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Impact of charging of electrical vehicles on the Norwegian distribution grid and possibilities for demand response

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"We are at the very beginning of time for the human race. It is not unreasonable that we grapple with problems. But there are tens of thousands of years in the future. Our responsibility is to do what we can, learn what we can, improve the solutions, and pass them on."

Richard Feynman

Abstract

The increasing popularity of electric vehicles (EVs) may have an impact on the distribution network as penetration through EV charging may cause transformer overload. This study analyzes the impact of various EV penetration scenarios on a rural distribution transformer in Norway. The results of the case study indicate that although the transformer has sufficient capacity in some scenarios EV charging may lead to overload. Demand response (DR) strategies are proposed to reduce harmful new peaks and minimize investments in infrastructure upgrade. Both EV stagger charge and household load control were tested in a simulation. I conclude in the case of this particular site the distribution grid has sufficient capacity for EV penetration. Further development in smart grid and demand response technologies is recommended in order to increase grid reliability and efficiency. A review on relevant literature is included to give a better understanding on the subject.

Sammendrag

Den økende populariteten av elbiler (EV) kan ha utslag på distribusjonsnettet på grunn av stor pågang til nettet ved elbil-lading. Det kan medføre at transformatorer blir overbelastet. I denne masteroppgaven blir det analysert effekten av flere elbil-lade scenarier på en landlig liggende distribusjons-transformator. Resultatene er at transformatoren har generellt nok med kapasitet men i noen lade-scenarier blir den overbelastet. Det blir foreslått demand response (DR) strategier for å unngå skadelige topper i forbruket og redusere investeringer i nettutbyggingen. Det ble testet to metoder, EV stagger charge og household load control, med hjelp av en simulasjon. Jeg konkluderer at den undersøkte transformatoren har tilstrekkelig kapasitet til EV-lading. Ytterligere fremvekst innen smart grid og demand response teknologier blir anbefalt for å øke nettstabilitet og effektivitet. En litteraturstudie ble inkludert for å fremme en dypere forståelse av oppgaveteamet.

Acknowledgements

I would like to thank my supervisors Torjus Folsland Bolkesjø and Stig Ødegaard Ottesen, for continuous support and inspiration. Furthermore I would like to thank NCE Smart Energy Markets and Fredrikstad Energi AS for the supply of data and information from the project site. I would also like to thank Marian Schubert and Marshall Shepherd for taking the time to review this thesis and put some sense into my writings.

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Abbreviations

AMI	**A**dvanced **M**etering **I**nfrastructure
AMR	**A**utomatic **M**eter **R**eading
CPP	**C**ritical **P**eak **P**ricing
DG	**D**istributed **G**eneration
DR	**D**emand **R**esponse
EV	**E**lectrical **V**ehicle
HAN	**H**ome **A**rea **N**etwork
HVAC	**H**eating **V**entilation **A**ir **C**onditioning
IBP	**I**ncentive **B**ased **P**rogram
LAN	**L**ocal **A**rea **N**etwork
LSE	**L**oad **S**erving **E**ntity
PBP	**P**rice **B**ased **P**rogram
PMU	**P**hasor **M**easurement **U**nit
RTP	**R**eal **T**ime **P**ricing
SCADA	**S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition
TOU	**T**ime **O**f **U**se
WAN	**W**ide **A**rea **N**etwork
VPP	**V**irtual **P**ower **P**lant
V2G	**V**ehicle **2**(to) **G**rid
V2H	**V**ehicle **2**(to) **H**ome

Chapter 1

Introduction

Growing environmental awareness and declining fossil fuel resources have resulted in increasing popularity of electrical vehicles (EVs). In December 2013 ca. 20,000 EVs were registered in Norway, only five months later the number of registered EVs had increased to 30,000 [12]. With the rapid increase of EVs the thought arises whether the distribution grid is able to host and support that many of them. Whereas the high voltage transmission grid was equipped with smart monitors and controlling, the distribution grid has not evolved much in the last decades. The high penetration of EVs, especially when plugged in simultaneously, might become a problem in power supply stability and quality.

Shao *et al.* [25, 26], Sundström *et al.* [33] and Putrus *et al.* [24] have studied EV penetration on the US American, Swedish and British distribution grid. All three concluded that high EV penetration and uncontrolled charging will have negative effects on the grid. They also found that demand response strategies and/or controlled charging could minimize grid impact to acceptable levels.

Due to high hydro resources Norway is one of few countries which uses electricity as its major source for space heating. Therefore, the overall electricity consumption is higher than the European and Northern American average. So far, no study has investigated how high EV penetration could affect the Norwegian distribution grid and how demand response strategies could be applied in this system.

In this thesis I investigate the impact of EVs on a local distribution grid with the help of a simulated case study. Furthermore I propose to test charge control and demand response strategies to implement EVs in the existing grid.

This thesis consists of two parts. Part one gives a theoretical introduction into the terms smart grid and demand response and reviews relevant literature. Part two is the case study where EV impact on the distribution grid and demand response are studied on real data of a Norwegian distribution grid transformer.

Chapter 2

Background

2.1 Introduction

With an increasing amount of intermittent energy generation and an ongoing and increasing electrification of human life, the conventional grid structure is going to face major challenges. The quality of frequency in Norway significantly decreased within the last two decades (see figure 2.1).

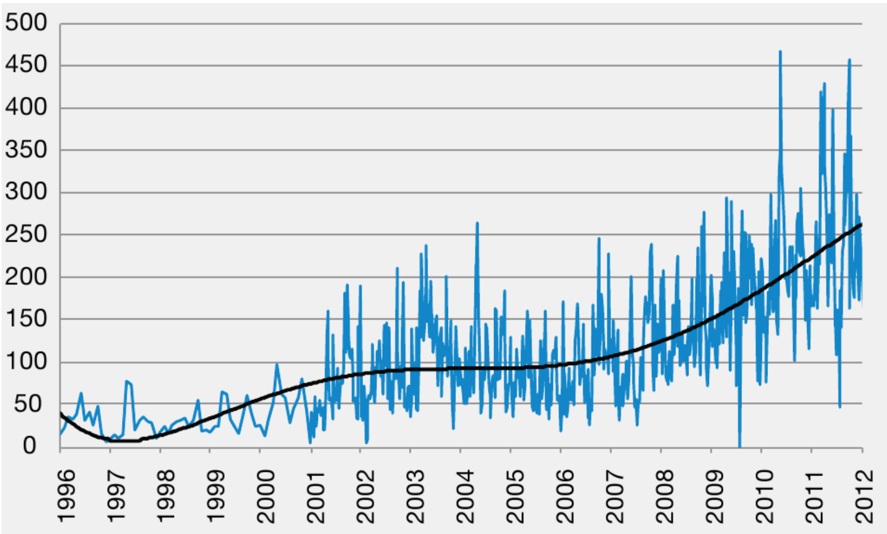

FIGURE 2.1: Development of frequency deviation in Norway from 1996-2011 [32]. (Specified in minutes outside 49,90-50,10)

Major upgrades in grid hardware are necessary to keep up with the ongoing electrification but are not sufficient. With more instability on both producer and consumer side, more flexibility within the system is essential to meet the challenges. To achieve this, a smarter grid with more opportunities for monitoring and controlling seems to be one of the best solutions. By adapting demand and supply to the particular power market situation, costs for upgrading grid hardware could be minimized. This Section's purpose is to give an introduction on smart grid technologies and demand response strategies and to inform about the role of EVs.

2.2 Smart Grid Technologies

2.2.1 What is Smart Grid?

The term "Smart Grid" can be defined as grids being more intelligent through monitoring, communication and controlling to enhance reliability, capacity and customer service and to minimize environmental impact [6]. Figure 2.2 shows how a smart grid could look like.

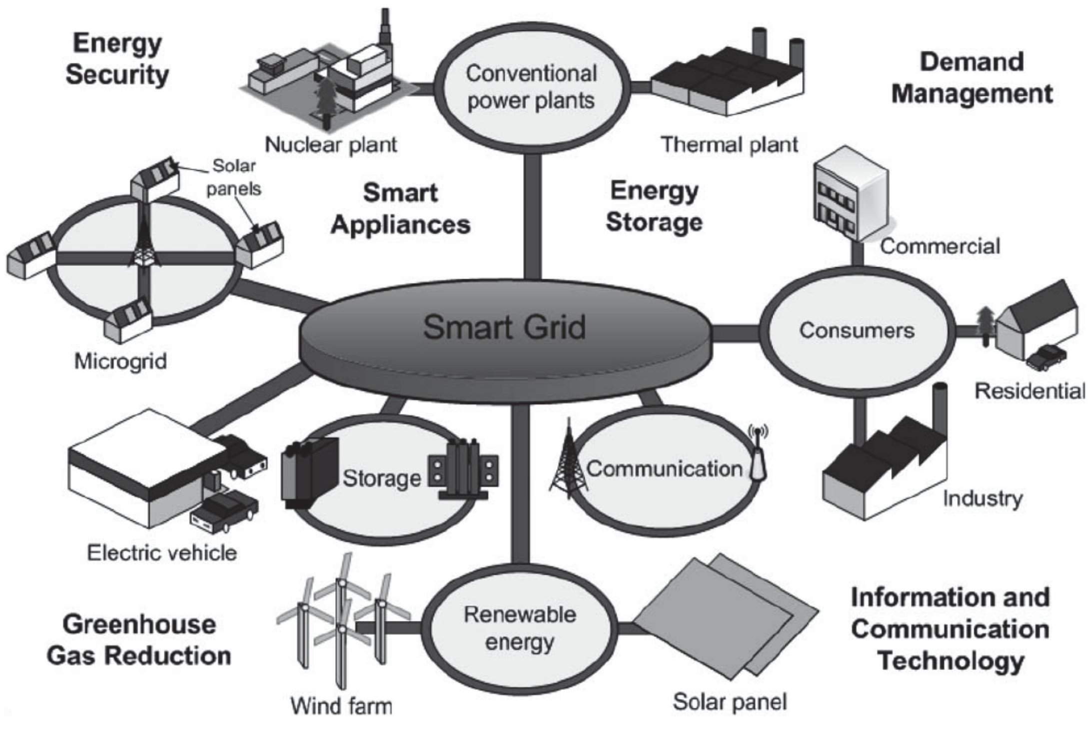

Figure 2.2: Vision of a future electric smart grid [27]

By enabling the integration of more diverse and clean power generation resources as well as increasing efficiency of power generation and distribution, smart grids will help to reduce the impact on climate and environment. Furthermore through monitoring and two-way communication customers and producers can adapt their supply and demand.

In a smart grid the integration of distributed electricity generation, like small wind turbines or photovoltaic cells, is easier to accomplish than within a conventional grid.

2.2.2 What are the benefits of Smart Grids?

The advantages of a smart grid compared to the existing grid are illustrated in table 2.1.

Table 2.1: Advantages of the Smart Grid compared to the existing grid [9]

Existing Grid	Smart Grid
Electromechanical	Digital
One-Way Communication	Two-Way Communication
Centralized Generation	Distributed Generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-Healing
Failures and Blackouts	Adaptive and Islanding
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices

The existing grid is organized in a hierarchical system with centralized power plants on the top supplying consumers on the bottom through distribution stations [13]. This system is based on one-way communication (top to bottom) and has no real-time information of the demand. As a result the system is over-equipped to enable sufficient supply at demand peaks [9]. With continuing growth of electricity demand the system has to be upgraded in excess of the average demand in order to withstand maximum anticipated peak demands. However, this is highly inefficient. Over the last few years some efforts have been made to improve the system with more controllability e.g. supervisory control and data acquisition (SCADA). This software is able to collect data from remote facilities and sends limited control instructions to those facilities [5]. It is mostly used on transmission grid level and helps detect errors or abnormalities in the usual flow. However, most outages and failures occur on the distribution level and grid operators often depend on customers to be informed of the failure. To adapt to the present needs and future challenges the grid has to be modernized. Li *et al.* [17] described the benefits of smart grids as follows:

- **Digitalization** The backbone of the future smart grid will be the digitalization of the entire grid. That means employing a digital platform for fast and reliable sensing, measurement, communication, control, protection, visualization and maintenance. The platform aims to be user-friendly and has a high tolerance for man-made errors.

- **Flexibility** The flexibility of the smart grid makes it easy to integrate diverse generation technologies and adapt production and demand in real-time.

- **Intelligence** Intelligent technologies pared with human expertise will lead to self-awareness of the system operation state and self-healing.

- **Resilience** Online computation and analysis will enable a fast and flexible network operation and control. This will enable a secure and reliable delivery of electricity in any case of external or internal disturbance or hazards. Self-healing will enable the system to reconfigure itself dynamically and recover quickly from any error.

- **Sustainability** The future grid will be sustainable through implementing environmental friendly energy production and enhanced energy efficiency through innovative technology in energy delivery and system operation.

- **Customization** The future smart grid will be user-friendly leaving customers with multiple energy consumption options for a high quality/price ratio.

2.2.3 Smart Grid Components and Devices

Farhangi *et al.*, 2010 proposes several layers of the smart grid: the HAN (home area network), LAN (local area network) and WAN (wide area network). HAN operates within the customer's premises and enables communication between sensors, smart appliances and communicating loads. LAN connects the customer's premises with distribution substations and WAN connects upstream utility assets such as power plants, substations and distributed storage (see figure 2.3).

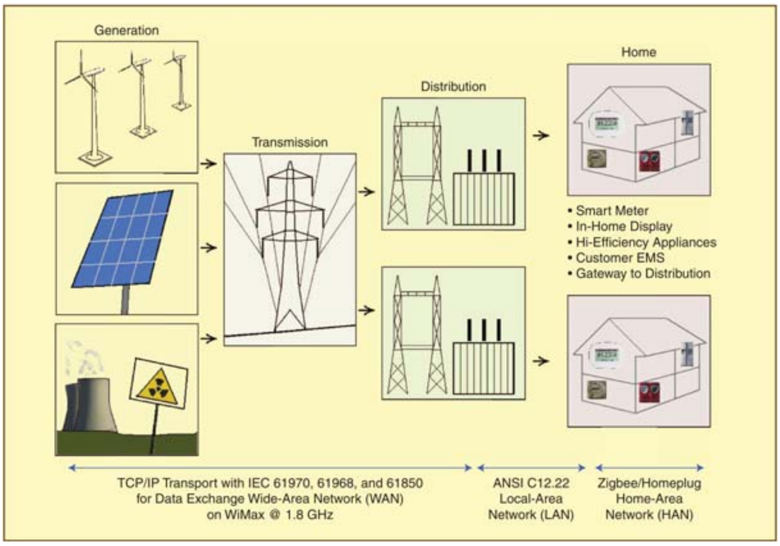

FIGURE 2.3: Network structure of the future grid proposed by Farhangi *et al.*, 2010.

The interface between WAN and LAN are substation gateways and between LAN and HAN smart meters.

Within the HAN environment optimization will occur for one household and is therefore easily managed. The most feasible optimization objects are demand shifting and peak shaving (see Chapter 2.3). Even energy storage or generation can be managed and adapted to either local or global needs. The management on household scope is easy to realize, no communication to others is necessary (high level of privacy) and no external entity decides which appliances are switched on or off (higher social acceptance) [21]. Even island houses, which are physically isolated from the grid, are possible if energy generation like e.g. photovoltaic cells are installed. Figure 2.4 shows an example of a home area network with internal power supply and the two-way communication with the superior grid.

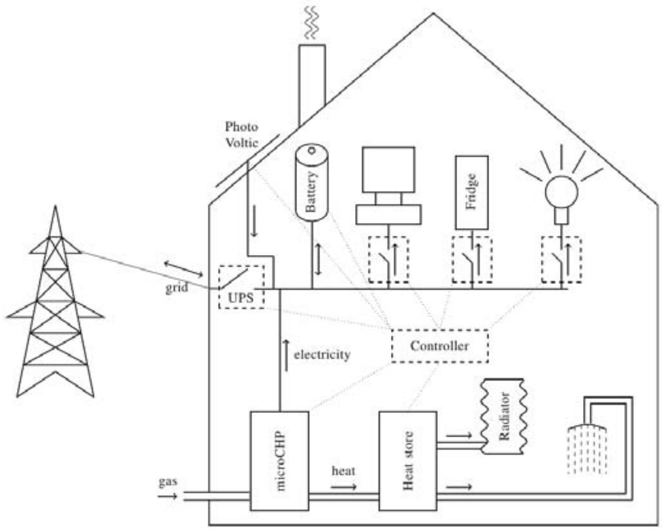

Figure 2.4: Example of a home are network proposed by Molderink *et al.*,2010.

Within the LAN environment a group of houses and/or larger scale distributed generation (DG) optimize their import to and export from the grid. This is also called microgrid. The objectives can also be load shifting and peak clipping. Due to a higher number of participants the potential of a microgird is higher than that of single households. The overall load profile is less dynamic and startup peaks of appliances disappear in the combined load. However, a more complex optimization methodology is required [21].

Within the WAN environment large groups of micro-generation and/or power plants are organized and controlled. The aggregation of multiple micro-generation units run by a central control entity is also called Virtual Power Plant (VPP)[8]. A VPP is more efficient and flexible than a conventional power plant. However to run a VPP efficiently a complex optimization methodology is necessary as well as communication with single participants which may evoke privacy and acceptance issues [21]. To make all this possible, independent agents with robust operating systems at each intersection within the network are necessary. These agents monitor and control their own subsection (e.g. microgrid) and must be able to communicate with other agents or other devices within the network resulting in a large computing platform [18].

Technical devices capable of monitoring and communicating are mandatory in smart grid networks[3]. On the transmission and distribution level the phasor measurement unit (PMU) is used to measure electrical waves to determine the stability of the grid. The measurement is sent to a control unit by global positioning system (GPS) in real-time and from disperse geographical areas [8]. The voltage and current is measured on intersections such as substations several times per second. By comparing the alternating current, system operators can control the state of the grid at all times and react quickly

in the event of a failure[8].
On the household level smart meters are an important tool within the smart grid. The first introduced automatic meter reading (AMR) provided the operator with diagnostic, consumption and status data. This makes it easier for the operator to detect and solve failures on the distribution level. Due to the accurate and more frequent reading of the consumption, electricity bills are more accurate and comply more with the actual power price. AMI is the follow-up of AMR differing in being able to two-way communication. This opportunity opens up a lot more possibilities where end-users can be integrated in power and demand management[8].

2.2.4 Challenges with Smart Grid Solutions

The infrastructure of smart grids does not just open up for a lot of possibilities but also for a number of vulnerabilities and security concerns. I will distinguish between risks which can occur due to the infrastructure of the smart grid without malicious ulterior motives and distinctive cyberattacks with the motive to harm the system and it's participants.

Infrastructure problems. Smart grids will be designed in a way that all participants are able to communicate with each other. In the conventional grid producers and grid operators have the control over the network and just have to communicate with each other. They often have distinctive medias and communication protocols which are not accessible to anyone else but them. With the smart grid network control will be decentralized (to DG and households) and the communication media will be easy accessible (e.g. Internet, phone lines)[15]. This requires that all participants are able to interact in a proper way and also will do so. It is only logical that controlling and communication infrastructure will increase heavily compared to today's system. For example SCADA, which is used as a controlling and monitoring tool today, collects one data point every 1 to 2 seconds whereas the new PMUs (see chapter 2.2.3) collects 30 to 60 data points per second. This makes the system more reliable but also more complex to process. The amount of data that has to be processed will increase severely [15]. It needs more labor, better technical equipment and new methods to handle that amount of data. Especially in cases of failure the system has to be able to reboot and heal itself which gets more complicated with more participants and increasing amount of data. Khurana *et al.* 2010, concludes this issue with "the system will need a defense supervisory system which can process high amounts of data to evaluate system status, identify failures, predict threats and suggests remediation.

Cyberattacks. Another challenge, some say one of the biggest [4, 20], are malicious cyberattacks. The threats are various and more or less precarious to society. Less dangerous to society but not less problematic might be the manipulation of smart meters on household level to imitate a power demand in favor of a reduced electricity bill. Smart meters could also be hacked to obtain information of the house owners habits. Examples might be detecting when the owners are on holidays, at work or simply asleep to plan criminal activities [15]. Micrograds could be hacked causing local blackouts or instability within the microgrid. On a more global level larger areas or bigger power plants could be hacked resulting in disturbances and blackouts throughout large areas or energy market chaos which might evolve to national security threats[20]. However since the smart grid will consist of multiple independent agents it may get harder to penetrate wide-area or global systems.
The research on smart grid is evolving fast and the implementation into the existing grid has already started. For some of the mentioned challenges solutions have already been found. Yet, solutions for other challenges still have to be found before the smart grid takes over the conventional grid to ensure a safe future.

2.3 Demand Response

2.3.1 Definition and Importance

The re-modeling of the existing grid towards a smarter one opens possibilities for end-users in adapting their demand in order to stabilize the grid and minimize costs. This chapter explains demand response and presents several management options with focus on the benefits for operators and end-users. According to the U.S. Department of Energy (DEO) demand response is defined as:
"Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [10].
Most customers in today's power market are not exposed to actual power prices and therefore have no incentive to react to the power market situation. An electricity tariff with an hourly power price might already help to encourage customers to think about the timing of their electricity consumption. But since most of the customers are not used to responding at critical times this might not be enough. To create consciousness it may help to introduce incentives when reducing load at critical times. It is also possible to introduce penalty fees for not reducing load at critical times or both. Demand response

can comprehend both decrease and increase of electrical usage depending on market situations.

2.3.2 DR benefits and costs

DR benefits Demand Response benefits can be distinguished in *direct, collateral* and *other* benefits (see table 2.2 from the DEO). Direct benefits regard all participants who perform demand response, collateral and other benefits regard all participants of the electricity system. It is the collateral benefits which have system-wide impacts that motivate policy makers to encourage demand response.

DR costs Costs of demand response can be divided into participant and system cost and within those two groups into initial and ongoing costs. The U.S. Department of Energy published an decent overview explaining the costs in the mentioned groups, which can be seen in table 2.3 [34].

Table 2.2: Benefits of Demand Response [34]

<table>
<tr><th>Type of Benefit</th><th>Recipient(s)</th><th>Benefit</th><th>Description/Source</th></tr>
<tr><td rowspan="2">Direct Benefits</td><td rowspan="2">Customers undertaking demand response actions</td><td>Financial Benefits</td><td>Bill savings
Incentive Payments (IBP)</td></tr>
<tr><td>Reliability benefits</td><td>Reduced exposure to forced outages;
Opportunity to assist in reducing risk of system outages</td></tr>
<tr><td rowspan="3">Collateral Benefits</td><td rowspan="3">Some or all consumers</td><td>Market impacts (short-term)</td><td>Cost-effectively reduced marginal costs/prices during events;
Cascading impacts on short-term capacity requirements and load serving entities (LSEs)contract prices</td></tr>
<tr><td>Market impacts (long-term)</td><td>Avoided (or deferred) capacity costs;
Avoided (or deferred) grid infrastructure upgrades;
Reduced need for market interventions (e.g. price caps) through restrained market power</td></tr>
<tr><td>Reliability benefits</td><td>Reduced likelihood and consequences of forced outages;
Diversified resources available to maintain system reliability</td></tr>
<tr><td rowspan="5">Other Benefits</td><td rowspan="5">Some or all consumers,
LSE,
Grid Operator</td><td>More robust retail markets</td><td>Market-based options provide opportunities for innovation in competitive retail markets</td></tr>
<tr><td>Improved choice</td><td>Customers and LSE can choose desired degree of hedging;
Options for customers to manage their electricity costs, even where retail competition is prohibited</td></tr>
<tr><td>Market performance benefits</td><td>Elastic demand reduces capacity for market power;
Prospective demand response deters market power</td></tr>
<tr><td>Possible environmental benefits</td><td>Reduced emissions in system with high-polluting peak plants</td></tr>
<tr><td>Energy independence/security</td><td>Local resources within states or regions reduce dependence in outside supply</td></tr>
</table>

Table 2.3: Costs of Demand Response [34]

Type of Costs		Cost	Responsibility/Recovery Mechanism[1]
Participant Costs	Initial costs	Enabling Technology Investment	Customer pays; incentives may be available from public benefit or utility DR programs to offset portion of costs
		Establishing response plan or strategy	Customer pays; technical assistance may be available from public benefits or utility demand response programs
	Event-specific costs	Comfort/inconvenience costs	Customer bears "opportunity costs" of foregone electricity use
		Reduced amenity/lost business	
		Rescheduling costs (e.g. overtime pay)	
		Onsite generator fuel and maintenance	
System Costs	Initial costs	Metering/communication system upgrades	Level of costs and cost responsibility vary according to the scope of the upgrade (e.g., large customers vs. mass market), the utility business case for advanced metering system or upgrades, and state legislation/policies
		Utility equipment or software costs, billing system upgrades	Utility typically passes cost through to customers in rates
		Customer education	Ratepayers, public benefits funds
	Ongoing program costs	Program administration/management	Costs are incurred by the administering utility, transmission/distribution operator and are recovered from ratepayers
		Marketing/recruitment	
		Payments to participating customers	
		Program evaluation	
		Metering/communication	

1

[1]Information in this column is subjective and specified by the U.S. Department of Energy. Some information may apply for other countries as well whereas some of the costs or methods of recovery may be different handled in various countries.

2.3.3 DR Program classification

"Demand Response includes all intentional electricity consumption pattern modifications by end-use customers that are intended to alter the timing, level of instantaneous demand, or total electricity consumption" [2, 14]. DR programs can be classified in two groups: *incentive-based demand response (IBP)* and *price-based demand response (PBP)*. The U.S. Department of Energy recommends to introduce DR with incentive-based programs. When the end-users are used to DR, the Department recommends to transfer the program to price-based DR [34]. There are several tariff and program option within these two classes. The most commonly implemented ones are described below.

Incentive-based DR programs. The IBP are divided into two classes, classical and market-based programs. The classical programs include direct control and interruptible/curtailable programs and the market-based programs include demand bidding, emergency DR programs, capacity market and ancillary services market. In the classical programs end-users are rewarded for participating in DR by a bill credit or discount rates. In market-based programs end-users are rewarded with money depending on the amount of load reduction during DR events [2].

- *Direct Control.* This program is mainly offered to residential or small business customers. The operator has the opportunity to shut down electrical devices such as space heating/cooling or water heating of customers on a short notice.
- *Interruptible/Curtailable Programs.* This program is usually offered to large industry or commercial customers. In the case of system contingencies customers in this program are asked to reduced demand to a predefined value and receive payment for this. If customers do not respond as contracted they can face penalty charges or removal from the program.
- *Demand Bidding.* This program is also most suitable for larger customers like industry or commercial customers. Participants can bid in the wholesale market for load reduction at a price they are willing to reduce load for. If the bid goes through they must reduce load or face penalty charges. There are also cases where the operator is offering a utility-set price and the customer is defining how much load can be reduced for this price (Buyback program)[34].
- *Emergency DR.* In case of a reliability-triggered event customers are offered incentive-based payments for measured load reduction by the operator. If the customers are not reducing load they may or may not face penalty charges [34].

- *Capacity Market.* Customers in this program have agreed to a predefined load reduction in case of system contingencies. They are usually notified on a day-ahead basis and face penalties if they not respond. They get upfront reservation payments, based on capacity market price and optionally a further payment in case of the actual contingency event based on the load reduction [34].

- *Ancillary Services Market.* In this program customers have the opportunity to bid as operating reserve in the transmission operator (balancing) market. If the bid goes through they are paid the market price to be on stand-by. In the case of a DR event the system operator calls the customer to reduce load[34].

Price-based DR programs. The PBP have dynamic pricing rates in which electricity prices are not flat. The rates follow the fluctuations of real-time costs of electricity. The major idea is to flatten the demand curve by offering high prices at peak demand times and low prices at off-peak times [2].

- *Time of Use (TOU).* TOU tariffs are unit prices divided into different blocks during a 24h day. These blocks are usually OFF-peak, peak and shoulder (which is prior to and after the peak). Each block has it's own price which is the average of production and distribution costs at this time. These prices are typically pre-determined for several months and vary during the seasons. Figure 2.5 shows a 24h schedule of a TOU tariff with OFF-peak, peak and shoulder blocks.

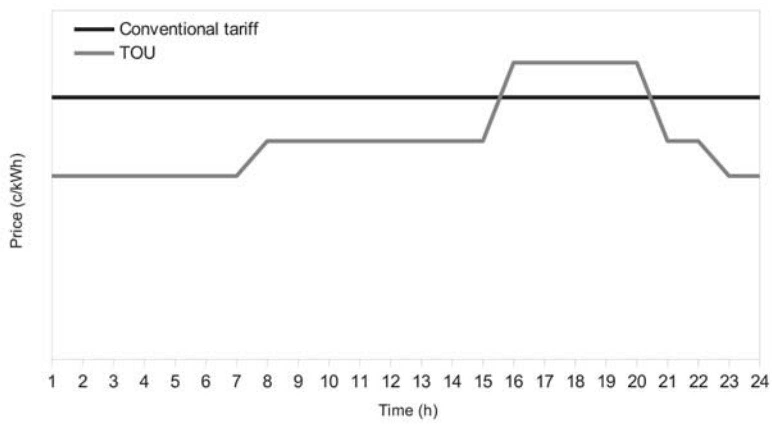

Figure 2.5: 24 hour schedule of a TOU tariff with different priced blocks: OFF-peak block (21 c/kWh), shoulder block (25 c/kWh), peak block (33 c/kWh); compared to a conventional "flat"-tariff. Modified after [7]

- *Critical Peak Pricing (CPP).* CPP is a rate which is only used during contingencies or high wholesale prices a few days or hours a year[2]. This tariff is usually superimposed on another tariff (e.g. TOU or flat) and customers are informed on a day-ahead basis.

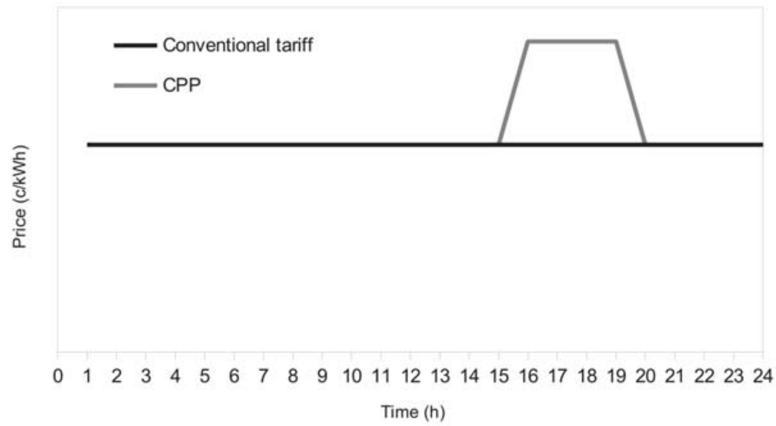

FIGURE 2.6: Schematic diagram of a CPP tariff which is superimposed on a flat-tariff.

- *Real Time Pricing (RTP)*. RTP is a rate with hourly fluctuating prices reflecting real costs of the wholesale market (see figure 2.7. Customers are informed about the prices on a day-ahead or hour-ahead basis. This is the most direct and transparent tariff and is according to [11] the most suitable for competitive electricity markets.

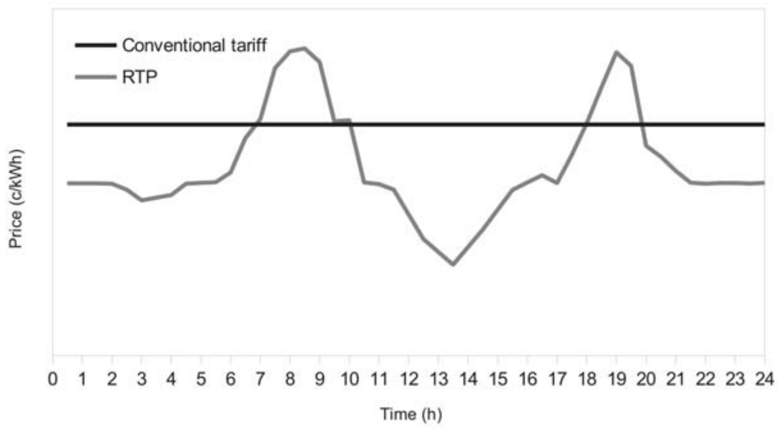

FIGURE 2.7: Schematic diagram of a RTP tariff which is based on the wholesale power price.

2.3.4 Customer response possibilities

There are several possibilities to alter demand to respond to sudden demand increase (peaks) or other stimuli (e.g. failures). The following three are discussed here: Foregoing, Shifting and On-site Generation [2, 34].

- **Foregoing.** Foregoing (also called peak-clipping) is the reduction of demand at the occurrence of high prices or other events without balancing it before or after the reduction. Examples can be the down-regulating of thermostats to reduce heating or turning off light. Office buildings or industries might turn off office equipment or reduce production. In any case, foregoing comes along with a temporary loss of amenity and comfort.

- **Shifting.** Load shifting is the shift of load away from times with high peaks or other events with balancing before or afterwards. For example in households clothes dryers or dishwashers can be delayed until the electricity price has normalized. Space heating can be turned up before peak times so that it can be turned off or regulated down in critical times. Industrial production can be rescheduled to non-critical times. The loss of amenity and comfort is minimal and made up prior to, or subsequent to, critical times.

- **On-site Generation.** Customers with this option have the possibility of generating their own electricity with the help of generators at peak times. There is no loss in amenity and comfort but only a few customers have the facilities to do that[34].

In order to make DR beneficial for all participants it is important to make DR reliable and available in times of need. Electricity is a low interest good for customers and only a few will be interested enough to adapt their own demand. It is therefore important to have an automatic demand response unit that will adapt the demand consistent with the customers prospects and needs. Attractive and easy comprehensible interfaces on home control units will make it easier for the customer to engage in DR. Shao *et al.* 2011, proposed at method which combines the customers preferences and automatic response. They imply that the customer has a HAN environment and that all non-critical loads[2] are connected to and controlled by the HAN environment. All the customer has to do, is to set a list with priority and convenience preferences (see table 2.4)[26].

Table 2.4: Example of a preset load priority and convenience level[26]

Load Type	Load Priority	Convenience Preference
EV	1	Complete in 2,5 hours
Water Heater	2	Water temp $\geq$ 38°C
HVAC	3	Room temp $\leq$ 28°C
Clothes Dryer	4	Complete in 2,5 hours

[2]Household loads can be divided in critical and non-critical load. Non-critical loads are all loads which are controllable and have no noticeable impact on customer's lifestyle (e.g. HVAC). Critical loads are all other loads which are either not controllable or have impact on the customer's lifestyles (e.g. lighting and other plug loads[26].

In table 2.4 the clothes dryer has the lowest priority with the constraint that the cycle has to be dry within 2,5 hours. In case of a DR event the clothes dryer is the first appliance to be turned off. Should the event extend beyond the 2,5 hours the clothes dryer is turned on again and the next load type is turned off (in this case HVAC) and so on. The control center monitors the household load and preferences continuously to response in a best possible way to DR events with the lowest possible impact to the end-user. In figure 2.8 Shao *et al.* 2011, presents a operation chart of a HAN control center.

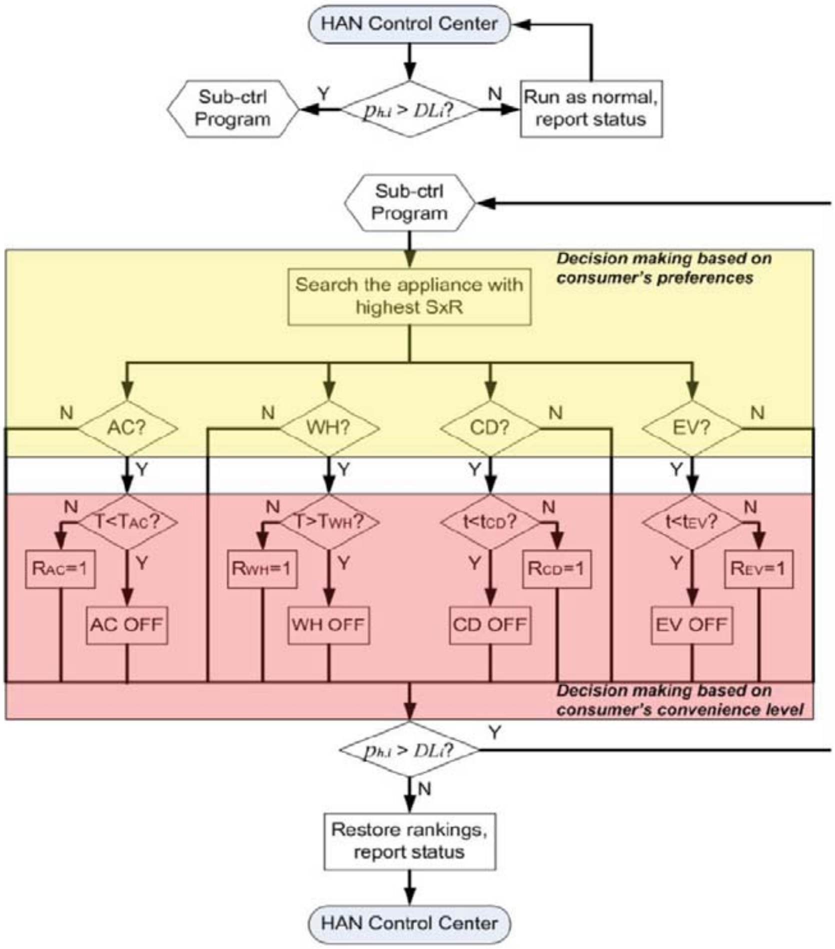

Figure 2.8: HAN control center operational chart.[26]

The HAN control center monitors the household and transformer load constantly. If the transformer load is within the transformer's capacity all household loads run normal (run as normal, report status). In case of a transformer overload the HAN control center starts the DR program (Sub-ctrl Program) which searches for the least important load to turn it off. This is done by multiplying the load priority with the status (ON=1,OFF=0) of the load. The load with the highest number is then turned off. The HAN control center checks then the status of the transformer load and restores the household rankings. This method is efficient and, according to Shao *et al.*,2011, working well. The customers do not need to invest much time in DR which has in return, low impact on their lifestyle. In addition the DR program is run on the household level and no external intrusion is necessary, which supports a high level of privacy.

2.4 The role of Electrical Vehicles

EVs can account for a high share of total electricity consumption depending on the amount of penetrating EVs and on the charging options. They can have a high impact on the grid and increase demand peaks if charged in an uncontrolled manner. The higher the penetration of charging EVs the more necessary smart grid technologies, are. Demand response actions that schedule charging to OFF-peak hours are mandatory as well. These technologies would also reduce the investments in grid modernization [22]. However with increasing battery capacity EVs are more often noticed as potential distributed storage devices. They may feed electricity stored in their batteries back into the grid in times of need (V2G, vehicle-to-grid) or into the home or office environment (V2H, vehicle-to-home). EVs as most cars are parked major parts of the day. They could be connected to the grid almost every time when they are parked for a longer period (at home or at work) and offer DR. This may be particularly useful during very brief and sudden surges in the system. Most people like to have the safety of a fully charged vehicle at all times but if charging facilities are frequent and wide spread EV owners might consider to feed power into the grid at the right price. To charge an EV one minute and feed-in the next takes advanced technologies and clear DR contracts. The potential storage capacity provided by EVs is a function of the number of connected EVs and battery capacity [22].

Chapter 3

Case Study

3.1 Method and Data

3.1.1 Hourly Load Curves with electrical vehicles (EV)

The calculation of the impact of EVs on a distribution transformer was performed with a quantitative method using numerical data. The numerical data used for the analysis were gained from the DeVid project from Vesterøy, Hvaler municipality in Norway.
The data used in this thesis include all costumers connected to the transformer 15 H Ødegaard. The transformer has a capacity of maximum 315kVA and supplies power to 25 households, 11 commercial buildings and 25 cabins. However the transformer runs most effective when not exceeding 95%, 300kW of its rating, which will serve as the maximum load in this study. The data obtained from this transformer are hourly load profiles for 2013.
The load profiles used are the basis of the following scenarios for Ev charging:

- 25 of the 25 households start charging their EV at 4 pm using normal charging
- 17 of the 25 households start charging their EV at 4 pm using normal charging and one-third (8) households using quick-charging
- All commercial buildings offer charging stations for two EVs for employees starting at 8 am using normal charging.

The charging options have the following characteristics (see table 3.1):

Table 3.1: EV charge options used in this study.

Charging Circuit	Charge Power	Charge Duration
Normal Charge (230V/16A/1 phase)	3,5 kW (3,3kW [3])	6 hours
Quick Charge (230V/32A/ 3 phase)	12 kW	1,5 - 2 hours

To calculate the impact of EVs on the transformer load the amount of EVs was multiplied by 3,3 and 12 kW respectively and added to the household and commercial buildings load respectively:

$$EVImpact = (\sum EVs * 3,3kW) + (\sum EVs * 12kW)$$

$$HouseholdLoadprofile = \sum EVImpact + \sum HouseholdLoads$$

To run the scenarios the aim was to choose the coldest and the warmest days of 2013 to investigate differences between winter and summer. The coldest weather was measured on 23rd of January in 2013 with a low temperature of minus 18°C. The warmest day was 21st of July with a high temperature of 27°C [35]. However this day was a Sunday were the customer load is in general lower than during work days. Therefore I chose the 22nd of July as the representative for the summer month. Vesterøy is located on the sea coast and hosts many cabins which are preferably used in the summer months.

3.1.2 EV Charge Control and Demand Management

To investigate possibilities of EV charge and demand control we used scenarios similar to those described in Shao et al., 2009 [25]. Two different methods of demand response were used to study effects on load reduction:

- staggering EV charging time
- performing household load control

The method of EV stagger charge requires in addition to Advanced Metering Infrastructure (AMI) also a EV control unit and remote switches. The remote switches are used to control the ON/OFF status of EV outlets and household loads [25]. The EV control

[3] Nissan Leaf is the most common EV in Norway and it charges usually 3,3kW so I used 3,3kW in the normal charge scenario

unit monitors the transformer load information based on the household loads from AMI and compares it with a pre-defined loading value, i.e. 95% (280kW) of the transformers capacity. EVs will be charged as long as the transformer load does not exceed 280 kW. If the transformer loading is greater than the pre-defined loading value, charging EVs will be delayed until the transformer loading falls below this threshold [25]. It was assumed that households using quick charge do not wait for charging so they were not staggered. For the household load control non-critical loads will be deferred or shed when EVs start charging and the transformer load exceeds the transformers maximums capacity.According to [29] households in Norway use 64% of their electricity consumption for space heating (see figure 3.1).

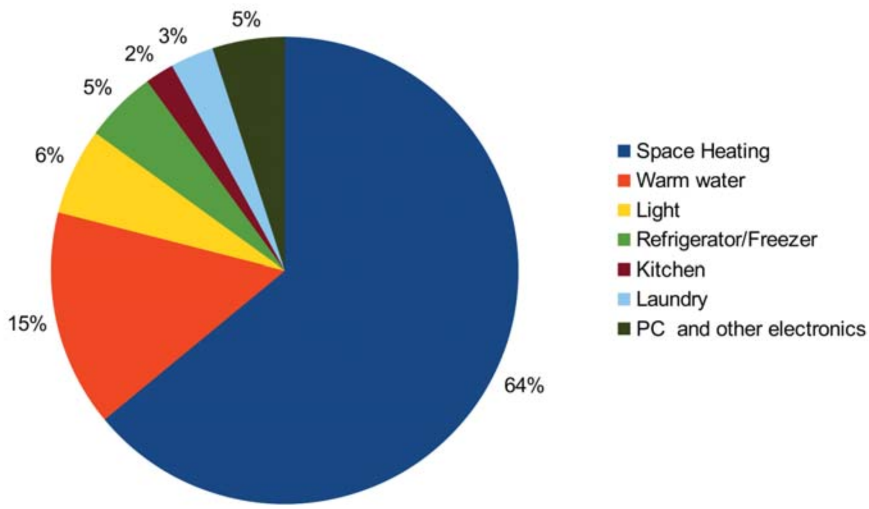

Figure 3.1: Electricity consumption of Norwegian households.[29]

In peak times and when the transformer is going to be overloaded the space heating and water heating is shed for a short time of period to enable EV loading. According to [30] the room temperature is declining very slowly and space heating can be shed for several hours without any lack of comfort 3.2. To enable shedding electrical heaters,underfloor heating systems and hot water boilers have to be manageable by a control unit that is communicating with the AMI and the transformer to monitor household and transformer load. This is the easiest way to regulate loads on the household level if a transformer overload occurs [25]. In this case the control unit will get the signal to shed non-critical load i.e. space heating and water heating. In this study we used 60% for the shedding since it was not clear if the hot water boilers were in use at this specific time period. It was assumed that the EV charging had the highest priority but it could also be used for shedding in times of need (especially when charging is not that urgent).

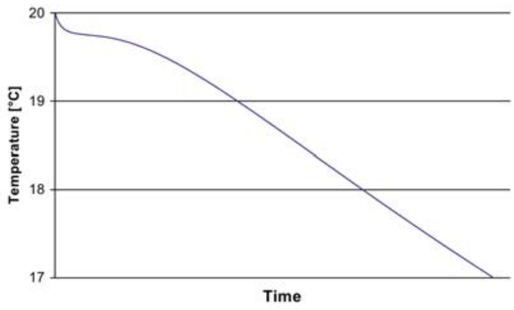

FIGURE 3.2: Temperature decline (qualitative) after heating system is switched of [30].

3.2 DeVid Project

The Norwegian government decided to replace all conventional power meters with advanced metering infrastructure (AMI) meters by 2016 [16]. The DeVid project was established to test and verify smart grid technologies and increase knowledge in order to reduce risk with the large investments to come [1]. The DeVid project has two experimentation sites, the Demo Steinskjer and Smart Energi Hvaler. The Demo Steinskjer site is located north of Trondheim in Trøndelag municipality. The Smart Energi Hvaler project is located in the southern part of Norway in the Hvaler municipality. The data used in this thesis was obtained from the Hvaler project and more precisely from a transformer on the Vesterøy island. The main aims are to test the AMI equipment and to monitor loads from all costumers in the area.

3.3 Results

3.3.1 Distribution Transformer Load Profiles without EVs

The load profiles of the 315kVa transformer is shown in figures 3.3 and 3.4. Most households in Norway heat with electrical heaters which explains why the demand in winter is twice as high as in summer. The transformer loading level on 23rd of January is about 60% of its rating which is less than 180 kW for a 315 kW transformer. The biggest part of the load was demanded by households and commercial buildings. The demand is lowest at 3am and increases slowly to 10am where it is stable until midnight.There is no distinctive peak in the load profile however there is a slight increase at 5pm. The transformer loading level for the 22nd of June 2013 is about 35 % of its rating which is less than 105kW. Commercial buildings take the major part in this profile. There is no peak neither in this profile. It can be seen that the demand of commercial buildings is higher compared to the winter month. The demand of households and cabins is significantly lower in summer than winter. The load is lowest in the early morning (6-8 am), increases at 9 am and is constant until midnight before decreasing again.

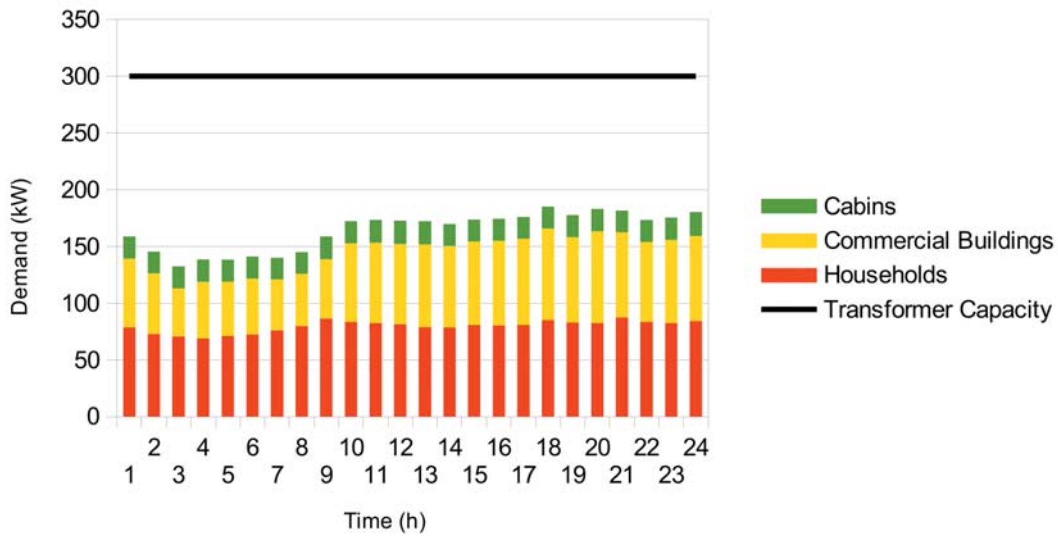

Figure 3.3: Load Profiles of a 315kVA distribution transformer serving 25 homes, 25 cabin, 11 commercial buildings on the 23/01/2013.

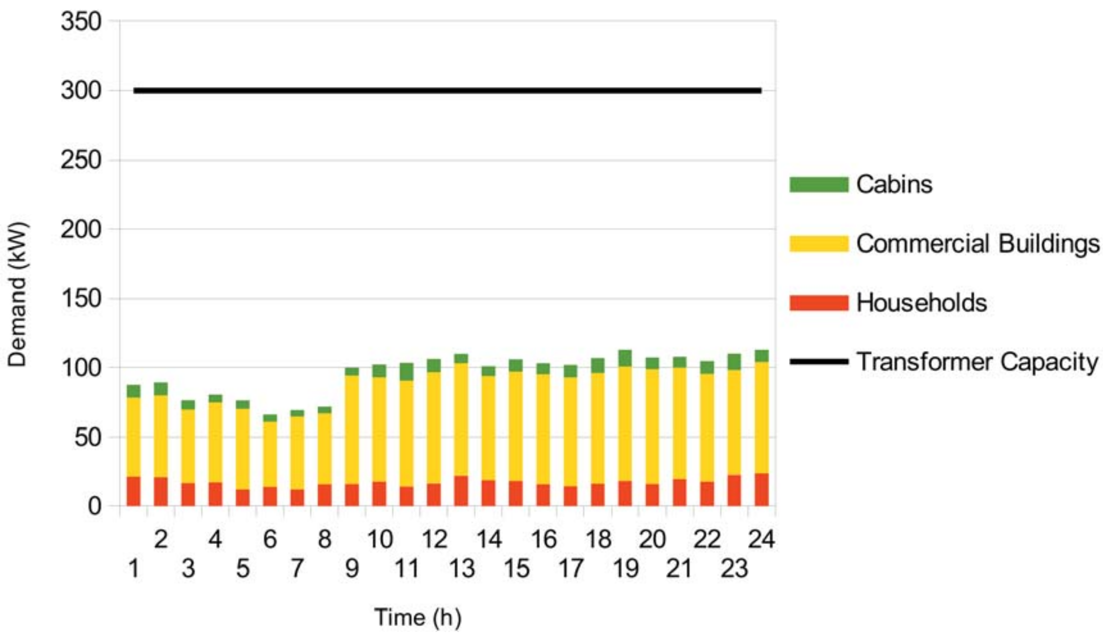

Figure 3.4: Load Profiles of a 315kVA distribution transformer serving 25 homes, 25 cabin, 11 commercial buildings on the 22/07/2013.

3.3.2 Distribution Transformer Load Profiles with various charging scenarios

3.3.2.1 Scenarios with normal charging

In this section the impact of EV loading with 3,3kW over a time period of 7 hours was investigated. The results are shown in figures 3.5 and 3.6. In January the demand reaches up to 90 % of the transformers rating, which is 270 kW. The transformer is not overloaded and has still 30 kW buffer before reaching the maximum load.

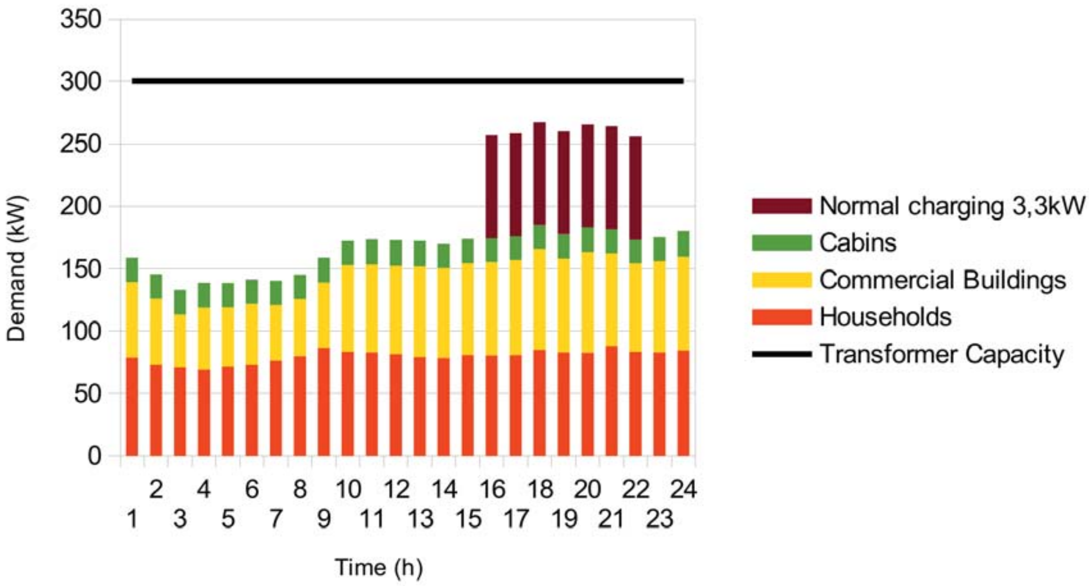

Figure 3.5: Load Profiles of a 315kVA distribution transformer serving 25 homes, 25 cabin, 11 commercial buildings and 25 EVs charging at 3,3 kW (normal charge) in the peak evening hours on the 23/01/2013.

The demand in June reaches up to 64 % of the transformers rating, which is 190 kW.

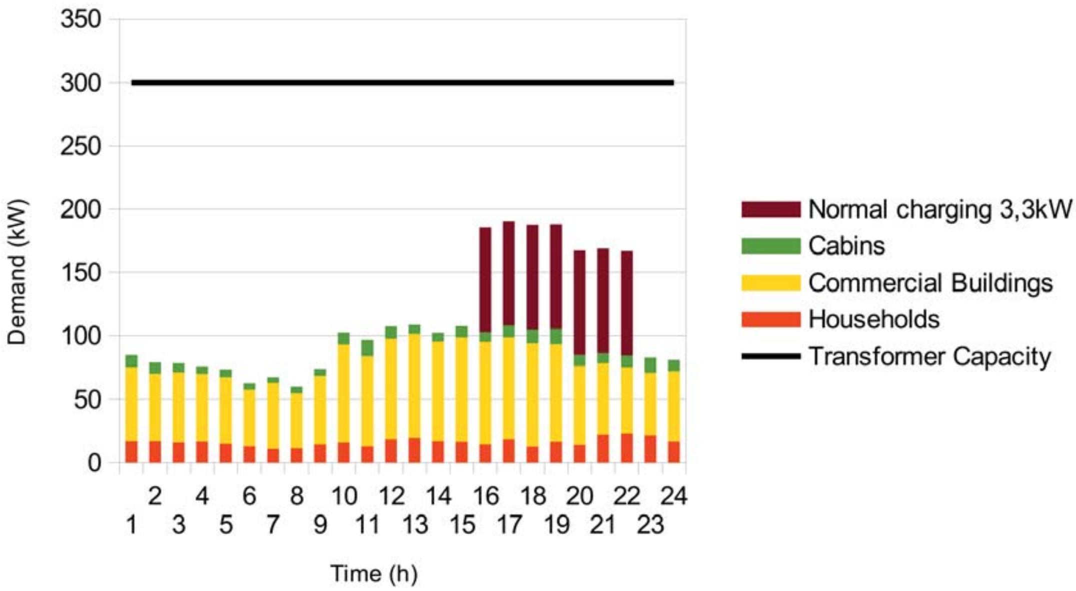

Figure 3.6: Load Profiles of a 315kVA distribution transformer serving 25 homes, 25 cabin, 11 commercial buildings and 25 EVs charging at 3,3 kW (normal charge) in the peak evening hours on the 22/07/2013.

3.3.2.2 Scenarios with Quick charging

More and more Evs can be charged with higher strength of current to reduce the time used for charging. In this thesis we simulated the charge of 25 Evs where 17 were charged with 3,3kW in 6 hours whereas the other 8 were charged with 12kW in 2 hours, all starting at 4 pm. The results for January 2013 is shown in figure 3.7. It can be seen that that the transformer exceeds its capacity by far between 4 and 6pm.

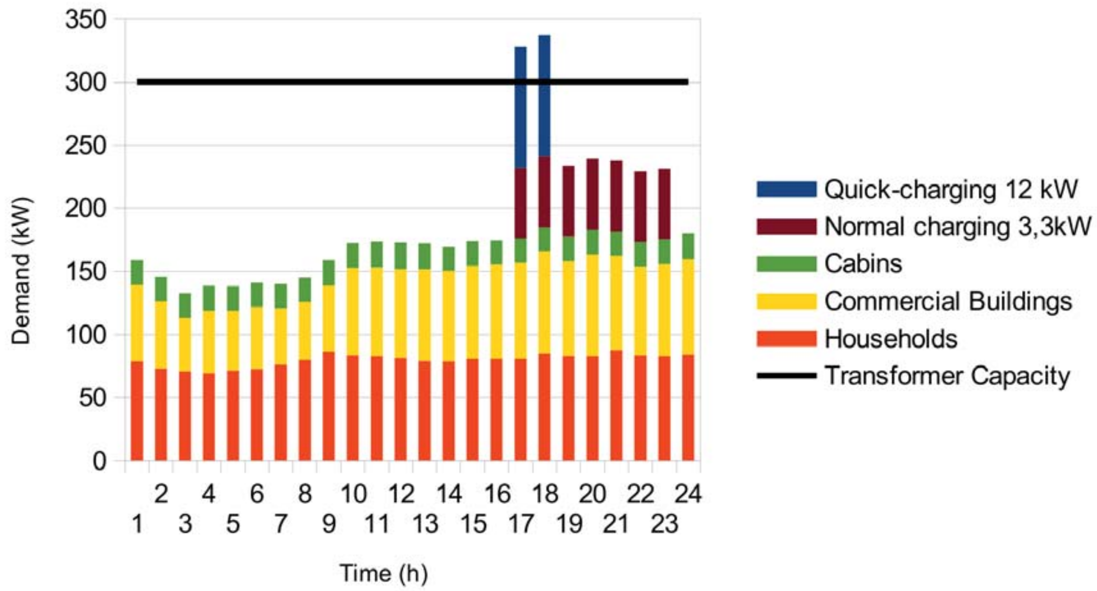

Figure 3.7: Load Profiles of a 315kVA distribution transformer serving 25 homes, 25 cabin, 11 commercial buildings and 25 EVs charging were 13 are charged with 3,3kW and 12 with 12 kW (quick charge) in the peak evening hours on the 23/01/2013.

The results for July 2013 are shown in figure 3.8. It can be seen that the transformer almost reaches its maximum load (300kW) in the second hour of charging.

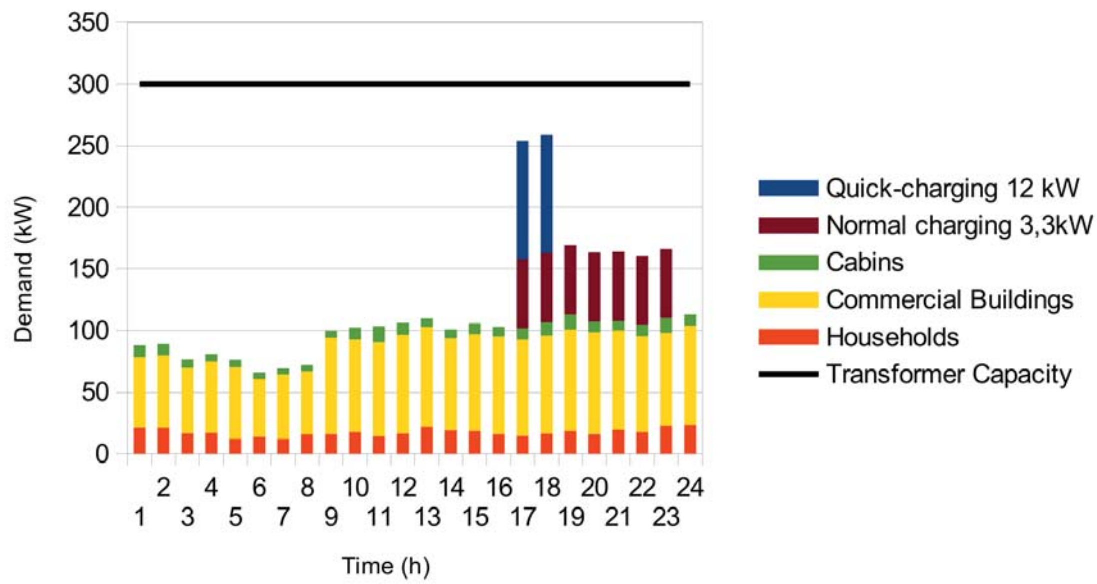

Figure 3.8: Load Profiles of a 315kVA distribution transformer serving 25 homes, 25 cabin, 11 commercial buildings and 25 EVs charging were 17 are charged with 3,3kW and 8 with 12 kW (quick charge) in the peak evening hours on the 22/07/2013.

3.3.2.3 Charging during day-time at commercial buildings

In this scenario the impact of day-time charging of employee EVs at commercial buildings was investigated. It was assumed that per building two EVs can and will be charged from 8am to approximately 2pm. The results for winter and summer are shown in figure 3.9 and 3.10, respectively. It can be seen that in both seasons EV charging at day-time is not reaching the maximum load of the transformer. In winter the transformer is loaded with 82 % (246kW) and in summer with 61% (183kW).

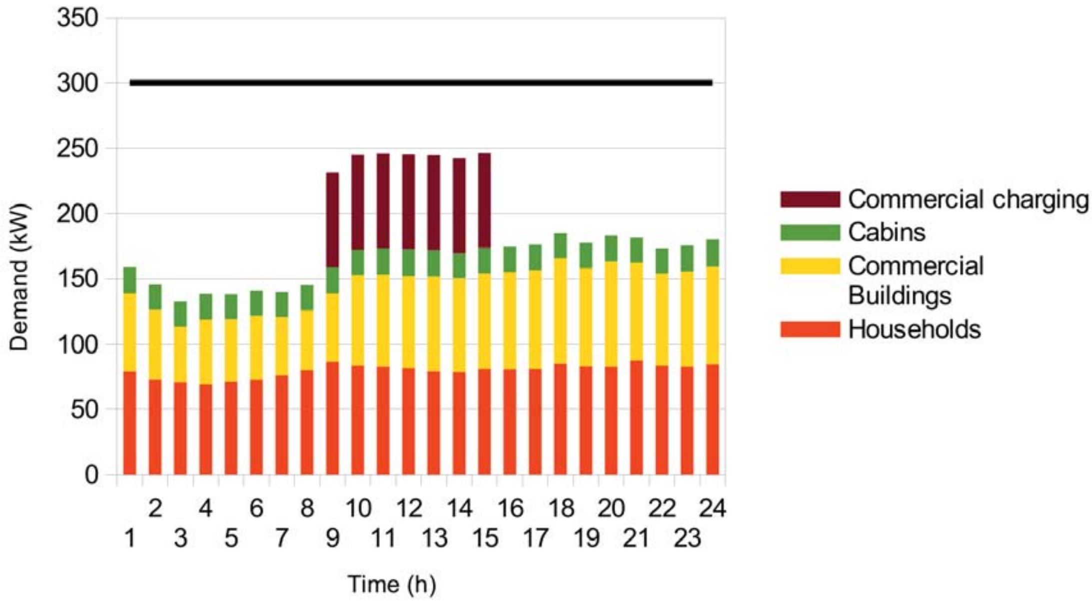

Figure 3.9: Load Profiles of a 315kVA distribution transformer serving 25 homes, 25 cabin, 11 commercial buildings and 22 employee EVs with 3,3kW starting at 8am until 2pm on the 23/01/2013.

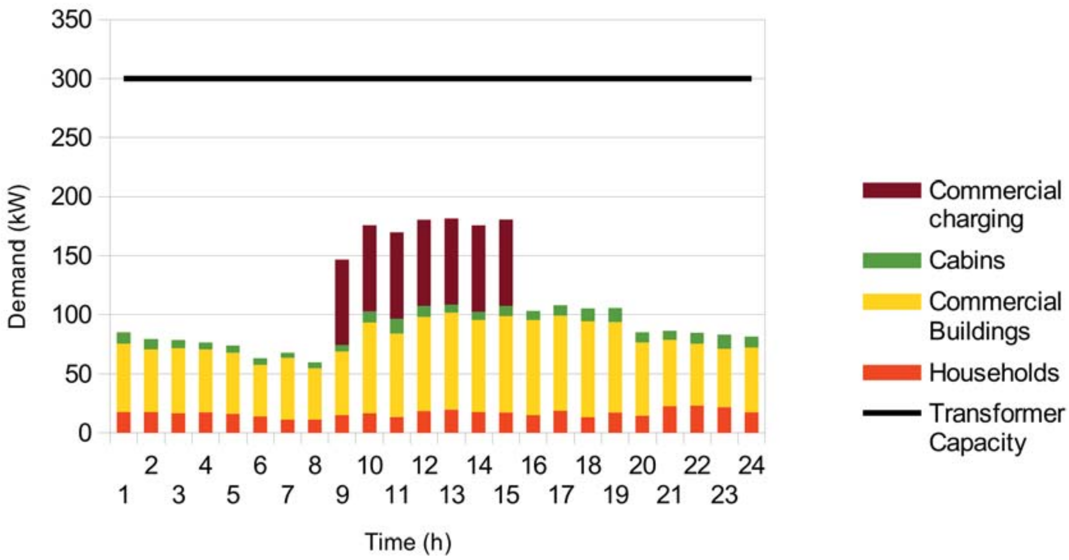

FIGURE 3.10: Load Profiles of a 315kVA distribution transformer serving 25 homes, 25 cabin, 11 commercial buildings and 22 employee EVs with 3,3kW starting at 8am until 2pm on the 22/07/2013.

3.3.3 Load Profiles with Load Shaping techniques

3.3.3.1 EV stagger charge

Figure 3.11 shows the staggered charge of 17 EVs in normal charge on 23rd of January 2013. As mentioned in the methods, the EVs with quick charge where not staggered since it is assumed that the owners did not want to wait (therefore quick charge). All other vehicles were plugged in at 4 pm as the quick charge ones. However since the transformer capacity would have exceeded the 280kW, charging is deferred until there is enough capacity. This is the case at 6 pm when the EVs with quick charge are finished charging. After this all other EVs can charge without reaching the pre-defined loading value (280 kW) of the transformer.

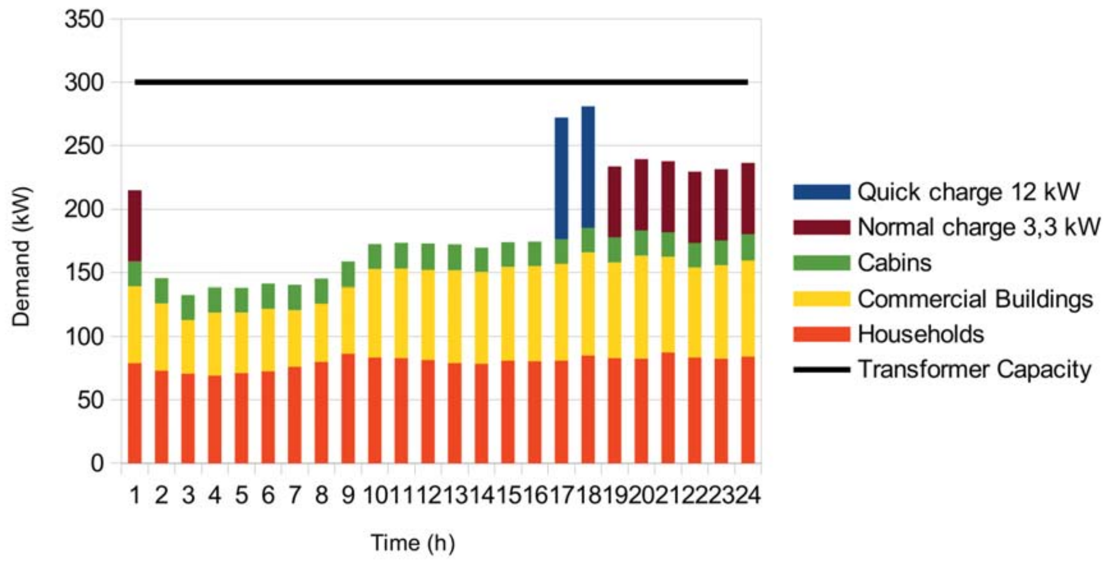

FIGURE 3.11: Hourly load profile seen by a 300kVA transformer serving 25 households, 11 commercial buildings and 25 cabins and 25 EVs where 17 were charged normal and 8 quick (staggered charge at normal charge)

3.3.3.2 Household Load Control

In this scenario the results from the previous section are simulated under household load control.The results are shown in figure 3.12. 60% of the original household demand was switched of during the first two hours of EV charging. This resulted in a peak difference from 328kW to 276kW for the first hour and from 337kW to 286kW for the second hour of EV charging. The load profile is under the transformer threshold and the transformer will not be overloaded.

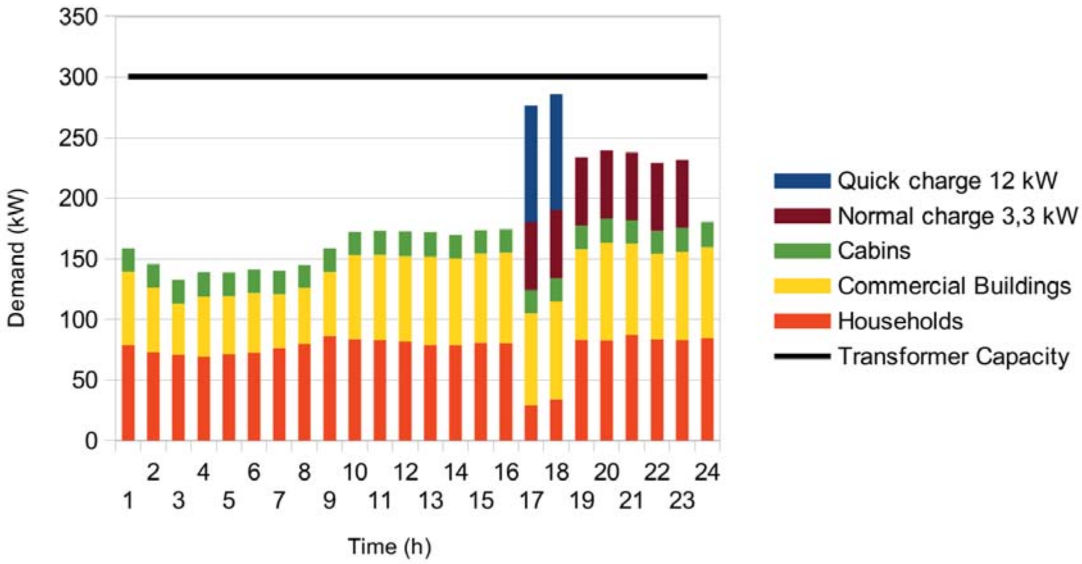

Figure 3.12: Hourly load profile seen by a 300kVA transformer serving 25 households, 11 commercial buildings and 25 cabins and 25 EVs where 17 were charged normal and 8 quick (with household load control)

3.4 Discussion

The transformer load profile without EVs shows sufficient capacity both in summer and winter. Compared to summer the household and cabin load was thrice as high in winter. Electricity is the most common energy resource for space and hot water heating in Norway and this explains the seasonal load difference. The commercial buildings had a higher consumption in summer than in winter. Probable reasons for this could be the use of air conditioning and other cooling devices during warm summer months. The winter consumption seems lower than the one of the households, however there are only 11 commercial buildings compared to 25 household buildings, which means that the consumption per building was actually higher for commercial buildings.
The graphs of the daily load profiles show no distinctive peaks in the morning and late afternoon as described in [31]. First of all the overall consumption is very high because of space heating which occurs all day automatically. Other electrical devices which might be used by customers when waking up or coming home from work do not demand as much electricity as heating and and are therefore not visible as distinctive peaks in the daily load profile. Another reason is the variety of customers of this transformer with different consumer habits. Commercial buildings in general have the highest consumption during the day [19]. That means that higher consumption of commercial buildings during the day and higher consumption of households in early morning and late afternoon might even out the load profiles masking the respective consumption peaks.

The transformer 15H Ødegaard has more than sufficient capacity to enable normal Ev charging (3,3kW) in the evening peak hours of all 25 households in both summer and winter. In terms of transformer capacity and performance no transformer upgrading or load management would be necessary. Customers in this scenario were assumed to first need the EV the next morning again. Even if the transformer has enough capacity it would be advisable to consider charge management to avoid high peak power prices during early evening hours. A consumer charging an EV during peak hours in the evening on 23rd of January 2013 would have paid more than twice as much compared to one who was charging from 8pm and during night [23]. Due to lower demand in July spotprices were much lower and stable during afternoon/evening hours on the 22nd July 2013 and charge management was economically not necessary [23].
When one-third of the customers with EVs were charging in quick charge mode (12kW), transformer overload occurred in winter. In this case either a transformer upgrade or load management is mandatory to avoid blackouts and high transformer abrasion. The load in summer was within the transformer's capacity and no upgrade and load management was necessary from a technical and economical point of view. It was assumed that customers who use quick charge do not wait with charging but charge as soon as they have the possibility. Those customers might be people who need the EV in the evening hours or those who want to have the safety of a full-charged car at all times. It was assumed that those customers would accept the higher expenses and those would not want to wait for charging. This assumption corresponds with the findings from Shao et al. [26]
Day-time charging from EVs from commercial buildings was also within the capacity of the transformer in summer and winter. Due to the different charging times there was no interference with EV charging from households and no overload occurred. However interference might occur when the charging times from commercial buildings overlap with the ones from household charging. This scenario is likely, because employees are not necessary also living in this commune. Furthermore, there are differences in the working hours of different people, which might lead to an overlap in charging times. But this was not tested in this study.
The scenario with one-third EVs in quick charge and the resulting transformer overload was used for the load management scenario. In both approaches, stagger charge and household load control, the aim was to prevent the transformer from overloading. Both strategies are thought to perform within the home area network which respects the consumers' privacy. The staggering helped to prevent overloading of the transformer and saved money for the customers charging their EV at normal rate (3,3kW) due to a lower power price in the evening [23]. Staggering is a powerful tool in managing distribution grid fluctuations as long as enough EV owners are willing to adapt the charging of their EV. The results correspond with the findings of Putrus *et al.* [24], where EV

charging was moved to late night charging and resulted in a adequate load reduction to counteract transformer overload. Singh *et al.* [28] found out that EV charging could help stabilize the Indian distribution grid when coordinated and staggered. Sundström *et al.* [33] included power prices in his simulation and concluded that both price-based and grid-aware price-based charging helped to counteract overload of the distribution transformer.

The scenario where household loads of EV owners were managed also showed a demand decrease in the critical period and a load removal of the transformer. However since the EVs in quick charge mode would consume a lot of the electricity, the household load would have to be drastically decreased. In our simulation only space heating was used for shedding. In case of uncomfortable decline in ambient temperature, hot water boilers could be used for shedding instead.

Cabins and commercial buildings could also participate in shedding, which was not simulated in this study due to simplicity reasons. Especially the cabins in this area, which are preferably used in summer, could contribute to demand altering in peak hours. Shao *et al.* [26] studied a similar approach with the simulation of a distribution transformer in the United States. They used the same method as in this study but simulated, instead of real data. Customers were ask to make a list with load priority and convenience preference. The load with lowest priority was then turned off first in case of a demand limit event. Shao *et al.* had good results shedding high EV penetration of the distribution transformer with this method at a minimal impact on customers' life styles [26].

The data used in this study are real data, the scenarios however are potential and virtual. Beside the hourly load of all customers the data contained no information on what the power was used for. Therefore the load management scenarios are based on general patterns and habits observed in Norwegian households [29]. To get more authentic results, data with hourly load curves of all non-critical and critical loads are necessary. However the knowledge acquired in this thesis is based on a rural study site and may not be transferable to other environments. To gain a reliable overview of transformer capacities and load profiles in Norway more data from various environments has to be collected.

Conclusion

The main objective of this study was to evaluate the impact of EV penetration on a rural distribution transformer and test selected demand response strategies to avoid overload. The transformer showed more than enough capacity to host one EV per household or two per commercial building as long as all the EVs were charged normal (3,3kW). However, if one-third of the household EVs were quick charged (12kW) the transformer was heavily overloaded. Both the charge staggering and the household load shaping strategy helped to prevent overload at peak-times. Due to a high share of electrical space heating in Norway and thereby a high overall demand, transformer have to have good capacity to provide customers with sufficient electricity at all times. This enables the possibility of high EV penetration without risking transformer overload. The high share in electrical space heating also opens up for vast possibilities in demand response on household level. Further studies are needed to investigate the implementation of DR technologies into the existing grid. It is important to survey the state of the distribution grid by collecting more data of transformer capacity and load profiles from various environments. This will contribute to the understanding in how to exploit the potential of the existing grid with regard to the smart grid technologies.

Bibliography

[1] The DeVid Project - Demonstration and Verification of Intelligent Distribution networks. Trondheim, 2012.

[2] M.H. Albadi and E.F. El-Saadany. A summary of demand response in electricity markets. *Electric Power Systems Research*, 78(11):1989–1996, November 2008.

[3] Andrew Armenia and Joe H Chow. A Flexible Phasor Data Concentrator Design Leveraging Existing Software Technologies. *IEEE Transactions on Smart Grid*, 1(1):73–81, June 2010.

[4] Todd Baumeister. Literature Review on Smart Grid Cyber Security. 2011.

[5] Stuart A. Boyer. *SCADA Supervisory Control and Data Acquisition*. ISA - International Society of Automation, 3rd edition, 2010.

[6] Electric Power Research Institute. http://smartgrid.epri.com/Index.aspx - accessed 03/07/14.

[7] Ergon Energy/Energex. Residential time of use tariff - https://www.yourpowerqld.com.au/energy-pricing-and-economy-rates/time-of-use-tariff - accessed 11/07/14.

[8] Xi Fang, Satyajayant Misra, Guoliang Xue, and Dejun Yang. Smart Grid — The New and Improved Power Grid: A Survey. *IEEE Communications Surveys & Tutorials*, 14(4):944–980, 2012.

[9] H Farhangi. The path of the smart grid. *Power and Energy Magazine, IEEE*, (february), 2010.

[10] Federal Energy Regulatory Comission. Assessment of Demand Response and Advanced Metering. Technical report, 2010.

[11] Clark W. Gellings and John H. Chamberlin. *Demand-side management: concepts and methods*. 1988.

[12] Grø nn Bil. http://www.gronnbil.no/statistikk - accessed 02/07/14, 2014.

[13] Marija D. Ilic. From Hierarchical to Open Access Electric Power Systems. *Proceedings of the IEEE*, 95(5):1060–1084, May 2007.

[14] International Energy Agency. The Power to Choose - Demand Response in Liberalized Electricity Markets. Technical report, Paris, 2003.

[15] Himanshu Khurana, Mark Hadley, Ning Lu, and Deborah A. Frincke. Smart-Grid Security Issues. Technical report, 2010.

[16] Energibedriftenes Landsforening. Avanserte måle- og styringssystemer - svar påhø ring av endringer i forskrift 301 MAF, 2009.

[17] Fangxing Li, Wei Qiao, Hongbin Sun, Hui Wan, Jianhui Wang, Yan Xia, Zhao Xu, and Pei Zhang. Smart Transmission Grid: Vision and Framework. *IEEE Transactions on Smart Grid*, 1(2):168–177, September 2010.

[18] S. Massoud Amin and B.F. Wollenberg. Toward a smart grid: power delivery for the 21st century. *IEEE Power and Energy Magazine*, 3(5):34–41, September 2005.

[19] M. Medrano, J. Brouwer, V. McDonell, J. Mauzey, and S. Samuelsen. Integration of distributed generation systems into generic types of commercial buildings in California. *Energy and Buildings*, 40(4):537–548, January 2008.

[20] Anthony R Metke and Randy L Ekl. Security Technology for Smart Grid Networks. *IEEE Transactions on Smart Grid*, 1(1):99–107, June 2010.

[21] Albert Molderink, Vincent Bakker, Maurice G. C. Bosman, Johann L. Hurink, and Gerard J. M. Smit. Management and Control of Domestic Smart Grid Technology. *IEEE Transactions on Smart Grid*, 1(2):109–119, September 2010.

[22] Trevor Morgan. Smart Grids and Electric Vehicles, April 2012.

[23] NordPoolSpot. http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/ALL1/Hourly - accessed 26/06/14.

[24] G.A. Putrus, P. Suwanapingkarl, D. Johnston, E.C. Bentley, and M. Narayana. Impact of electric vehicles on power distribution networks. In *2009 IEEE Vehicle Power and Propulsion Conference*, pages 827–831. IEEE, September 2009.

[25] Shengnan Shao, Manisa Pipattanasomporn, and Saifur Rahman. Challenges of PHEV penetration to the residential distribution network. In *2009 IEEE Power & Energy Society General Meeting*, pages 1–8. IEEE, July 2009.

[26] Shengnan Shao, Manisa Pipattanasomporn, and Saifur Rahman. Demand Response as a Load Shaping Tool in an Intelligent Grid With Electric Vehicles. *IEEE Transactions on Smart Grid*, 2(4):624–631, December 2011.

[27] Marcelo Godoy Simoes, Robin Roche, Elias Kyriakides, Sid Suryanarayanan, Benjamin Blunier, Kerry D. McBee, Phuong H. Nguyen, Paulo F. Ribeiro, and Abdellatif Miraoui. A Comparison of Smart Grid Technologies and Progresses in Europe and the U.S. *IEEE Transactions on Industry Applications*, 48(4):1154–1162, July 2012.

[28] Mukesh Singh, Indrani Kar, and Praveen Kumar. Influence of EV on grid power quality and optimizing the charging schedule to mitigate voltage imbalance and reduce power loss. In *Proceedings of 14th International Power Electronics and Motion Control Conference EPE-PEMC 2010*, pages T2–196–T2–203. IEEE, September 2010.

[29] REMODECE SINTEF. Nhttp://www.sintef.no/SINTEF-Energi-AS/Xergi/Xergi-2008/Nr-2—september/Ny-kunnskap-om-fordeling-av-stromforbruket - accessed 26/06/14.

[30] Ingo Stadler. Power grid balancing of energy systems with high renewable energy penetration by demand response. *Utilities Policy*, 16(2):90–98, June 2008.

[31] Statnett. http://www.statnett.no/Drift-og-marked/Data-fra-kraftsystemet/Produksjon-og-forbruk - accessed 30/06/14.

[32] Statnett. Systemdrifts- og markedsutviklingsplan 2012. Technical report, 2012.

[33] Olle Sundstrom and Carl Binding. Planning electric-drive vehicle charging under constrained grid conditions. In *2010 International Conference on Power System Technology*, pages 1–6. IEEE, October 2010.

[34] U.S. Department of Energy. Benefits of demand response in electricity markets and recommendations for achieving them - A report to the United States Congress pursuant to Section 1252 of the Energy Policy Act of 2005. Technical report, U.S. Dept. Energy, 2006.

[35] Weathersparks. http://weatherspark.com/history/28883/2013/Rygge-Ostfold-Norway - accessed 18/06/2014.

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