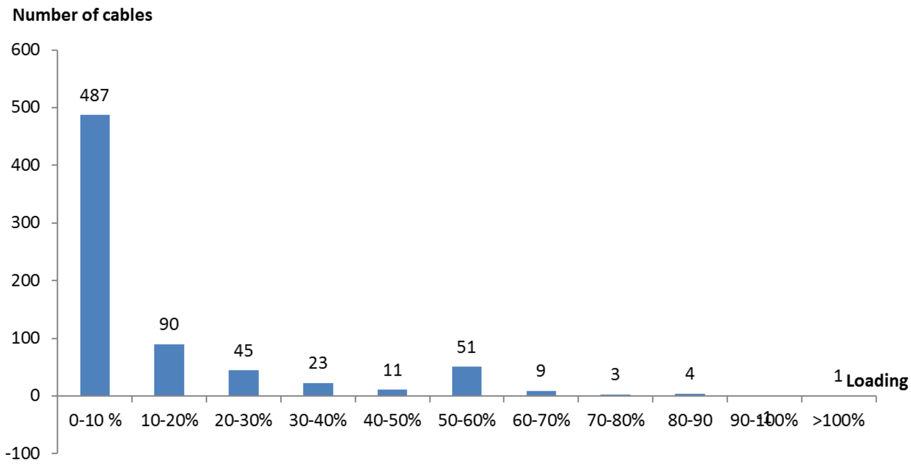

Figure C.5: High production - low load, loading of cables for the base case for scenario 2

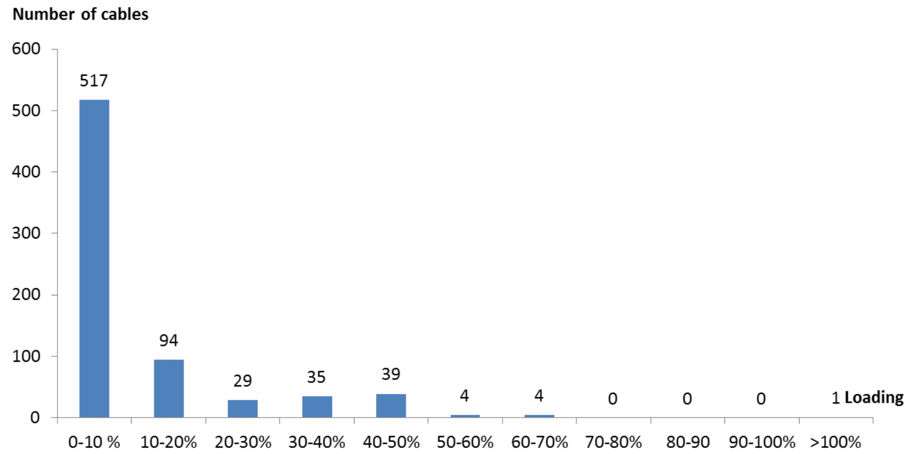

Figure C.6: High production - low load, loading of cables for the base case for scenario 1

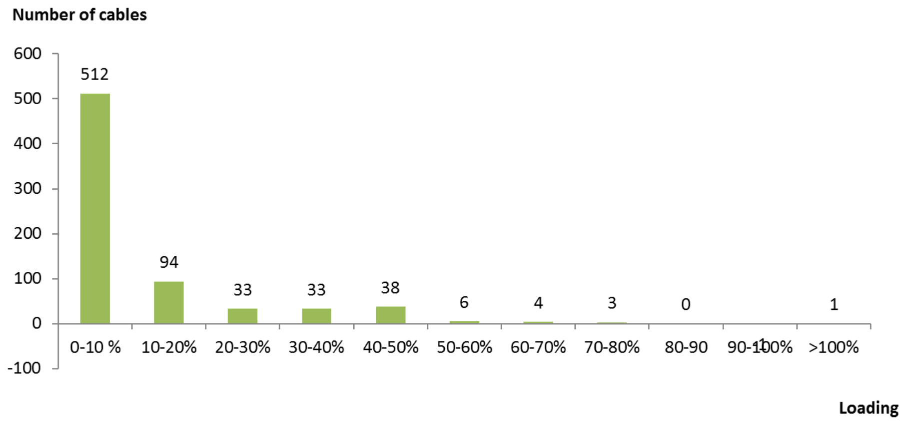

Figure C.7: High production - low load, loading of cables with load shifting implemented for scenario 2

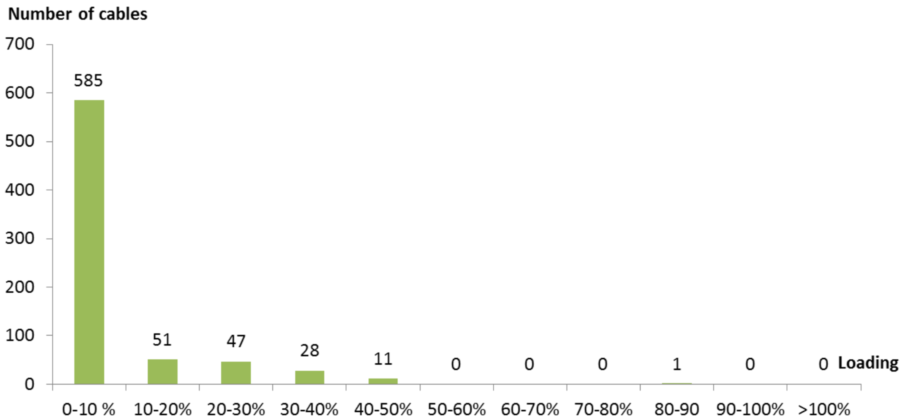

Figure C.8: High production - low load, loading of cables with load shifting implemented for scenario 1

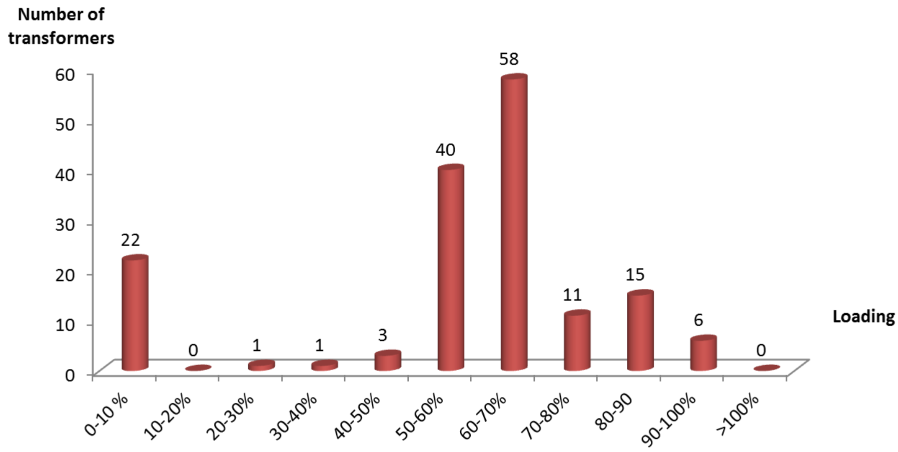

Figure C.9: High production - low load, loading of transformers with batteries implemented for scenario 2

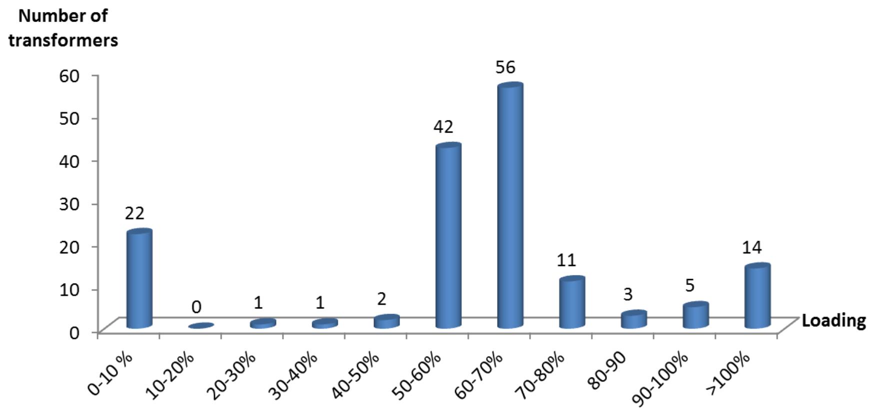

Figure C.10: High production - low load, loading of transformers for the base case for scenario 2

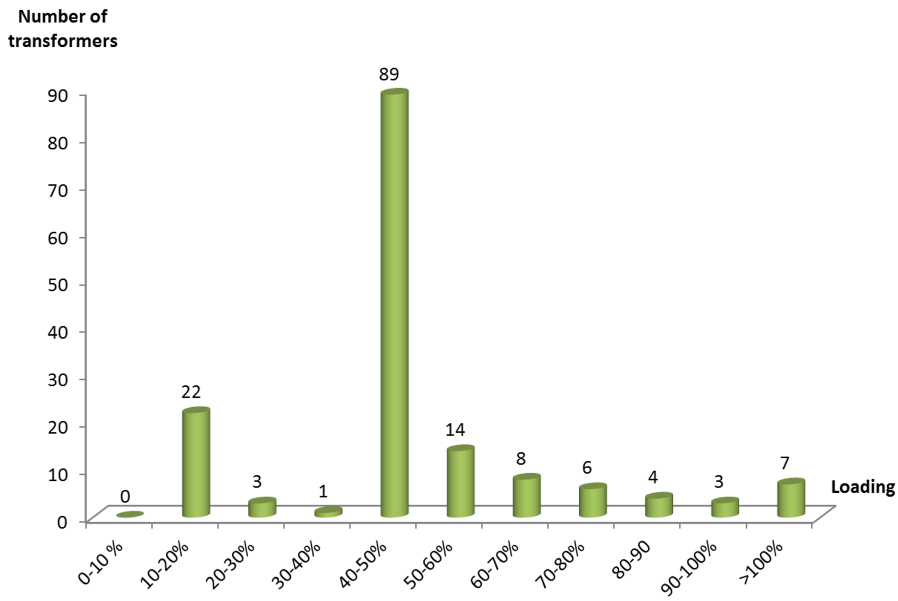

Figure C.11: High production - low load, loading of transformers with implementation of load shifting for scenario 2

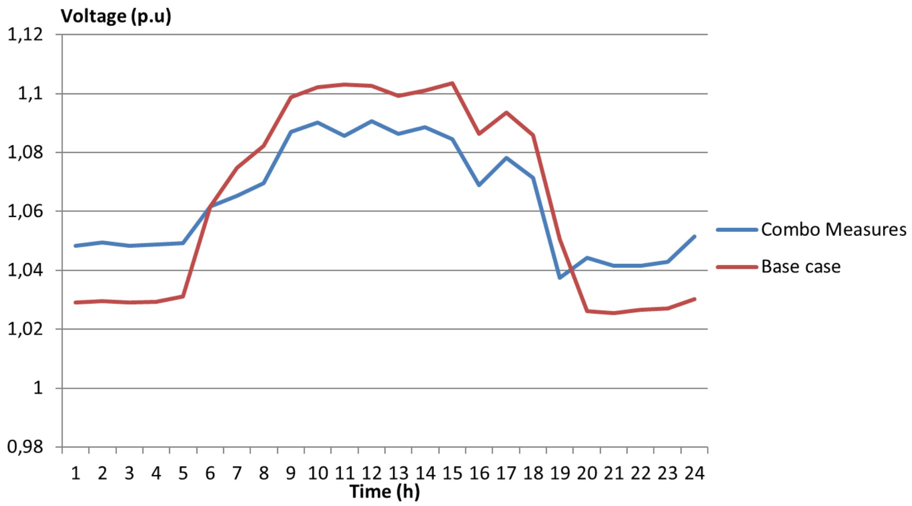

Figure C.12: Highest voltage in the grid in a summer day

Results	
Delivery to transmission grid (MW)	0.1
Load T1	26.30%
Load T2	4.50%
Highest voltage	1.080579
Lowest voltage	0.9930453
Voltage MV-HV	1.04
Voltage HV	1
Grid losses	1.8%

Figure C.13: Results for low production - low load, scenario 1

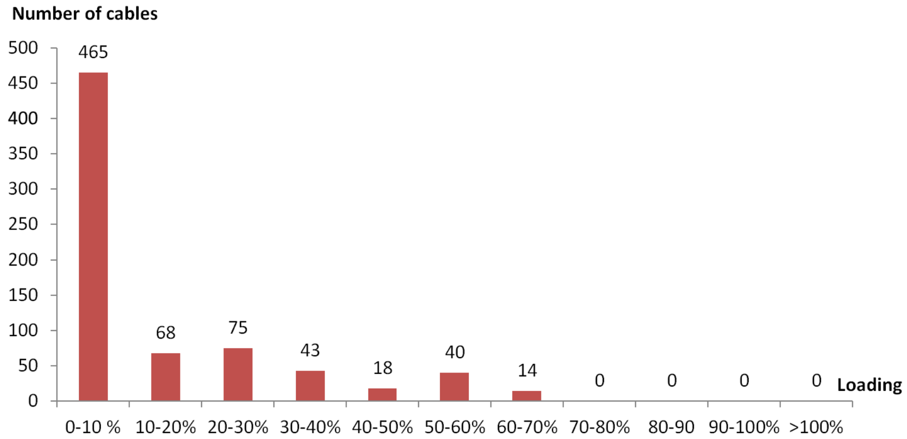

Figure C.14: Low production - high load, loading of cables with batteries implemented for scenario 1

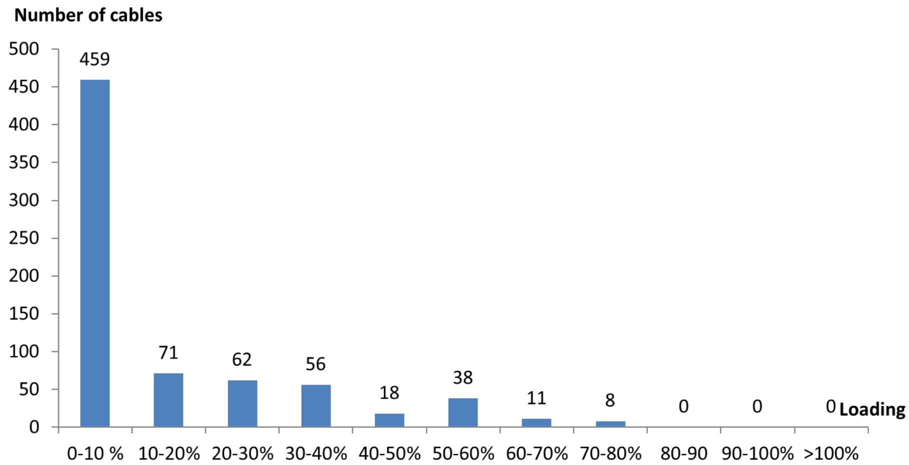

Figure C.15: Low production - high load, loading of cables for the base case for scenario 1

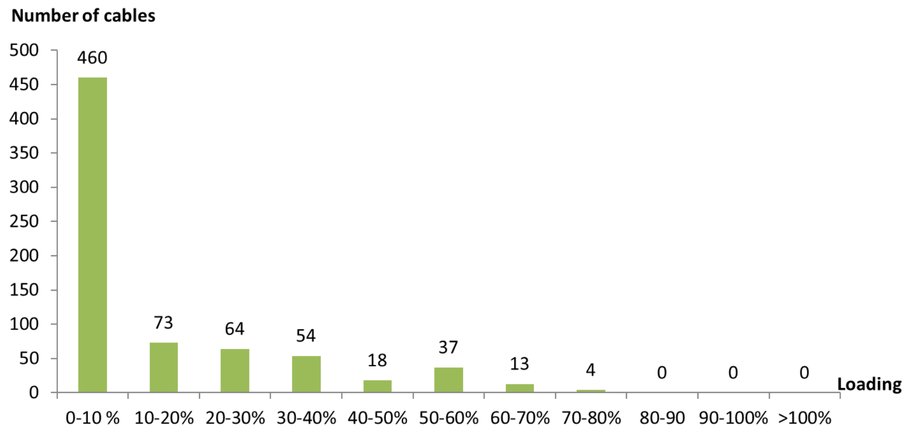

Figure C.16: Low production - high load, loading of cables with biomass power plant 1 implemented for scenario 1

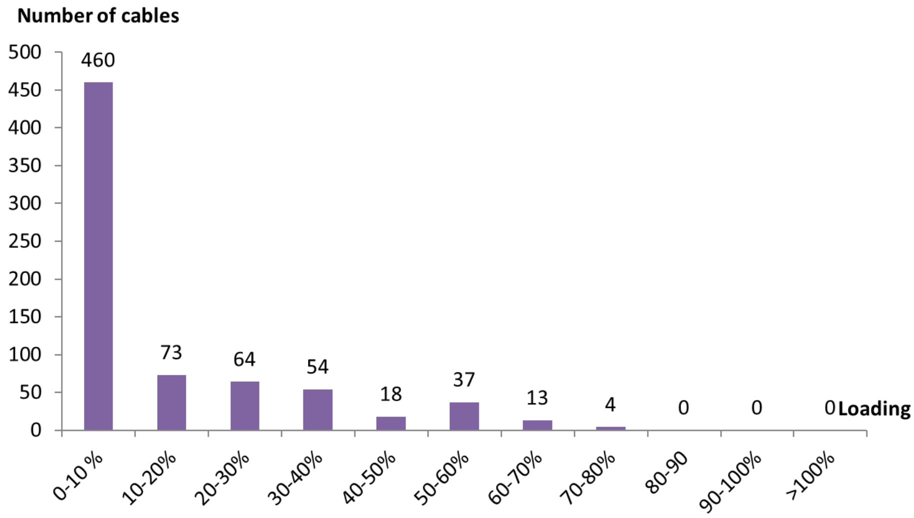

Figure C.17: Low production - high load, loading of cables with biomass power plant 2 implemented for scenario 1

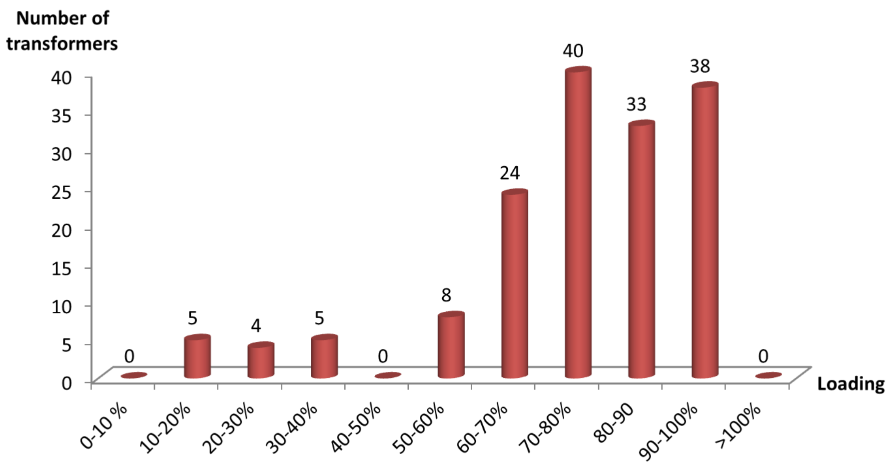

Figure C.18: Low production - high load, loading of transformers with batteries implemented for scenario 1

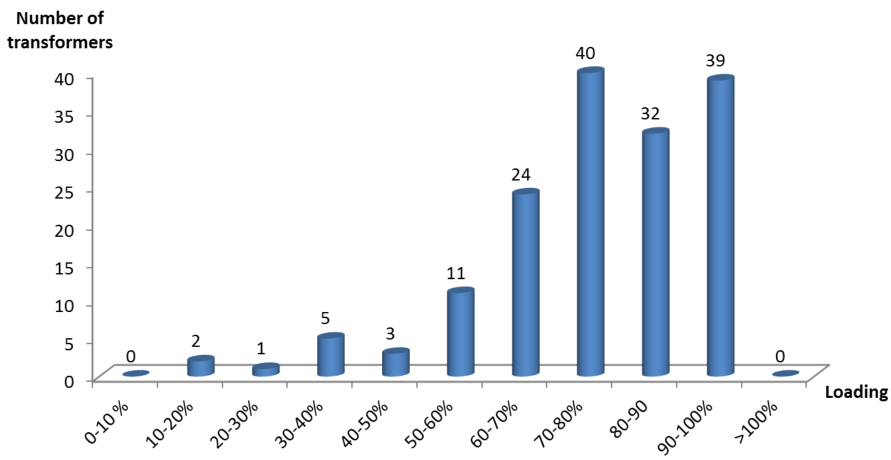

Figure C.19: Low production - high load, loading of transformers for the base case for scenario 1

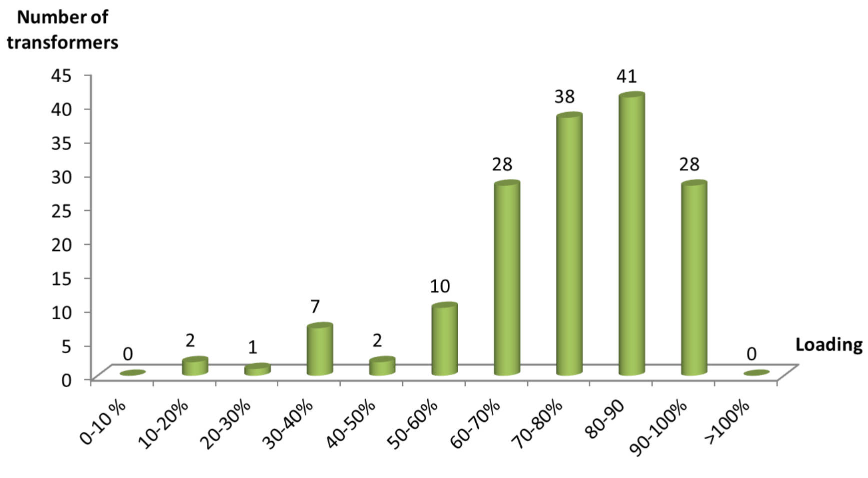

Figure C.20: Low production - high load, loading of transformers with biomass power plant 1 implemented for scenario 1

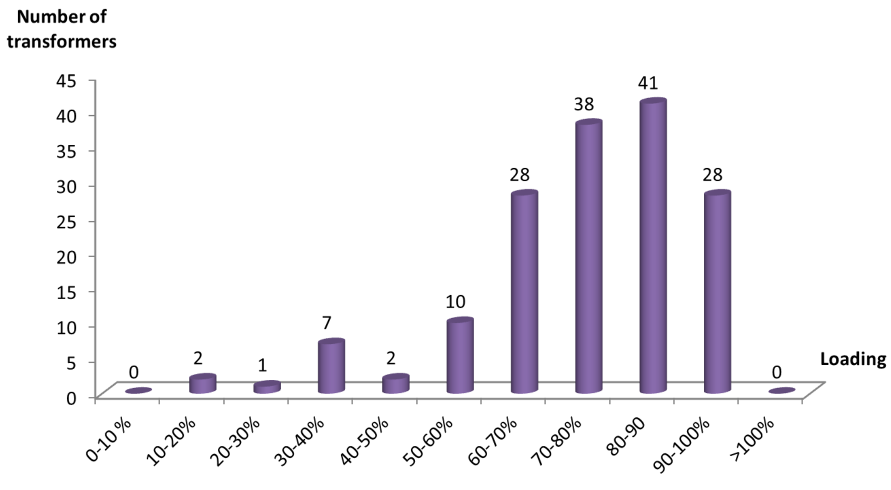

Figure C.21: Low production - high load, loading of transformers with biomass power plant 2 implemented for scenario 1

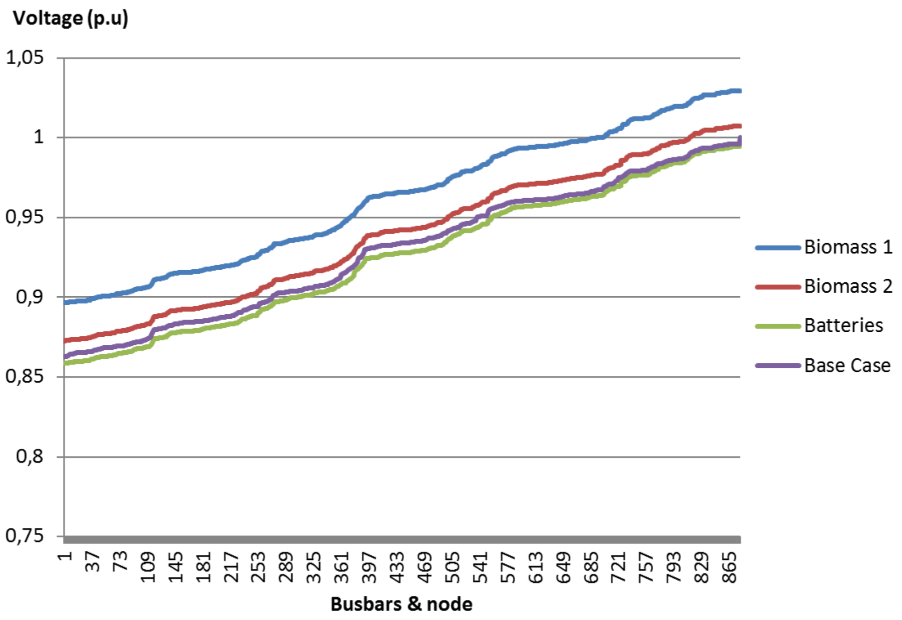

Figure C.22: Low production - high load, voltage in the grid for scenario 1

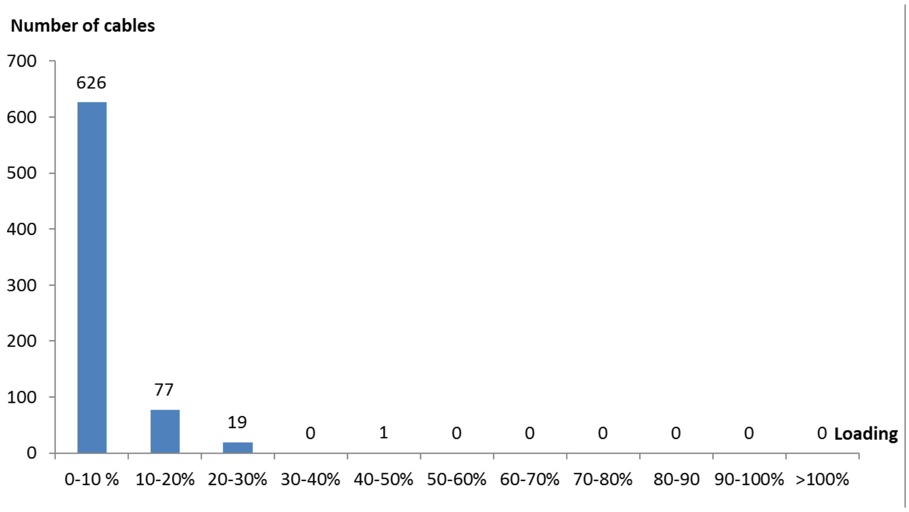

Figure C.23: Low production - low load, loading of cables for the base case for scenario 1

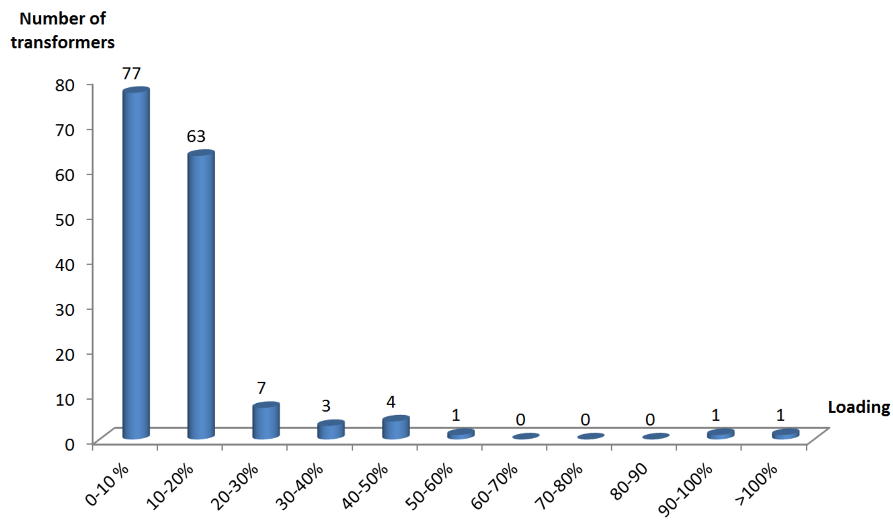

Figure C.24: Low production - low load, loading of transformers for the base case for scenario 1

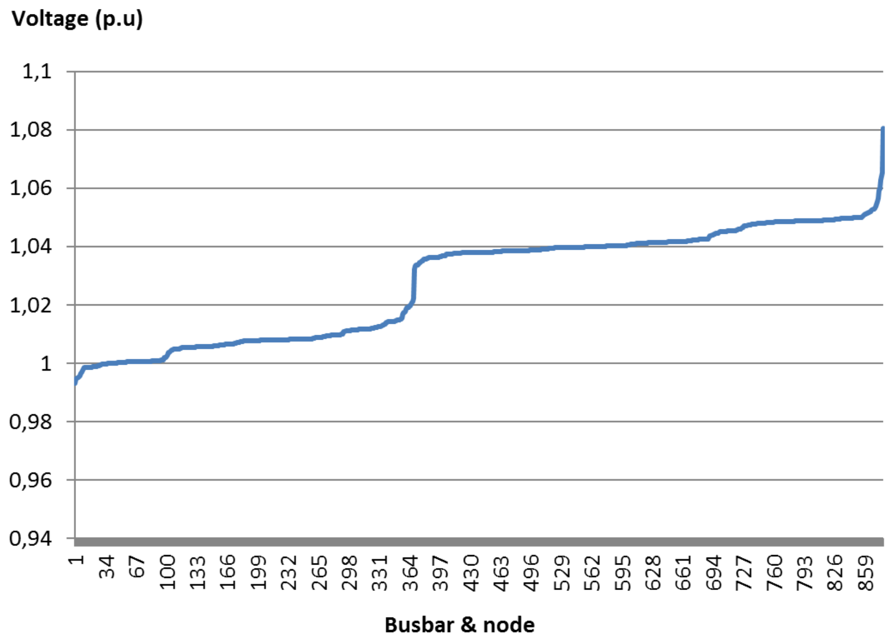

Figure C.25: Low production - low load, voltage in the grid for scenario 1

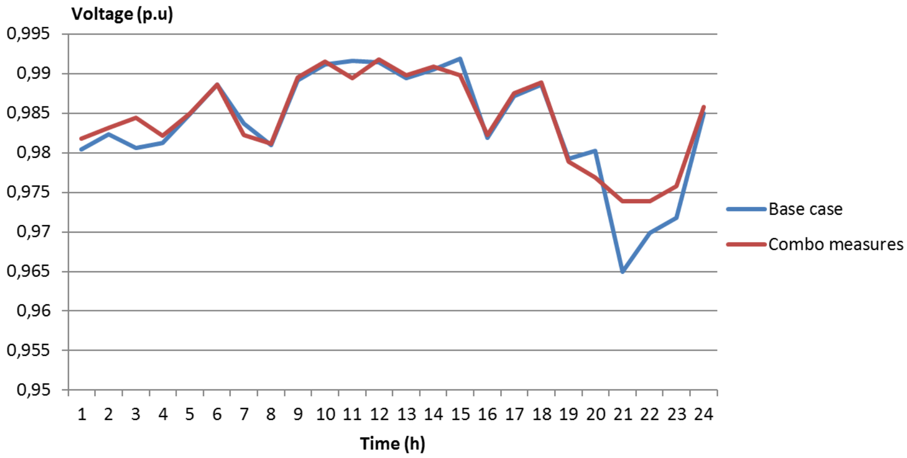

Figure C.26: Lowest voltages in the grid for a summer day scenario 1

	0	1	2	3	4	5	6	7	8	9	10	11	12
BatteryStorage1	0.11	0.11	0.11	0.11	0.09	0	-0.06	-0.1	-0.12	-0.12	-0.12	-0.12	-0.12
BatteryStorage10	0	0	0.06	0	0	0	0	0	0	-0.03	-0.03	-0.03	-0.03
BatteryStorage11	0.02	0	0.1	0	0	0	0	0	0	-0.01	-0.01	-0.01	-0.01
BatteryStorage12	0	0	0.05	0	0	0	0	0	0	-0.01	-0.01	-0.01	-0.01
BatteryStorage13	0	0	0	0	0	0	0	0	0	-0.02	-0.02	-0.02	-0.02
BatteryStorage14	0.15	0	0	0	0	0	0	0	0	0	-0.01	-0.01	-0.01
BatteryStorage15	0	0	0	0	0	0	0	0	0	-0.3	-0.4	-0.4	-0.4
BatteryStorage2	0.125	0.125	0.125	0.125	0	0.04	-0.03	-0.07	-0.1	-0.11	-0.11	-0.11	-0.11
BatteryStorage3	0.3	0.3	0.3	0.3	0	0	-0.08	-0.18	-0.25	-0.25	-0.26	-0.26	-0.26
BatteryStorage4	0.12	0.12	0.12	0.12	0	0	0	-0.04	-0.08	-0.09	-0.09	-0.09	-0.09
BatteryStorage5	0.12	0.12	0.12	0.12	0	0	0	-0.05	-0.08	-0.09	-0.09	-0.09	-0.09
BatteryStorage6	0.07	0.07	0.07	0.07	0	0	0	-0.02	-0.05	-0.05	-0.05	-0.05	-0.05
BatteryStorage7	0.05	0	0.05	0.05	0	0	0	0	-0.03	-0.03	-0.03	-0.03	-0.03
BatteryStorage8	0.07	0	0	0.07	0	0	0	0	-0.03	-0.03	-0.03	-0.03	-0.03
BatteryStorage9	0.03	0	0	0.03	0	0	0	0	-0.01	-0.01	-0.02	-0.02	-0.02

Figure C.27: Battery operation for a winter day scenario 1, part 1. Positive values is when the batteries are charging and negative are when they discharge, in MW

13	14	15	16	17	18	19	20	21	22	23
-0.13	-0.13	-0.13	-0.13	-0.13	-0.13	0.09	0.11	0.11	0.11	0.11
-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	0.06	0.06	0.06	0.06	0
-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	0.02	0.02	0.02	0.02	0
-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	0.05	0.05	0.05	0.05	0
-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	0.07	0.07	0.07	0.07	0
-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	0.15	0.15	0.15	0.15	0
-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	1.1	1.1	1.1	1.1	0
-0.12	-0.12	-0.12	-0.12	-0.12	-0.12	0.125	0.125	0.125	0.125	0.125
-0.27	-0.27	-0.27	-0.27	-0.27	-0.27	0.3	0.3	0.3	0.3	0.3
-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	0.12	0.12	0.12	0.12	0.12
-0.11	-0.11	-0.11	-0.11	-0.11	-0.11	0.12	0.12	0.12	0.12	0.12
-0.07	-0.07	-0.07	-0.07	-0.07	-0.07	0.07	0.07	0.07	0.07	0.07
-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	0.05	0.05	0.05	0.05	0
-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	0.07	0.07	0.07	0.07	0
-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	0.03	0.03	0.03	0.03	0

Figure C.28: Battery operation for a winter day scenario 1, part 2. Positive values are when the batteries are discharging and negative are when they are charging, in MW

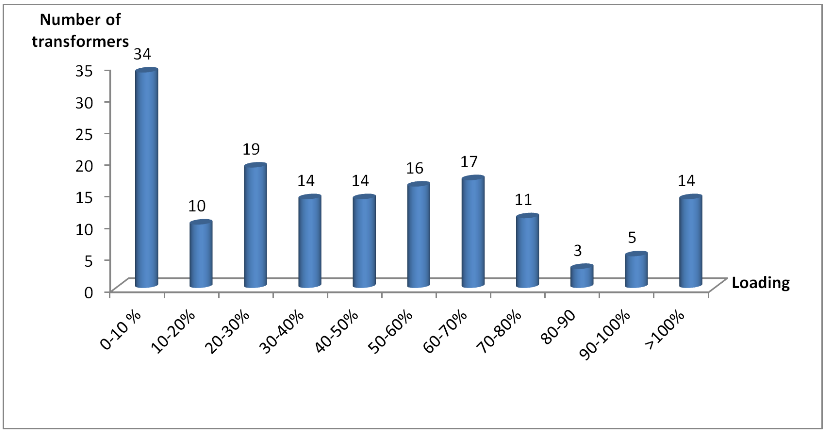

Figure C.29: The loading of the transformers for the base case profile 1.

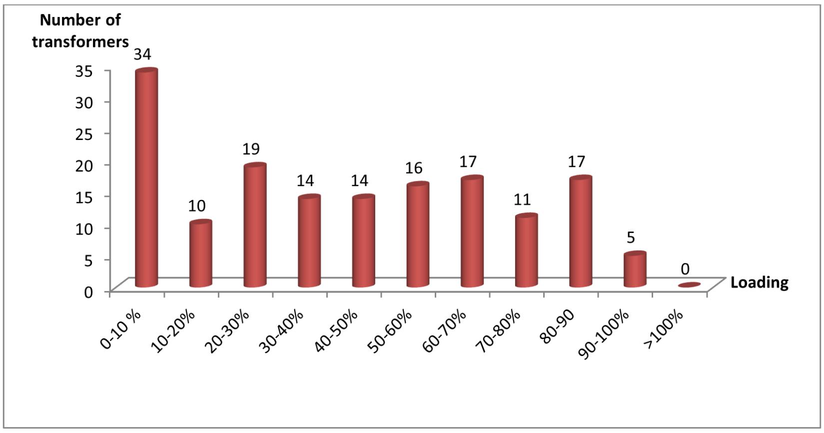

Figure C.30: The loading of the transformers for the implementation of batteries profile 1.

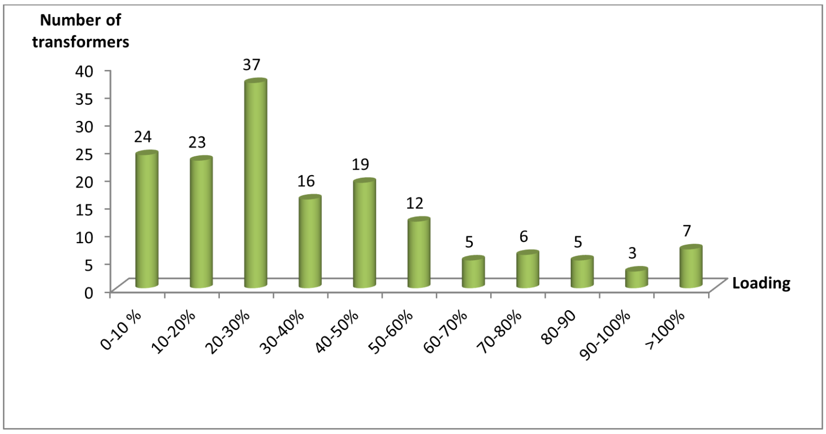

Figure C.31: The loading of the transformers for the implementation of load shifting profile 1.

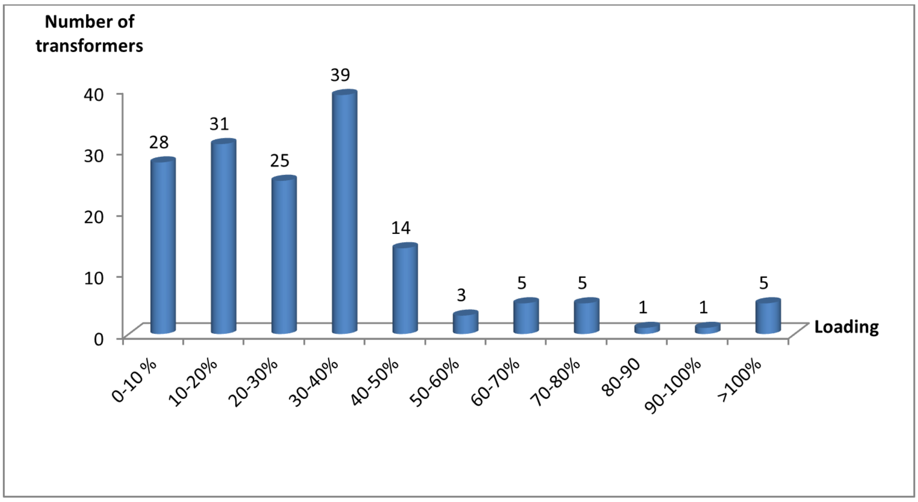

Figure C.32: The loading of the transformers for the base case profile 2.

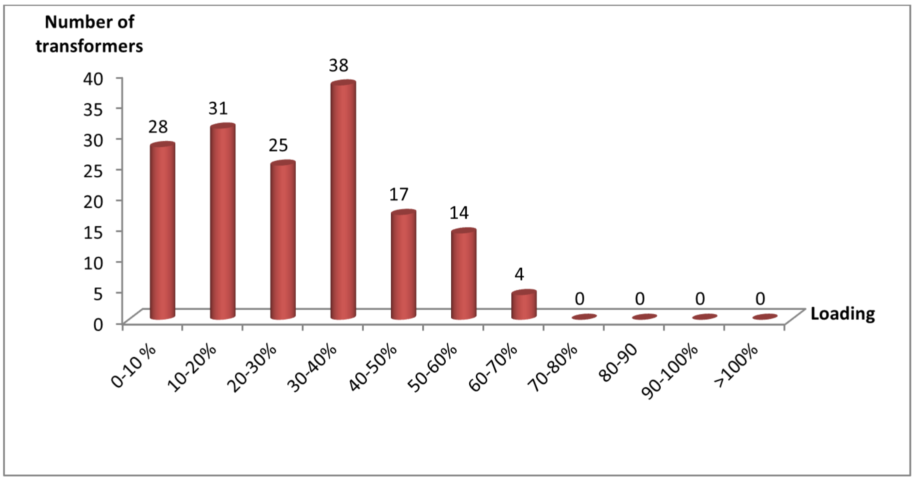

Figure C.33: The loading of the transformers for the implementation of batteries profile 2

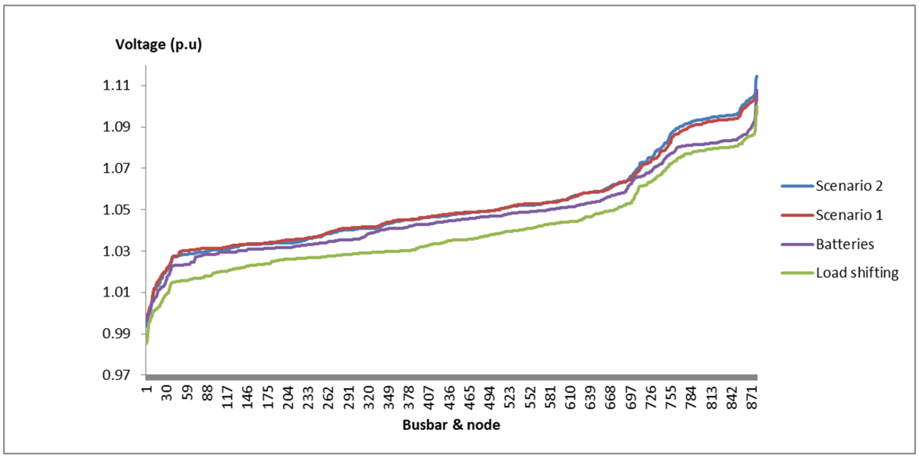

Figure C.34: The voltage over the busbars and nodes

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