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Kontraktsdesign mellom en aggregator av forbrukerfleksibilitet og et nettselskap

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Problem Description

The main activity of this thesis is to study possible *contractual relationships* between an aggregator of demand response and a grid company. How will different types of contracts affect the value chain profit and risk, in addition to the distribution of them between the two parties? The thesis will also look at how the contracts are affected by different information scenarios.

The development of the Smart grid is likely to provide many new business opportunities and maybe even new actors in the power grid. An important concept enabled by the smart grid is that of demand response, or demand side flexibility. Demand response is believed to be useful when the flexibility is aggregated to large volumes, and it is believed to be able to create value for several of the actors in the power system. Thus a potential new actor in the smart grid is the aggregator, which will aggregate and sell demand response. Demand response is believed to be especially valuable for grid companies because reducing peak loads in the grid can postpone, or even eliminate, the need for expensive grid reinforcements.

The purpose of this thesis is to assess possible contracts in order to reveal *the potential value* that can be extracted for a grid company utilizing demand response. Furthermore, the thesis aims to provide insight on how an aggregator can engage in a profitable contractual relationship with a grid company, with regards to distribution of profits and risk. The thesis will provide both theoretical analyses and illustrative examples.

Preface

This thesis concludes my Master's degree in Managerial Economics and Operations Research under the Department of Industrial Economics and Technology Management at NTNU. The thesis was written in the spring of 2016. The topic for the thesis was proposed by my main supervisor, Asgeir Tomasgard, but the final problem formulation was composed by me.

The topic given for this thesis was the Smart grid. I have spent much time and effort to map the existing literature within this topic in order to identify a relevant problem formulation.

I would like to thank my supervisors, Asgeir Tomasgard and Stig Ottesen, for their guidance and assistance in identifying TrønderEnergi as a collaborator. I would also like to thank Ståle Svenning and Arnt-Magnar Forseth at TrønderEnergi for interesting discussions and useful information for the case study presented in this thesis.

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Abstract

The power grid as we know it is currently in the process of being brought into a new technological era. As the way we produce and consume electricity changes, the power grid must change with it. An increased commitment to renewable energy sources and an overall more efficient use of energy is likely to cause a less predictable supply and demand of electricity. The development of the Smart grid will provide a more flexible grid and motivate electricity consumers to take a more active part in the power system. An important concept of the Smart grid is that of demand response, or demand side flexibility, which entails that consumers of electricity alter their consumption in response to given incentives. Demand response is enabled by the AMI roll-out, which is to take place in Norway over the coming years. The introduction of smart meters will increase the information flow to and from the consumers. Demand response is believed to be useful when the flexibility is aggregated to large volumes. The suggested applications of demand response are various and it is believed to be able to create value for several of the actors in the power system.

This thesis has explored and evaluated different ways demand response can create value for a distribution system operator (DSO). The evaluation led to an assumption that the largest values lie in postponed investments in the grid from reducing the peak load. The purpose of this thesis is to estimate the potential values that can be achieved from postponed investments in the grid and evaluate the business potential for an aggregator. In order to do this the thesis has evaluated possible contracts an aggregator can offer a DSO. The contracts have been assessed based on profits and risks, and have been evaluated for different information scenarios.

Before the contracts could be evaluated, it was necessary to define the cost curve of the aggregator and the benefit curve of the DSO. Both general methods of estimating the cost and benefit curves have been presented, as well as numerical

estimates. The thesis has studied existing contract forms, both linear and non-linear. Furthermore, the author has developed its own linear contract form that is meant to facilitate a CRP-service, which is believed to be better suited for trading flexibility in practice.

The thesis conducts a case study in order to assess the contracts. The case study has been performed for TrønderEnergi Nett and it has evaluated the potential for using demand response to postpone an investment in a residential area near the city center of Trondheim. Residential demand response will become highly relevant with the AMI roll-out, and the author wishes to fill a gap in the existing literature by attempting to quantify the value residential DR can have for a DSO. The case study revealed that the investment at Storhaugen could be postponed for a long time, which resulted in a high potential value of demand response at Storhaugen. Due to simplifications made in the thesis, the results presented in the case study are believed to be an upper limit of what is actually obtainable. Because the aggregator was the one designing and offering the contracts, the majority of the profit was left with the aggregator. In reality the DSO may be able to exert a larger bargaining power over the aggregator and obtain a greater share of the potential profits.

Sammendrag

Kraftsystemet slik vi kjenner det er i ferd med å bli blakt inn i en ny teknologisk æra. Ettersom måten vi produserer og konsumerer strøm på endrer seg, må også strømnettet endres. En økt satsning på fornybar energi og et generelt mer effektivt energiforbruk, vil trolig forårsake mindre forutsigbarhet i produksjon og forbruk. Utviklingen av Smart grid vil skape et mer fleksibelt nett og motivere strømforbrukere til å ta en mer aktiv rolle i kraftsystemet. Et viktig konsept ved Smart grid er forbrukerfleksibilitet, som innebærer at strømforbrukere tilpasser sitt forbruk som en respons til gitte insentiver. Forbrukerfleksibilitet blir muliggjort av innføringen av smarte strømmålere, som vil gjennomføres i Norge i løpet av de kommende årene. Smartmålere vil øke informasjonsflyten til og fra forbrukerne. Forbrukerfleksibilitet vil trolig være nyttig når den aggregeres opp til store volum. Det er mange foreslåtte bruksområder for forbrukerfleksibilitet, og bruken av den vil trolig kunne skape verdi for mange aktører i kraftsystemet.

Denne oppgaven har utforsket og evaluert ulike måter forbrukerfleksibilitet kan skape verdi for et nettselskap. Evalueringen førte til en antakelse om at det er utsatte investeringer i strømnettet grunnet redusert maks-last som er av størst verdi. Hensikten med denne oppgaven har vært å estimere den potensielle verdien som kan oppnås fra utsatte investeringer i nettet og å evaluere forretningsmuligheten for en aggregator. For å gjøre dette har oppgaven evaluert mulige kontrakter en aggregator kan tilby et nettselskap. Kontraktene har blitt vurdert ut fra profitt og risiko, og de har blitt evaluert for ulike informasjonsscenarioer.

Før kontraktene kunne bli vurdert var det nødvendig å definere kostnadskurven til en aggregator og verdikurven til et nettselskap. Både generelle metoder for å estimere kurvene og numeriske estimater har blitt presentert. Oppgaven har studert eksisterende kontraktsformer, både lineære og ikke-lineære. Videre, har forfatteren

utviklet sin egen kontraktsform som skal tilrettelegge for en CRP-tjeneste. Forfatteren mener at en CRP-tjeneste er bedre tilpasset salg av fleksibilitet i praksis.

Oppgaven utfører et eksempelstudium for å evaluere de mulige kontraktene. Eksempelstudiet har blitt utført for TrønderEnergi Nett og det har vurdert muligheten for å bruke forbrukerfleksibilitet for å utsette en investering i et boligområde i nærheten av Trondheim sentrum. Forbrukerfleksibilitet fra husholdninger vil bli meget relevant med innføringen av smartmålere i Norge, og forfatteren ønsker å fylle et hull i den eksisterende litteraturen ved å kvantifisere verdien forbrukerfleksibilitet fra husholdninger kan ha for et nettselskap. Eksempelstudiet viste at investeringen på Storhaugen kunne bli utsatt i lang tid, og at dette ville medføre store verdier. Forenklingene som har blitt gjort i utregningene har trolig overestimert den potensielle verdien av forbrukerfleksibilitet, og kan brukes som en øvre grense for hva som vil være mulig å aktualisere. Fordi kontraktene ble utformet av aggregatoren, var det den parten som satt igjen med majoriteten av profitten. I virkeligheten er det sannsynlig at nettselskapet vil ha en større forhandlingskraft og kan gjøre krav på en større andel av overskuddet.

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Abbreviations

AMI	**A**dvanced **M**etering **I**nfrastructure
CRP	**C**onditional **R**e**P**rofiling
DG	**D**istributed **G**eneration
DR	**D**emand **R**esponse
DSO	**D**istribution **S**ystem **O**perator
EV	**E**lectric **V**ehicle
NPV	**N**et **P**resent **V**alue
NVE	Norwegian Water Resources and Energy Directorate
SRP	**S**cheduled **R**e**P**rofiling
TEN	**T**rønder**E**nergi **N**ett
TS	**T**ransformer **S**tation
TSO	**T**ransmission **S**ystem **O**perator

Chapter 1

Introduction

The Smart grid is a term used of the technological advances changing the configuration of the power grid, which in turn will alter the interaction between the actors in the power system. The Smart grid can be seen as a response to a change in how electricity will be produced and consumed in the future. As society wishes to engage in a more sustainable energy consumption, there is a large focus on renewable energy sources and energy efficient solutions. These developments require a more flexible grid. The Smart grid will enable the consumer to take a more active part in its consumption and is meant to increase the flexibility of the grid.

The power consumption is expected to increase in future years due to a general increase in electricity consumption, as well as energy efficient electric appliances using more power (energy per time). The power consumption in the grid varies greatly throughout the day and year and the power grid needs to be dimensioned for the peak load imposed on the grid. Increased peak loads in the grid are likely to necessitate grid reinforcements, which involve high costs for the DSOs. An alternative to grid reinforcements, enabled by the Smart grid, is that of demand response. This entails using flexibility on the consumer side to even out the power consumption throughout the day, thus reducing peak loads. Demand response is currently used to some degree in Norway by imposing power based grid tariffs on large electricity consumers. However, the AMI roll-out will enable all electricity consumers to engage in demand response.

In the field of Smart grid research and development in Norway, there is currently a focus on how to procure flexibility from electricity consumers. However, few projects are concerned with quantifying the economic values of demand response. The intention of this thesis is to contribute to quantifying the value demand response can have for a DSO by postponing investments in the power grid. This is done by evaluating contracts an aggregator can offer a DSO to trade large amounts of flexibility. Evaluating these contracts is believed to show the value that can be extracted from postponed investments in the grid and how they will be distributed between the DSO and the suppliers of flexibility. The thesis will derive optimal contracts on a general basis and present a case study to give numerical examples.

Chapter 2 includes a review of background information relevant for the thesis and Chapter 3 discusses the potential values demand response can create for a grid company. Chapter 4 presents the cost and benefit curves the contract design will be based upon, while Chapter 5 and 6 presents and evaluates the contracts. Chapter 7 reviews a case study performed in cooperation with TrønderEnergi to provide numerical examples and assess the suggested contracts. Finally, chapter 8 gives a conclusion to the thesis.

Chapter 2

Background Information

2.1 The Smart Grid

This section will give an overview of the Norwegian power system and an introduction to the Smart grid.

2.1.1 Reasons for the Smart Grid Development

The traditional Norwegian power grid was built between 80 and 120 years ago. It was designed to facilitate the flow of electricity from large generators to the consumers. For many years the Norwegian power industry has been characterized by large generators using controllable energy sources, more specifically hydro energy, which contributes to about 99 percent of Norwegian power production. There is currently an increased commitment to other renewable energy sources, such as wind-, solar- and tidal energy. These sources provide a much less predictable power generation. In other words, there will be a shift from a power generation characterized by a few large and controllable energy sources to one characterized by the addition of several smaller, less controllable and less predictable energy sources. This creates the need for a smart and flexible grid. [1]

Furthermore, the consumption of electricity is also changing. It is expected to be an increase in the electricity consumption due to a number of factors, among them is an increased use of Electric Vehicles. EVs are especially popular in Norway due to the government giving users many incentives to buy EVs instead of traditional fuel driven cars. As an increased share of consumers' activities are supported by electrical devices we become more dependant on a stable and secure supply of electricity. [1]

2.1.2 Actors in the Smart Grid

This subsection will present the actors in the Smart grid and how they interact with each other.

Regulator: The Norwegian regulator is the Norwegian Water Resources and Energy Directorate (NVE). The regulator is responsible for securing an efficient energy market, regulate the monopolized TSO and DSOs, as well as protecting the interests of electricity consumers.[2]

Nord Pool: Nord Pool Spot organizes the Nordic power exchange, which primarily consists of the Day-ahead market, Elspot, and the intraday market, Elbas. In the day-ahead market, generators and retailers report their forecasted supply and demand for electricity each hour for the next day and Nord Pool sets the electricity prices and clears the market accordingly. [3]

Generator: The generators are electricity producers who sell their electricity, either on the Nord Pool Spot exchange or directly to retailers. Generators are responsible for *production balancing*, meaning that they must balance actual production with the planned production they have sold. If they fail to uphold their balancing responsibility they can incur imbalance fees from the TSO.

TSO: The TSO is the system operator and this role is held by Statnett in Norway. The TSO is responsible for the security of supply on a national level. It must ensure a well-functioning and balanced power market. Statnett does this through regulating the generators and retailers, but is itself regulated by the NVE. [4]

DSO: The DSOs are the grid companies, who operate the distribution grids. DSOs are bound to geographical locations and they are natural monopolies, because having several grids covering the same area would be highly inefficient. The DSOs are regulated by the NVE to ensure they don't exert their monopoly power and operate inefficiently. A DSO is legally obligated to supply everyone who demands electricity within their geographical area and they are responsible for the security of supply to their customers. The term DSO and grid company will be used interchangeably in this thesis.

Retailer: The retailers purchase electricity, based on forecasts, and sell it to the electricity consumers. The retailer is responsible for *demand balancing*. Similarly as with the generator, the retailer must match actual demand with forecasted demand or pay imbalance costs to the TSO. Electricity consumers are free to choose from the retailers in their country, unlike the geographically determined DSOs.

Electricity Consumer: The electricity consumers are the end users in the electricity supply chain. They are often divided into large industrial consumers, business consumers and household consumers. Traditionally, the consumers have been very passive in the power market and function as price takers with a very inelastic demand. In the future Smart grid the consumers are encouraged to take an active part in the power market.

A concept of the modern electricity grid is the *prosumer*. A prosumer is a widely used term and generally describes a consumer of a good who also takes on some of the characteristics of a producer of that same good. In the context of the Smart grid the prosumer is an electricity consumer that also produces its own electricity. Eurelectric [5] defines the prosumers as "customers who produce electricity primarily for their own needs, but can also sell the excess electricity. Prosumers are connected to the distribution network with small to medium installed capacity." The prosumer will usually be connected to the electricity grid for supply security and will have the option to use or sell its own supply of electricity. [5] The prosumer is a consequence of distributed generation, a term that will be further explained later in this chapter.

Aggregator: An aggregator is a new actor to the power market and is a result of the Smart grid developments. There are many different definitions of an aggregator, but for the purpose of this text the definition provided by He et al. [6] will be used. It stated that aggregators are "entities that facilitate the demand response transaction between consumers, who provide flexibility, and demand response procurers, who use flexibility to optimizetheir businesses, through contracts". Thus, the aggregator enters contracts with providers and users of demand flexibility in order to aggregate flexibility to a large scale so that it is possible to extract the potential gains of the flexibility.

LOS is the only actor who is currently operating as an aggregator in the Norwegian market, and they target business consumers. Currently, there are no commercial aggregators targeting households.

2.1.3 Smart Metering

An Advanced Metering Infrastructure (AMI) is a key component of the Smart grid and it entails that all consumers are equipped with a smart meter. A smart meter registers the power consumption on an hourly basis and transmits the consumption information automatically to the DSO. This provides more accurate measurements of the power consumption and therefore a better basis to form the customer's bill. The smart meters make two-way communication possible between the consumer and the DSO. Consumers can be provided with continuous information concerning their consumption, prices for electricity and grid tariffs.

The NVE have started a transition to AMI in Norway and have a goal that all Norwegian electricity consumers should have a smart meter by January 1st 2019. The DSOs are responsible for the smart meter roll-out and the AMI operations, but consumers are also free to acquire these services from other service providers. The AMI will make many new services available for the consumers, many of them related to consumption management. It is intended that better informed consumers will develop a more active relationship to their power consumption, and that they will be more adaptive to price changes. AMI will enable the consumers to participate in demand response, a subject that will be explained later in this chapter. [7]

2.1.4 Distributed Generation

The term distributed generation (DG) is used to describe energy generation facilities that are not centralized, but rather located closely to the loads they serve. They are usually characterized by having a much lower capacity than the centralized facilities. The DG is connected to the electricity grid, but due to its closeness to the point of consumption there are less transportation costs associated to DG than centralized generation. [5]

The deployment of distributed generation poses opportunities and challenges for actors in the market. In general, the challenges are linked to the fact that most of the DG is based on renewables. Power generation from renewable energy sources is less predictable and may interfere with the forecasts from power generators and suppliers. When DG is used by prosumers, the prosumer can have a reduced demand of electricity from its retailer, and in some cases, when the prosumer produces more than it uses itself it can create an increased supply. [5]

2.1.5 Microgrids

Microgrids are local energy grids that are able to function independently of the traditional power grid (macrogrid). A microgrid will usually be connected to the macrogrid, but has the option to disconnect from it. Microgrids can increase the resilience of the traditional grid and reduce the effect of grid disturbances by disconnecting from the traditional grid when needed. They also make for a more flexible grid by enabling the integration of renewable energy and increases grid efficiency as there are less losses in transmission when using local energy sources.[8]

2.2 The Norwegian Electricity Grid

The Norwegian electricity grid is divided into three levels.

1. The central grid

2. The regional grids

3. The distribution grids

The *central grid* is often compared to being the highways of the grid. It has a high capacity and connects all the producers and consumers in the grid. It also has connections to other countries to allow for international trading of electricity. The *regional grids* connect the central grid to the distribution grids and also supply some end customers directly. Finally, the *distribution grids* are the local grids supplying the electricity consumers. The large electricity producers are primarily connected at the central grid, but can also be connected at the regional grids. Smaller generators are connected at the regional or distribution grids. The voltage of the electricity provided in the grid is highest at the central grid and lowest in the distribution grid. [9]

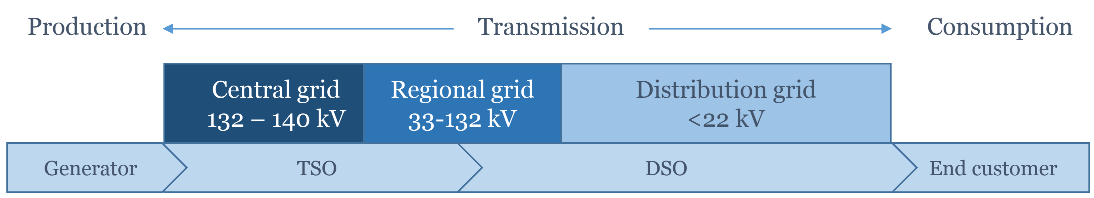

FIGURE 2.1: A graphical representation of the electricity grid and the actors involved

2.2.1 The Distribution Grid

The distribution grid can also be divided into several levels with decreasing voltage. A simplified representation, that will suffice for the use of this paper is presented in Figure 2.2. As can be seen, the distribution grid consists of many transformer stations, each supplying several substations, which in turn supply end consumers. A transformer station (TS) will usually supply a large geographical area, and consists of one or more transformers with a certain power capacity. The TS can run at a small overcapacity for a few hours at a time, but if the overcapacity is too large or occurs over a longer period of time, this will endanger the security of supply. So, usually if the geographical area supplied by a TS exceeds its power capacity the TS will need to be upgraded. This is a very costly investment. Similarly, the substations also have certain power capacities and these will be lower than that of the TSs. [10]

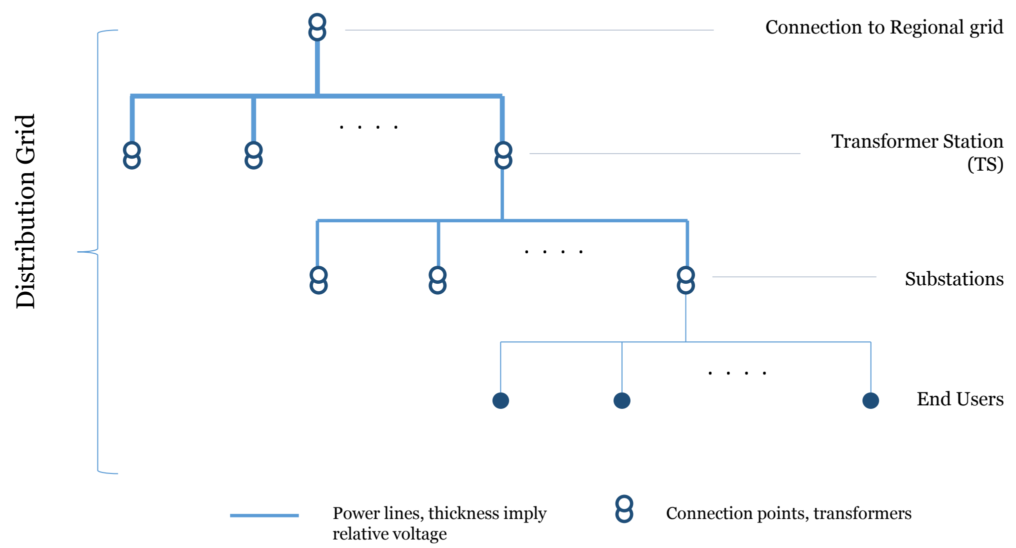

FIGURE 2.2: A graphical representation of the distribution grid

It is possible for substations to be supplied by several TSs. This can be used to balance the power consumption over the TSs, so that when one transformer station is at maximum capacity, some of the substations supplied by this can be supplied by another TS with excess load capacity. This is an important tool the DSOs use in order to avoid expensive upgrades. It will usually be cheaper to connect some substations to another TS instead of upgrading a TS. [10]

2.2.2 Monopoly Control of the DSOs

As previously mentioned, the DSOs are natural monopolies and are therefore subject to monopoly control from the NVE. This control includes requirements for the quality and reliability of the electricity delivered, the measuring of consumption and the design for calculating grid tariffs. Grid services must be offered in a way that does not discriminate any consumers, and the DSOs are obligated to serve all customers within their geographical area. An actor operating as a DSO cannot take on any other roles in the power market. However, a DSO can be vertically integrated with other actors in the power market. [9]

Furthermore, the NVE imposes an individual yearly income cap for each DSO. The income of a DSO mainly comes from the grid tariffs paid by the customers, and the tariffs must be calculated in a way that the yearly income of the DSO does not exceed its income cap. The income cap is, among other things, based on the realised costs of the DSO and considers local cost driving factors such as climate, topography and settlement patterns.

In order to incentivizethe DSOs to minimize costs and thus minimize the grid tariffs paid by the consumers, the income cap is also based on the individual company's cost performance compared to that of the other DSOs. This is referred to as the cost norm. Currently, when calculating the income cap the costs of the specific company are weighted by 40 percent and the cost norm by 60 percent. [9]

An additional factor to the income cap is related to the occurrences of disruptions on the grid. This is done through the KILE (compensation for undelivered energy) scheme, which obligates the DSO to financially compensate its customers for any disruptions in the grid. Thus the net income of the DSO will be lowered from disruptions in the grid. The compensation considers the duration and the time of day of the disruption.[9]

2.2.3 Future Challenges for the DSOs

Over the last decades there has been a dramatic increase in Norwegian energy and power consumption, and this trend is likely to continue. Many initiatives to reduce the Norwegian CO_2 production have lead to an increased demand for electric energy. An example that is believed to contribute heavily to this is the increased use of electric vehicles (EVs). As the electricity production in Norway comes from 99 percent hydro power, and thus produces no CO_2 emissions, EVs are a great alternative to fuel driven vehicles. Technological advancements enable the production of more energy efficient appliances, but many of these have a higher power consumption. Examples include induction ovens and heat pumps. The development of electricity and power consumption have both been increasing, but the maximum power imposed on the grid has increased even more rapidly than the total electricity consumption. This is demonstrated by Figure 2.3. Note that there is a distinction between electricity and power consumption. Electricity consumption refers to the total amount of energy used and is measured in kWh. Power consumption refers to the energy consumed per time unit and is measured in kW. The maximum power consumption over a given period is often called the peak load.

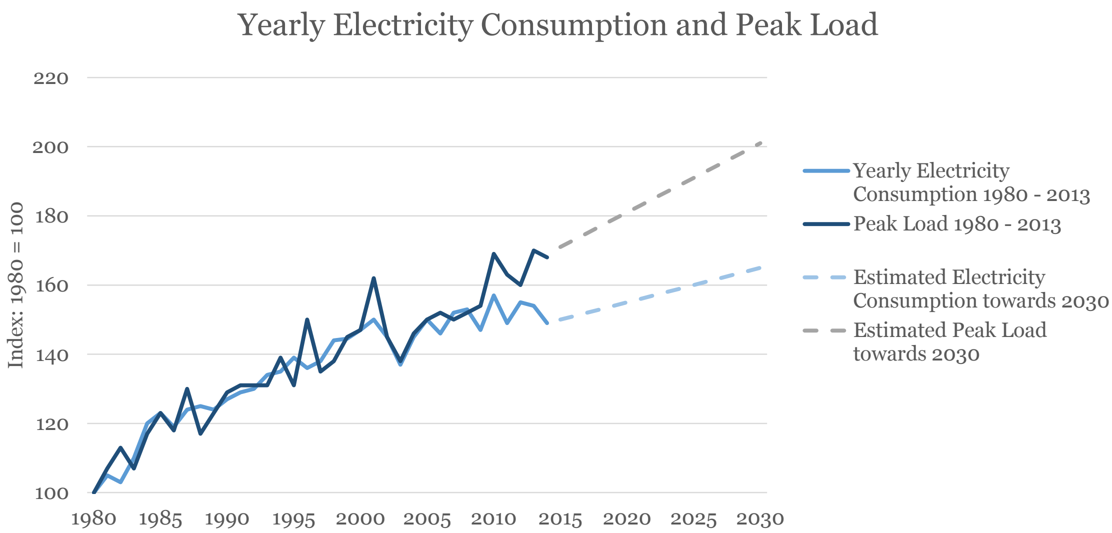

FIGURE 2.3: A graphical representation of the development of electricity consumption and peak load in Norway

The electricity grids have local limitations to the amount of power they can supply and the grids must be dimensioned to withstand the highest peak load of the year. Otherwise the grid can experience voltage loss or even power outages when the peak load occurs. Therefore, the increase in peak load poses a challenge for DSOs, as they will be required to facilitate this increase while still maintaining a secure grid.

A possible, but costly solution to this challenge is to reinforce the grid to withstand a higher maximum load. However, the load imposed on the grid varies greatly depending on the time of day and time of year, which implies that the grid is rarely used to its maximum capacity. A suggested solution uses this fact and is based on using demand side flexibility to even out the power consumption throughout the day and thereby reducing the maximum power requirement of the grid.

2.3 Demand Response

Demand side flexibility, or demand response (DR), is a term used to describe that consumers change their electricity consumption from their normal consumption pattern as a result of a given incentive. [11]. The flexibility can come from reducing or removing a load, or from shifting a load. A load shift means that the total energy consumption remains the same, but the load is moved in time to a time where power consumption is lower. Demand response can be provided by all electricity consumers, and they are often referred to as suppliers of flexibility. Demand response utilizing the flexibility of household consumers will in this paper be referred to as *residential demand response*. Demand response is used to some degree in Norway today. However, it is assumed that there is a large unused potential in DR, and that it can be used to reduce the peak loads in the grid. There are many different ways to categorize demand response and the categorization to be used in this text will be presented in the following.

2.3.1 Direct VS Indirect Control of Demand Response

Indirect control of demand response describes flexibility where the electricity consumer is in control of its own consumption and flexibility is supplied as a response to incentives given by the DSO or a third party actor, such as an aggregator. The signal is most likely a price signal, such as power based grid tariffs.[6] Indirect control is used in Norway today in the shape large electricity consumers being subject to power based grid tariffs. NVE are currently considering introducing power based grid tariffs for all consumers, as a part of the AMI roll-out. [12]

Direct control of demand response describes flexibility as a result of someone other than the electricity consumer taking control over one or more loads and remotely changes the load profile of the consumer when needed. This type of control requires additional equipment in order to enable the remote control. [6]

In this text demand response aggregation will be assumed based on direct control. The author believes that this makes for a more predictable supply of flexibility, which is crucial if the flexibility is to be used to its full potential by actors like the DSOs. For instance, an aggregator offering a peak load reducing service to a DSO, must be able to specify the amount of flexibility it will be able to provide at a given time, in order for the service to be useful for the DSO. The aggregator is believed to be much better equipped to specify this amount in advance, and ensure that this amount of flexibility is realised, if the aggregator has direct control of the flexible loads.

2.3.2 Scheduled VS Conditional Reprofiling

Demand response can be offered to potential buyers through many different types of services. It is common to separate between two different modes of selling the flexibility, Scheduled and Conditional Reprofiling (SRP and CRP).

Scheduled Reprofiling entails that the buyer and seller of flexibility agree upon a specified amount of flexibility to be provided at a given time. The seller is bound to deliver this reduction in consumption. [13]

The case of *Conditional Reprofiling* is quite similar to the SRP, but the predetermined power reduction needs to be triggered by the buyer in order to be activated by the supplier. The buyer will pay a fixed price determined by the amount of flexibility it wishes to reserve at a given time, and an additional fee will be charged if the buyer chooses to utilize the flexibility in the end. The buyer will be able to trigger the flexibility at short notice, for instance an hour ahead. [13]

The two forms of reprofiling are suitable for different types of suppliers. Typically industrial firms will depend on being able to schedule their production some time ahead, and so are mainly suited for supplying flexibility for SRP. Households, on the other hand, can provide more time flexible loads and will be able to deliver a power reduction quickly, making them suitable for CRP. Businesses are likely to have loads suitable for both types of reprofiling.

2.3.3 Loads Used for Demand Response

Different types of consumers have a consumption characterized by different types of loads, and different types of loads have varying suitability for demand response. He et al [6] categorize loads into four different types.

Storable loads are characterized as having the electricity consumption of the load decoupled from the use of the appliance causing the load. Examples include charging of electric vehicles and boilers. Storable loads are highly suited for demand response as their power consumption can easily be shifted to reduce peak loads and they often have a high power consumption.

Shiftable loads are unable to store energy, but the use of the loads can be shifted without affecting the user. An example is dish washers. These loads are also suited for demand response, but not as much as the storable loads.

Curtailable loads are not storable nor shiftable. These loads can be altered or moved in time, but not without affecting the user. Therefore these loads are not very suited for demand response.

Base loads are non-curtailable loads, meaning that they cannot be altered or shifted. An example is the burglary alarm of a household or a commercial building. These loads are not to be used for demand response.

The relationship between the different types of loads are showed i figure 2.4.

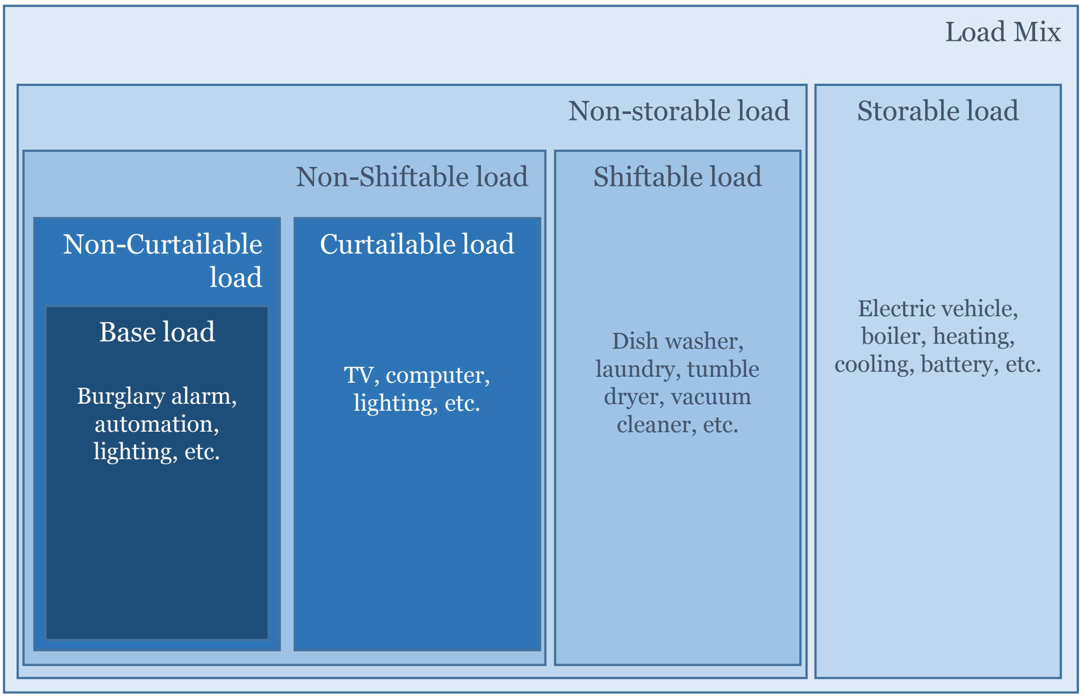

FIGURE 2.4: The relationship between the different types of loads

2.3.4 Previous Research Within DR in Norway

This section is based on a recent report from THEMA Consulting Group [14] that has reviewed the current activities in Norway within demand response and consumption management. It includes research and development projects, demo projects and solutions already implemented in the market. The report was written on request from the NVE and is a part of a project aiming to map the potential of customer participation as a result of the smart meter roll-out. THEMA obtained information through conducting interviews with the project leaders and written documentation. There were in total 18 activities included in the report, and they were chosen in cooperation with NVE. The selection was intended to be representative of the activities within demand response in Norway.

The majority of the projects are concerned with the supply side of demand response. Common interest areas are the incentives required to acquire flexibility, and how much flexibility it is possible to procure.

Implemented Activities

The currently implemented solutions primarily entail efficient energy consumption services directed towards large energy consumers such as commercial and municipal buildings. These types of consumers have had hourly energy readings and power based tariffs for years. Indirect demand response is present, but in a low degree. A cooperation between LOS and Enfo is in the process of offering an aggregator service to offer flexibility from large consumers in the regulatory market.

Some current solutions are directed towards households. At the time of the report the Norwegian DSO Eidefoss were the only DSO to have implemented power-based tariffs to all their customers, including households and cottages. They had not experienced any change in consumption on an aggregated level, but had not conducted enough analyses to determine if there were certain smaller areas where consumption was adapted to the new tariffs. There is an increase in products aimed towards energy consumption management. Suppliers of these products include Norwegian actors, with Lyse at the forefront, and the international actors Google and Apple.

Research and Demo Projects

Most of the research and demo projects considered by THEMA were focused towards reducing peak loads in households and cottages. A consistent characteristic when household consumers were in charge of the loads, was that they were unaware of the difference between energy and power. Most power reductions were a consequence of a general reduction on energy consumption, and there are few signs of shifted loads. When direct demand response is used there appears to be a relevant amount of flexibility potential from households. However, the projects have a limited scope and the participating households are not necessarily representative for the average household when it comes to willingness to provide flexibility.

Areas Not Covered by Current Activities

The report points out some areas where THEMA have observed little to none research being done so far. The focus of current activities is directed towards the technical potential of demand response, and how to trigger a technical potential. In general, there is a lack in quantification of the potentials of demand response. Little documentation can be found on the volumes of flexibility that has been experienced, both in implemented and research activities, and the value that flexibility has created for the power market. Knowledge about the realisable amount of flexibility, efficient business models and the value of flexibility for actors in the power market will be essential if demand response is to be evaluated as a viable alternative to grid reinforcements.

Chapter 3

The Value of Demand Response for a DSO

As highlighted by the THEMA report previously referred to, there have been few activities concerned with quantifying the potential values of utilizing demand response, both in Norway and internationally. The aim of this thesis is to make a contribution to quantifying the value of demand response for a DSO through evaluating contracts between an aggregator and a DSO. The applications of demand response are complex, and as a consequence, so are the potential values of it. In order to understand where the values of demand response lie for a DSO, it is necessary to identify the different ways DR can benefit a DSO and analyse each value adding component.

3.1 Potential Uses for Demand Response Aggregation for a DSO

As technological advancements pave the way for an increased use of demand response, there are many benefits that can be extracted by a DSO. The following will look at the potential services an aggregator can offer a DSO and the potential values of the services. There are many potential business models for how the services can be sold to the DSO, but this section will only focus on the end result of the service provided. The section is inspired by a master's thesis written by Q. Lambert [15].

3.1.1 Peak Load Shaving

Peak load shaving is the reduction of peak loads in the grid through demand response. The reduced peak load will entail a more stable load profile.

Postponed investments due to reduced peak load

As mentioned, the DSOs are obligated to supply electricity to everyone within their geographical area. They also need to provide a secure grid that can handle the peak load on the grid. As peak loads are expected to rise, many DSOs must be prepared to make expensive investments in their grids in order to handle this increase. However, demand response can be used to reduce the peak loads, and thereby postpone the need for these investments. This benefit is assumed to be of the greatest value to a DSO, considering the high costs associated with grid reinforcements.

Postponed investments due to reduced abrasion on the grid

The power grid will experience more abrasion from an unstable power profile with large differences in maximum and minimum power used. Demand response can be used to even out the power usage throughout the day, and thus reduce the wear on the grid. This may in turn delay the need for grid maintenance. This effect is assumed to be relatively small, due to the fact that the majority of maintenance activities on the grid are caused by factors unrelated to power consumption, such as the weather, falling trees and animals.[16]

3.1.2 Distributed Generation Supply Optimization

The increased use of DG and ”prosumtion” will lead to more unpredictability in the supply and demand. A DSO could benefit from aggregated demand response that adapts the consumption curve to the production from the DG. The following presents different ways DG supply optimization can create value for a DSO.

Reduced losses and congestion in the grid

When DG makes the power input in the grid unpredictable, there is a higher risk that the power input and outtake from the grid does not match. This will cause strain on the grid and may lead to KILE-costs for the DSO if disturbances in the grid occur. Demand response could contribute to reducing these costs.

Potential for independent microgrids

The Norwegian geography includes many small secluded areas with a low population. For instance, the Norwegian coast is filled with small islands, many of which are connected to the grids on the mainland. These areas are often unprofitable to supply as the low population generates little tariff income, but still causes grid costs. There is a possibility that these areas could be cut loose from the grid and be self sufficed if they are supplied by DG and the power consumption is adapted to the DG output by demand response. [10] This potential cost saving is at present time only hypothetical, as there are issues concerning regulations, service obligation and the lack of a model for running a local power market.

3.2 Grid Investments

Before evaluating the potential of postponed investments in the grid it is important to understand how grid companies plan investments. As mentioned earlier, both transformer stations and substations have load capacities and may have the need for an increase in capacity. There are higher costs associated with increasing the capacity of TSs than substations.[10] Planning investments is a complex task and final decisions about making investments often happen a short time ahead, especially with regards to increasing power capacity. Because these investments are very expensive, the DSO wishes to postpone such investments as long as possible. The possibility that an area can be supplied from several transformer stations causes that one can not isolate one transformer station to calculate when it will need to be reinforced. It must be seen in context with the other TSs that can supply parts of the same area. The DSO will typically avoid making overlapping investments. [10]

Due to the design of the income cap imposed by the NVE the DSO is compensated more for the development of new lines than for reinforcing existing lines. It is therefore often preferable to relieve one TS by connecting some substations to other transformers with excess capacity, rather than upgrading the TS.[10] This complicates any to attempt to calculate how much it is possible to postpone investments and simplifying assumptions must be made.

Chapter 4

Modelling the Cost and Benefit of Demand Response

The previous chapter explained the various ways in which demand response can be of value for a grid company. This implies that there may be a business opportunity for an aggregator to provide a flexibility service to a DSO in order to actualize the potential value. The purpose of this thesis is to evaluate possible contracts between an aggregator and a DSO, and in order to do this their respective cost and benefit functions must be established. This chapter and the next is inspired by a masters thesis written by Stine Berntsen and Hege Vatn [17]. Their thesis was concerned with contracts offered by a buyer of flexibility to a seller. Some of their formulations and methods have been used as a starting point in order to model the cost and benefit of supply, and later on to evaluate different contracts. Improvements and adaptations have been made in order to fit with the purpose of this thesis. This chapter will present general expressions for the cost and benefit functions of flexibility, and provide methodologies for how they can be quantified.

This thesis models the cost and benefit functions on an hourly basis. Also, they are estimated for times of high demand of flexibility, as this is when the flexibility is likely to be traded. For the DSO this will entail that their benefit curve is based on the value of demand response in times of peak load. For the suppliers it implies that the cost of flexibility is based on them having a high discomfort of giving it up.

4.1 Cost Function for Suppliers of DR

This section will provide a general expression for the cost function of a supplier and propose a method for modelling an aggregator. Also, the section will provide numerical estimations of the cost coefficients for different types of suppliers.

4.1.1 Factors Influencing the Cost

The cost of supplying demand response is difficult to quantify and depends on many aspects. For many suppliers the cost is not only monetary. For instance, for many households the largest cost of providing flexibility will be a decrease in comfort. The most important factors influencing the cost of flexibility are listed below.

- Volume
- Duration
- Timing
- Individual willingness of the supplier

An obvious factor affecting the cost is the *volume* of flexibility supplied. As mentioned in Chapter 2, different types of loads have varying suitability for DR. Intuitively, the loads that are best suited for demand response will be the first to be used, such as storable and shiftable loads. In order to provide larger volumes of flexibility the supplier must use less suitable, and thereby more expensive, loads.

Another important factor is the *duration* and *timing* of the flexibility. At times of the day when the electricity consumption is high, suppliers are likely to value their flexibility higher. For the purpose of this thesis, it is assumed that flexibility will be used at times of high electricity consumption, and the cost function does not use the timing as a variable. Also, the cost will increase with the duration of the reduction of a load. This has been simplified in this thesis, and the proposed cost function will be independent of the duration of the curtailment.

Finally, suppliers will have individual preferences and *willingness* to supply DR. This can take into account how they value non-monetary factors. For a household this can represent the loss in comfort from providing flexibility, while for an industrial manufacturer it can represent the inconvenience of having to alter a production schedule. The following model for the cost curve will only be a function of volume and willingness, and the duration and timing have already been fixed to one hour at a time of high demand for flexibility. This will be taken into account in the estimations of the cost coefficients.

4.1.2 Cost Function and Supply Curve

The cost function to be presented will express the cost as a function of the volume of flexibility and the willingness of the individual supplier. The cost functions will be different for different types of suppliers. This thesis differs between households, businesses and industries. The cost $C_s(\theta_s, x_s)$ of curtailing a load of x_s kW for a supplier with willingness θ_s is proposed to be given as

$$C_s(\theta_s, x_s) = a_s x_s^2 - b_s(1 - \theta_s)x_s \qquad \forall s \in S \tag{4.1}$$

In this function a_s and b_s represent the cost coefficient for the supplier and will be the same for all suppliers of the same type. θ_s represents the supplier's willingness to supply flexibility and will be a number in the interval [0, 1]. This will be individual for each supplier within the same type and a high willingness is conveyed through a high θ_s. In this thesis θ_s is assumed to be uniformly distributed. The general shape of the cost curve using a polynomial function is presented in Figure

4.1. The convex shape of the cost curve exemplifies how higher volumes of flexibility will call for the curtailment of more expensive loads. In reality the flexibility supplied cannot exceed the total consumption of the supplier. This is not ensured by this estimation of the cost curve, but it is assumed that the rising costs will prevent a solution where that situation occurs. It is however important to do a reality check of calculations using this cost curve to ensure that the quantity supplied is reasonable.

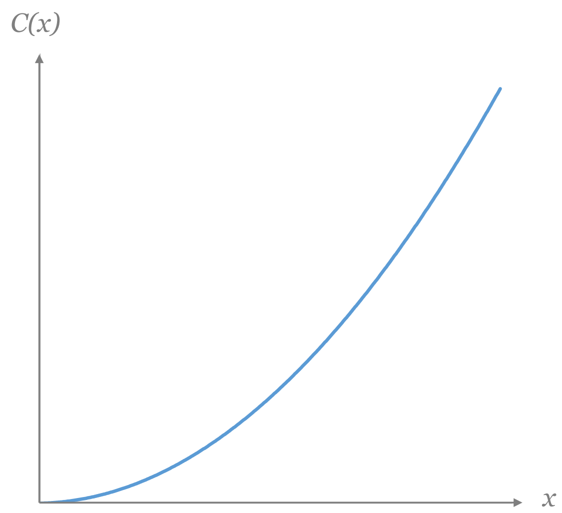

FIGURE 4.1: The cost curve of flexibility supplied

4.2 Quantifying the Cost

Quantifying the cost of demand response is a comprehensive and complex task. As mentioned, not all costs are monetary and the valuation of these will be individual to each supplier. There are few existing implemented projects that can help reveal the true cost suppliers have for their flexibility, and so more theoretical approaches must be used. Kjølle [18] presents a method for quantifying the cost of energy not supplied (CENS) by combining different kinds of surveys conducted among electricity consumers. One could use a similar approach to estimate the cost coefficients of flexibility for different types of consumers. Kjølle presents three types of surveys that can be used for this purpose:

- *Direct Worth* maps the respondent's direct costs associated with providing different volumes of flexibility
- *Willingness-to-pay* will reveal the amount the respondent is willing to pay to avoid providing the flexibility
- *Willingness-to-accept is* will make the respondent specify the monetary compensation it will require in order to provide the flexibility

A combination of at least two different surveys should be used in order to make a more precise estimation. The willingness-to-accept survey, is considered a very appropriate survey type to determine the cost curve of a supplier, because it will be representative of what an aggregator will have to pay a supplier to get it to offer its flexibility.

4.2.1 Estimation of the Cost Coefficients

In lack of having access to such surveys conducted to determine the cost curve of different suppliers, an approximation is made by using the results presented by Kjølle [18] for the CENS-rates. The article presents the results of two surveys, Direct Worth and Willingness-to-pay, in order to determine the cost of electricity not supplied for different types of customers. The mean of the two surveys for the customer types defined for this thesis is presented in Table 4.1.

	Average CENS
Industry	70.5
Business	99.6
Household	8.6

Table 4.1: Results from surveys estimating CENS

The CENS represents the cost in cases where the consumer loses electricity entirely. This will be different from supplying flexibility, where only a part of the electricity consumption is reduced or shifted. However, as the volume of flexibility supplied increases, so will the discomfort of the supplier and the cost of providing flexibility will start to approach the CENS-rate. In order to estimate the cost of flexibility , the CENS-rates are scaled in order to reflect different volumes of flexibility supplied. The calculations behind the estimates can be found in Appendix A.2, and the resulting coefficients are presented in Table 4.2.

	Estimated a	Estimated b
Industry	0,0868	0,7221
Business	1,4795	1,0788
Household	0,7593	0,0641

Table 4.2: Cost coefficients for the different types of flexibility suppliers

4.2.2 Modeling an Aggregator

In order to model the cost curve of an aggregator it is possible to represent the aggregator as a the sum of its suppliers. The aggregator's cost curve can easily be derived by horizontally adding those of its suppliers. Each supplier of the aggregator will be defined as one of the three consumer types and the cost curve of each supplier will be estimated using the cost coefficients in Table 4.2. This will be a simplification as the suppliers in the aggregator's portfolio may not have the exact cost curves as given by Table 4.2. However, the estimate is believed to be increasingly appropriate as the number of suppliers of each type increases.

The aggregator is likely to be engaged in contracts with its suppliers so that the suppliers have achieved some profit and not just covered their costs. Therefore the cost of procuring flexibility will likely be higher than just the sum of the costs of the suppliers. In addition to the cost of procuring flexibility from its suppliers, the aggregator is likely to have some variable costs associated with running its business and managing loads. These costs are not taken into account in this thesis for the sake of simplicity.

Since the purpose of this thesis is to consider the relationship between an aggregator and a DSO it is important to note that when considering peak load reducing services an aggregator can offer a DSO the geographical location of each supplier will be relevant. In the case study to be presented in Chapter 7, the method of modeling an aggregator's cost curve presented in this section will be used.

4.3 Benefit Function for Buyers of DR

A benefit function describes how actors in the power grid value flexibility. Just as in the case of the cost function the benefit for a buyer will depend on many different factors. These factors are primarily the same as for the cost, with the exception of the willingness factor, which is not relevant for the benefit of the buyer. The benefit curve is also modeled on a one hour basis and for a time of high demand for flexibility. The benefit function will only be a function of the volume of flexibility.

The benefit $B_j(x_j)$ for buyer j of having access to an amount x_j kW of flexibility is assumed to be given by

$$B_j(x_j) = -\alpha_j x_j^2 + \beta_j x_j \qquad \forall j \in J \tag{4.2}$$

where α_j and β_j are the value coefficients for the buyer. Both coefficients will take values above zero. The negative sign in front of the α implies that a higher α will give a lower benefit, and the positive sign of the β cause a higher beta to give a higher benefit. The value coefficients will be individual for each buyer. However, the general shape of the benefit function will be the same for all buyers and is illustrated in Figure 4.2.

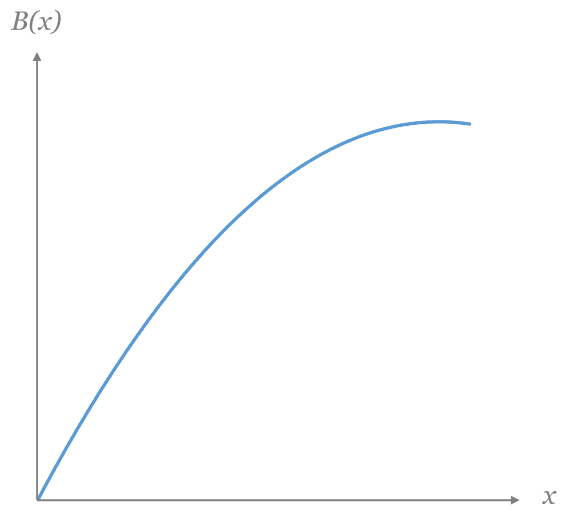

FIGURE 4.2: The benefit curve of flexibility supplied

The concave shape shows that for small amounts of flexibility can give great benefit, and the benefit per kW decreases as the total volume increases. Eventually the volume of flexibility will reach a point where the benefit has reached a maximum. In the case of a DSO this will be when the amount of flexibility exceeds both the present and forecasted over consumption in the grid.

4.4 Quantifying the Benefit

This thesis is only concerned with how a DSO values flexibility, and not the other actors in the power system. Chapter 2 discussed different benefits and uses DR can provide a DSO. Using a net present value model the benefit $B_G(x)$ for a DSO of x kW of flexibility is formulated as

$$B_G(x) = I - (1 - \rho(x))I - \frac{\rho(x)I}{(1+i)^{n(x)}} + \Delta C_{ENS} + \Delta C_R \tag{4.3}$$

In this model I represents the cost of a postponed investment and $\rho(x)$ is the percentage of the investment that can be postponed, given a certain amount of flexibility available, x. i is the discount rate and $n(x)$ is the amount of years the investment can be postponed. Furthermore, the model includes the reduced costs of energy not supplied, ΔC_{ENS}, and the reduction in costs related to operational reliability, ΔC_R. For the purpose of this paper the two latter reduced costs are neglected, as the value of postponed investments is believed to be the greatest. Note that the model considers the possibility that only a fraction of the investment is postponed.

This section has briefly presented an approach to quantifying the benefit of a DSO, but will not provide numerical estimates. That will however be presented in the case study in Chapter 7, along with a more thorough explanation of the method.

Chapter 5

Contract Design for Scheduled Reprofiling

There are many different options for how one can trade flexibility in order to extract its potential value. This thesis will explore a contractual approach, where a supplier of flexibility enters a bilateral contract with a buyer of flexibility. Different contracts will allocate the profit and risk differently. The purpose of this chapter is to provide a basis for identifying the optimal contract an aggregator can offer a DSO for different information scenarios. The supply chain for trading flexibility when including an aggregator is presented in Figure 5.1.

FIGURE 5.1: A visualization of the flexibility value chain

This thesis will not consider the contractual relationship between the flexibility suppliers and the aggregators. Tthe simplified value chain that will be considered in this thesis is presented in Figure 5.2, where the aggregator is considered a supplier of flexibility.

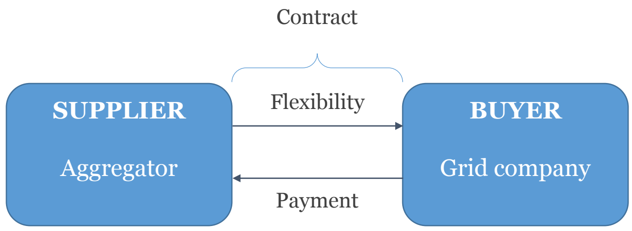

FIGURE 5.2: A visualization of the simplified flexibility value chain

This chapter will apply principal agent theory where the principal, here the supplier, is to design and offer a contract to the agent, here the buyer, who will accept or reject the contract. The buyer must design the contract based on its available information about its own cost structure and the buyer's willingness to pay for the flexibility. The contract types to be evaluated in this chapter are:

- Profit sharing contract
- One-part linear contract
- Two-part linear contract
- Non-linear contract

Optimal contracts are usually difficult to achieve in reality due to incomplete information. Both parties of the value chain can have private information concerning their costs or benefits, implying information asymmetry. Also, it is possible for costs or benefits to be uncertain for both participants. It is likely that different contracts should be chosen for different information scenarios. The information scenarios that will be considered are:

- Complete Information
- Uncertain Information
- Asymmetric Information

Not all contracts will be considered for all information scenarios. For each scenario the author has made a selection of contracts it believes to be relevant. For instance, non-linear contracts are used to handle information asymmetry, and will only be evaluated for that specific information scenario.

A factor affecting the contract design is the duration time of the contracts. Contracts can be long-term and short-term. The author believes that an aggregator designing a contract to offer a DSO should use a long-term contract. Since the majority of the benefit of flexibility for the DSO is believed to come from postponed investments, the DSO will need to be assured that they will be able to utilize the flexibility over a longer period of time, most likely until they decide to carry out the grid reinforcement. Contracts can also be designed as a one-time offer or as a repeating offer. This will affect the behaviour of the participants and also how an optimal contract should be designed. In this thesis the time perspective and the repetitiveness of the contracts will not be considered in the contract design. The contracts will be evaluated on a more general basis.

The contract design to be presented in this thesis is based on the assumption that both supplier and buyer act in order to maximize their own profit. Furthermore, it is assumed that the supplier is always able to deliver the volume of flexibility it has sold. This is a rough assumption, as there is a risk that the supplier is not able to deliver the agreed upon volume, and should be subjected to a penalty fee in such a case. This is, however, not considered here. Although this thesis is focused on contracts an aggregator can offer a DSO, the derived expressions are generalized to apply to any supplier and buyer of flexibility. This chapter will present and evaluate contracts for scheduled reprofiling, while chapter 6 will be concerned with the case of conditional reprofiling.

The purpose of the following derivations is to express the optimal contracts and their resulting variables through the cost and value coefficients. For some contracts it is also necessary to define probability distributions and reservation profits. The optimal contracts and their resulting variables have been found using the same method as Corbett and Tang [19]. The solution steps will be explained for the contracts as the solutions are presented.

5.1 Contract Design with Perfect Information

In the scenario of perfect information, both parties have full information of the cost and benefit curves. This implies that the supplier will know the response of the buyer to any contract it proposes, and is able to design optimal contracts. Such situations rarely occur in reality, but numerical results from these contracts can be used to compare and assess the performance of contracts in other information scenarios.

This section will study three different contracts. They are profit sharing, one-part linear and two-part linear and are denoted C1, C2 and C3, respectively.

5.1.1 Profit Sharing, C1

In a profit sharing contract the supplier of demand response offers the buyer a share, $1-\rho$, of the total value chain profit they achieve, which is given as

$$\pi_{VC,C1} = -\alpha x^2 + \beta x - ax^2 - b(1-\theta)x \tag{5.1}$$

where a,b and θ are the cost coefficients and willingness parameter of the supplier, and α and β are the value coefficients of the buyer. The maximization problem for the supplier, who gets a share ρ of the profits, becomes

$$\max \pi_{S,C1}(x) = \rho\pi_{VC,C1} \tag{5.2}$$

The maximization problem for the buyer, who gets a share $1-\rho$ of the profits, is given as

$$\max_{x} \pi_{B,C1}(x) = (1-\rho)\pi_{VC,C1} \tag{5.3}$$

Since both parties receive a predetermined percentage of the value chain profits, they will both maximize their own profit if they maximize the value chain profit. The optimal volume of flexibility is found by setting the derivative of the value chain profit with respect to x equal to zero, and solving for x. This yields

$$x^*_{VC} = \frac{\beta - b(1-\theta)}{2(a+\alpha)} \tag{5.4}$$

The same value for x^* would be found by using the same method to maximize the individual profits of the supplier or the buyer, given by (5.2) and (5.3). It is apparent that the volume traded is independent of ρ, as explained previously. Because a high benefit of flexibility for the buyer is characterized by a low α and a high β, the optimal volume will understandably increase when α decreases or β increases. Similarly, x^*_{VC} will increase when the cost of flexibility decreases, which is when a and/or b decrease or θ increases. The value chain profit expressed by the cost and value coefficients is obtained through substituting (5.4) into (5.1), giving

$$\pi_{VC,C1} = \frac{(b(1-\theta)-\beta)^2}{4(a+\alpha)} \tag{5.5}$$

As with the optimal volume, the value chain profit is expected to increase when the benefit increases or the cost decreases. Also, ρ does not affect the value chain profit, but it determines how the profit is distributed between the two parties. The value of ρ will be determined based on the bargaining power the two parties exert on each other. In the case of an aggregator offering a contract to a DSO, the aggregator is believed to have some power from being the one designing the contract. The bargaining power of the DSO will depend on what other options it has. For instance, if there exists competing suppliers that can offer the DSO a sufficient amount of flexibility, it will have a higher bargaining power than if the aggregator is the only supplier of flexibility operating in the area.

Note that the optimal volume found in this scenario will always be the volume that optimizes the value chain profit, and will give an upper bound to the value chain profit it is possible to achieve in other contracts and information scenarios.

5.1.2 One-Part Linear, C2

In a one-part linear contract the supplier presents a wholesale price, w, to the buyer and the buyer will determine the amount of flexibility it wishes to buy, x, based on the wholesale price. The supplier will determine w based on the maximization problem:

$$\max_{w} \pi_{S,C2}(w) = wx - ax^2 - b(1-\theta)x \tag{5.6}$$

It also knows that the buyer will decide its purchased amount based on the optimization problem:

$$\max_{x} \pi_{B,C2}(w) = -wx - \alpha x^2 + \beta x \tag{5.7}$$

This implies that the optimal volume of flexibility, x^*, purchased by the buyer for any given w is found by setting the derivative of the buyer's profit with respect to x equal to zero and solving for x

$$\frac{\partial \pi_{B,C2}}{\partial x} = -w - 2\alpha x + \beta = 0 \tag{5.8}$$

which gives the following expression for x^*_{C2}.

$$x^*_{C2} = \frac{\beta - w}{2\alpha} \tag{5.9}$$

(5.9) clearly shows that a higher unit price will give a lower optimal volume. Also, a higher benefit, given by a lower α and a higher β, will lead to a higher optimal volume. These relationships are intuitive. In order to solve the maximization problem for the supplier we use the same method of solving the first order condition for w.

$$\frac{\partial \pi_{S,C2}}{\partial w} = -2ax - b(1-\theta) + w = 0 \tag{5.10}$$

By inserting for $x = x^*_{C2}$, the optimal w becomes

$$w^*_{C2} = \frac{\beta(a+\alpha) + \alpha b(1+\theta)}{a+2\alpha} \tag{5.11}$$

The expressions for the buyer and supplier profits given by the cost and value coefficients are not included because they are too long and untidy. They will therefore not provide any particular insight. However, through the expressions that have already been provided it will be simple to calculate the resulting profits in a mathematical solver, such as Microsoft Excel. An interesting relationship to study is the ratio between the buyer and supplier profit, $\frac{\pi_{S,C2}}{\pi_{B,C2}}$. Numerical analyses conducted in excel showed that for all values of a and α that were tested, the relationship was always greater than 2, indicating that the one-part linear contract leaves the majority of the profits to the supplier. This is not surprising, considering that the supplier is the one designing the contract.

5.1.3 Two-Part Linear, C3

In a two-part linear contract the supplier will present to the buyer a wholesale unit price, w, per kW of flexibility and a fixed lump sum, L, that the buyer must pay regardless of the amount of flexibility bought. The supplier's optimization problem becomes

$$\begin{aligned} \max_{w,L} \pi_{S,C3} &= wx - ax^2 - b(1-\theta)x + L \\ \text{s.t.} \qquad \pi_{B,C3} &\geq \pi_B^- \end{aligned} \tag{5.12}$$

where π_B^- is the reservation profit of the buyer. The buyer will only accept the contract if its profit is equal to or greater than its reservation profit. The participation constraint given in (5.12) is binding because in the case of perfect information the supplier will know the exact value of the reservation profit. The buyer will optimize its profit with respect to the amount bought.

$$\max_x \pi_{B,C3} = -wx - \alpha x^2 + \beta x - L \tag{5.13}$$

In this scenario the lump sum L will not affect the amount of flexibility decided by the buyer. Therefore the supplier can set L so that the buyer is only left with $\pi_{B,C3} = \pi_B^-$. This implies that the optimal solution for the supplier is to set w to induce the x that will maximize the value chain profit, which will equal that from (5.4). Thus the supplier must set w based on the following

$$x^*_{C3} = x^*_{VC} \tag{5.14}$$

Knowing that x^*_{C3} will be determined by the buyer the same way as in C2, gives

$$\frac{\beta - b(1-\theta)}{2(a+\alpha)} = \frac{\beta - w}{2\alpha} \tag{5.15}$$

Solving for w this gives the optimal unit price

$$w^*_{C3} = \beta - \frac{\alpha(\beta - b(1-\theta))}{(a+\alpha)} \tag{5.16}$$

The optimal lump sum payment L is obtained by setting

$$\pi_{B,C3} = \pi_B^- \tag{5.17}$$

which gives

$$-wx - \alpha x^2 + \beta x - L = \pi_B^- \tag{5.18}$$

Inserting for x^*_{C3} and w^*_{C3} and solving for L yields

$$L^*_{C3} = \frac{\alpha(\beta - b(1-\theta))^2}{4(a+\alpha)^2} - \pi_B^- \tag{5.19}$$

The supplier profit becomes equal to the value chain profit minus the reservation profit of the buyer.

$$\pi_{S,C3} = \frac{(b(1-\theta) - \beta)^2}{4(a+\alpha)} - \pi_B^- \tag{5.20}$$

Consequently, the two part linear contract with complete information will ensure that the value chain profit is maximized. The buyer of demand response makes a profit equal to its reservation profit and the supplier obtains the excess profit. The reservation profit of the buyer will be determined by other opportunities the buyer can choose from. In this way the reservation profit of the buyer can be regarded as a representation of its bargaining power.

In the case where the buyer is a DSO a reservation profit of zero will imply that the only two options the DSO has to manage its peak loads is to either reinforce the grid or purchase flexibility from the supplier offering the contract. If the DSO has other viable options this will be represented by a higher reservation profit.

5.2 Contract Design with Uncertain Information

As explained more thoroughly in section 3.2, grid investments are highly complex as areas of the grid are interlinked and can often be supplied by several transformer stations. Therefore it is realistic to assume that there is uncertainty linked to the value coefficients of the grid company. This section will take this uncertainty into consideration in the contract design.

The benefit of the buyer is assumed to be uncertain to both parties at the time the contract is designed and the buyer decides the volume to purchase, x^*. However the value coefficients are assumed to be *uniformly distributed* within a given interval, meaning:

$$\underline{\alpha} \leq \alpha \leq \bar{\alpha} \tag{5.21}$$

$$\underline{\beta} \leq \beta \leq \bar{\beta} \tag{5.22}$$

Additionally, the coefficients are assumed to be independent of each other. The distribution is known to both parties at the time the contract is designed, and it will not be revealed until after the flexibility has been utilized. The relationship between the value coefficients and the benefit is

$$B(\bar{\alpha}) \leq B(\alpha) \leq B(\underline{\alpha}) \tag{5.23}$$

$$B(\underline{\beta}) \leq \beta \leq B(\bar{\beta}) \tag{5.24}$$

This section will study the same contract types that were evaluated for complete information in order to compare how they are affected by the uncertainty. In this section the contracts will be denoted by U1, U2 and U3. The method for deriving the optimal contract terms has been very similar to the complete information scenario, so it will not be explained thoroughly in this section.

5.2.1 Profit Sharing, U1

When assuming that α and β are independent of each other the maximization problem for both buyer and supplier becomes

$$
\begin{aligned}
\max_x E_{\alpha,\beta}[\pi_{VC,U1}(x)] &= E_{\alpha,\beta}[-\alpha x^2 + \beta x - ax^2 - b(1-\theta)x] \\
&= \int_{\underline{\alpha}}^{\bar{\alpha}} \int_{\underline{\beta}}^{\bar{\beta}} -\alpha x^2 + \beta x - ax^2 - b(1-\theta)x \quad dF(\beta)dF(\alpha) \\
&= -E[\alpha]x^2 + E[\beta]x - ax^2 - b(1-\theta)x
\end{aligned}
\tag{5.25}
$$

The end expression in (5.25) is the same as the maximization problem for contract C1, except α and β have been substituted by their expected values. Therefore the optimal contract be be found in the exact same way as for C1, and this gives the optimal volume as

$$
x^*_{U1} = \frac{E[\beta] - b(1-\theta)}{2(a + E[\alpha])} \tag{5.26}
$$

The expected value chain profit is also given by the expression from contract C1, but using expected values for α and β. However, whenever α or β deviate from their expected value, the volume purchased will be sub-optimal and the value chain profit will deviate from its expected value. Due to the profit sharing contract the risk from the uncertain benefit is divided equally between the two parties.

5.2.2 One-Part Linear, U2

For the one-part linear contract the optimization problem for the buyer becomes

$$
\begin{aligned}
\max_x E_{\alpha,\beta}[\pi_{B,U2}(x)] &= E_{\alpha,\beta}[-wx - \alpha x^2 + \beta x \\
&= \int_{\underline{\alpha}}^{\bar{\alpha}} \int_{\underline{\beta}}^{\bar{\beta}} -wx - \alpha x^2 + \beta x \quad dF(\beta)dF(\alpha) \\
&= -wx - E[\alpha]x^2 + E[\beta]x
\end{aligned}
\tag{5.27}
$$

Which gives the optimal quantity purchased

$$x^*_{U2} = \frac{E[\beta] - w}{2E[\alpha]} \tag{5.28}$$

The supplier will use this information in order to decide its unit price, w, and the optimal unit price becomes

$$w^*_{U2} = \frac{E[\beta](a + E[\alpha]) + E[\alpha]b(1 + \theta)}{a + 2E[\alpha]} \tag{5.29}$$

It can be seen that the expressions for the optimal one-part linear contract are the same as contract C2, but with expected values of α and β. The nature of the one-part linear contract places all the risk caused by the uncertainty with the buyer. The buyer will choose a volume of x^*_{U2} paying a unit price of w^*_{U2}, which ensures the profit of the supplier to be independent of the true benefit of the buyer.

5.2.3 Two-Part Linear, U3

For the two previous contract types the difference between complete information and uncertainty has been that in the latter case one will need to use expected values of α and β. The two-part linear contract with uncertainty will also be very similar to the case with complete information. The supplier should present a contract with a unit price that equals its marginal cost when optimizing the profit of the entire value chain. The buyer will decide its optimal ordering quantity based on expected values of α and β. Thus, the optimal unit price becomes:

$$w^*_{U3} = E[\beta] - \frac{E[\alpha](E[\beta] - b(1 - \theta))}{(a + E[\alpha])} \tag{5.30}$$

However, there will be some difference when it comes to deciding the lump sum payment, L. This was previously used in order for the supplier to extract all value chain profits less the reservation profit of the buyer. In this case the profit of the buyer is uncertain due to the uncertainty in α and β, and so if L is decided using expected values the buyer will not be guaranteed to make its reservation profit.

The supplier will therefore need to chose if it should offer a contract that gives the buyer an *expected profit* equal to its reservation profit, or if the contract should guarantee the buyer a profit of *at least* the reservation profit. Which of the two alternatives the supplier should choose will be decided by the buyer's attitude towards risk and if there is uncertainty linked to the reservation profit as well.

Risk Neutral

If the buyer is assumed to be risk neutral, the contract design becomes very simple, and will be as in the complete information scenario, only using expected values. The lump sum offered to a risk neutral buyer becomes

$$L^*_{U3,RN} = \frac{E[\alpha](E[\beta]-(1-\theta))^2}{4(a+E[\alpha])^2} - \pi_B^- \tag{5.31}$$

In this scenario the risk is placed entirely with the buyer, just as in the one-part linear contract.

Risk Averse

If there exists a situation where the buyer is risk averse and has a reservation profit based on a risk free option, the supplier will need to offer a contract that guarantees a profit larger than the reservation profit. Consequently, the lump sum must be set so that the buyer obtains its reservation profit when the benefit of flexibility proves to take its lowest value. According to (5.23) and (5.24) this will be when $\alpha = \bar{\alpha}$ and $\beta = \underline{\beta}$. This gives

$$L^*_{U3,RA} = \frac{\bar{\alpha}(\underline{\beta}-(1-\theta))^2}{4(a+\bar{\alpha})^2} - \pi_B^- \tag{5.32}$$

In this case the supplier will have to give up some profit to the buyer in order to get it to take on the risk from uncertainty. The higher the risk, indicated by a larger interval for α and β, the more profit the supplier must give up. If the risk is too large, the supplier may end up with a negative profit, and will not be willing to supply the flexibility.

For a DSO, a reservation profit based on a risk free option could for example be to extend its grid lines. An area running at under-capacity can be connected to the area in question in order to take on some of the load and relieve the area in question.

5.3 Contract Design with Asymmetric Information

The term asymmetric information is used of information scenarios where one or both parties have some private information that is not known to the other party. In these cases the participants can exploit the information asymmetry to increase their own profit. When doing so, an actor is said to be acting opportunistically. A consequence of such behaviour is *adverse selection*, and an example of this will be presented later in this chapter.

This section will design contracts for a situation where the benefit coefficients of the buyer, α and β are unknown to the supplier. The supplier does not know the exact value of the value coefficients, but knows their probability distribution. The range of α and β is given as $[\alpha_H, \alpha_L]$ and $[\beta_L, \beta_H]$. The subscripts H and L are used to denote a high and low benefit, implying that

$$B(\alpha_L) \leq B(\alpha) \leq B(\alpha_H) \tag{5.33}$$

$$B(\beta_L) \leq B(\beta) \leq B(\beta_H) \tag{5.34}$$

The notation for the upper and lower bound of value coefficients used in the previous section could also have been used here. However, in order to separate the two information scenarios and to avoid confusion in the following derivations, this new notation was chosen. The supplier will be modeled as a Bayesian expected utility maximizer, meaning that it will act in a way that maximizes its expected profit.

In this section a non-linear contract will be used as a way of managing the asymmetric information. The one-part linear contract has not been assessed for this scenario, as it previously has performed worse than the two-part linear contract. Therefore, the author believes that it will be sufficient to asses a profit sharing contract, a two-part linear contract and a non-linear contract. The contracts are denoted A1, A2 and A3, respectively.

5.3.1 Profit Sharing, A1

In the presence of asymmetric information, profit sharing contracts tend to become inefficient. The contract form gives the buyer a chance to act opportunistically and lie about its benefit of flexibility. From the supplier's perspective the maximization problem becomes

$$\begin{aligned} \max_x E_{\alpha,\beta}[\pi_{VC,A1}(x)] &= E_{\alpha,\beta}[\alpha x^2 + \beta x - a x^2 - b(1-\theta)x] \\ &= \int_{\alpha_H}^{\alpha_L} \int_{\beta_L}^{\beta_H} \alpha x^2 + \beta x - a x^2 - b(1-\theta)x \quad dF(\beta)dF(\alpha) \end{aligned} \tag{5.35}$$

By choosing a sub optimal volume the buyer can indicate a lower benefit of flexibility than it actually has, and then lie about the profit it has made. Then the buyer will be left with a higher profit than it would if it were honest about its benefit, but the value chain profit will decrease. If the buyer chooses to indicate a difference from the real α and β equal to $\Delta\alpha$ and $\Delta\beta$ the buyer obtains a profit equal to

$$\pi_{B,A1} = (1-\rho)E[\pi_{VC,A1}] + \Delta\alpha x + \Delta\beta x \tag{5.36}$$

Note that in order to give an impression of a lower benefit the buyer must indicate an α that is higher than actual and a β that is lower than actual.

5.3.2 Two-Part linear, A2

Under asymmetric information, the buyer still sits with full information, which implies that the buyer still determines its purchased quantity as it did in the case of complete information. This implies that the volume chosen by the buyer is given as

$$x^*_{A2} = \frac{\beta - w}{2\alpha} \tag{5.37}$$

The supplier on the other hand does not sit with full information and is faced with the following maximization problem

$$\begin{aligned} \max_w E_{\alpha,\beta}[\pi_{S,A2}(w)] &= E_{\alpha,\beta}[wx - ax^2 - b(1-\theta)x + L \\ &= \int_{\alpha_H}^{\alpha_L} \int_{\beta_L}^{\beta_H} wx - ax^2 - b(1-\theta)x + L \quad dF(\beta)dF(\alpha) \end{aligned} \tag{5.38}$$

The supplier does no longer know the benefit curve of the buyer and can no longer determine w to maximize VC profit and then use the lump sum L to extract the profits except the reservation profit of the buyer. Instead, it must for every value of w determine the highest L that is guaranteed to satisfy the buyers reservation profit for all values of α and β. This will mean that even if the buyer has its lowest possible benefit it must earn its reservation profit. This will be when $\alpha = \alpha_L$ and $\beta = \beta_L$. This implies

$$\begin{aligned} L(w) &= -\alpha_L x^2 + \beta_L x - wx - \pi_B^- \\ &= -\alpha_L(\frac{\beta_L - w}{2\alpha_L})^2 + \beta_L(\frac{\beta_L - w}{2\alpha_L}) - w(\frac{\beta_L - w}{2\alpha_L}) - \pi_B^- \end{aligned} \tag{5.39}$$

Now the supplier can determine the w that maximizes its expected profits. Using (5.35) and inserting for x and L, the objective function is given as

$$\begin{aligned}
\max_{w} E_{\alpha,\beta}[\pi_{S,A2}(w)] =& \int_{\alpha_H}^{\alpha_L}\int_{\beta_L}^{\beta_H} wx - ax^2 - b(1-\theta)x + L \quad dF(\beta)dF(\alpha)\\
=& \int_{\alpha_H}^{\alpha_L}\int_{\beta_L}^{\beta_H} w(\frac{\beta-w}{2\alpha}) - a(\frac{\beta-w}{2\alpha})^2 - b(1-\theta)(\frac{\beta-w}{2\alpha})\\
&+ L \quad dF(\beta)dF(\alpha)\\
=& - a(\frac{E[\beta^2]-2wE[\beta]-w^2}{4E[\alpha]})\\
&+ (w - b(1-\theta)(\frac{E[\beta]-w}{2E[\alpha]})) + L\\
=& - a(\frac{E[\beta^2]-2wE[\beta]-w^2}{4E[\alpha]}) + (w - b(1-\theta)(\frac{E[\beta]-w}{2E[\alpha]}))\\
&+ \alpha_L(\frac{\beta_L-w}{2\alpha_L})^2 + \beta_L(\frac{\beta_L-w}{2\alpha_L}) - w(\frac{\beta_L-w}{2\alpha_L}) - \pi_B^-
\end{aligned} \tag{5.40}$$

The optimal w is found by solving the first-order condition for w and results in the following:

$$w^*_{A2} = \frac{-\frac{aE[\beta]}{2E[\alpha^2]} - \frac{E[\beta]-b(1-\theta)}{2E[\alpha]} + \frac{\beta_L}{2\alpha_L}}{-\frac{a}{2E[\alpha^2]} - \frac{1}{E[\alpha]} + \frac{1}{2\alpha_L}} \tag{5.41}$$

Due to the information asymmetry, the supplier will set w in a way that causes a sub-optimal value chain profit in order to maximize its own. If the interval of α and β is too large, the lump sum may become so high that the supplier will earn a negative profit. In that case, the supplier will not be willing to offer the contract, and the trade will not take place. This will be an example of how *adverse selection* can cause market failure by reducing the size of or eliminating the market entirely.

5.3.3 Non-Linear, A3

Previous examples show that under asymmetric information there may be an opportunity for a buyer with a high benefit level to increase its profit by acting as a buyer of low benefit. This is the problem with linear contract forms. The purpose of a non-linear contract is to create a contract that does not create such an opportunity.

For the sake of simplicity, the non-linear contract is shown with the assumption that the benefit curve can take one out of only two shapes, a high benefit, B_H, or a low benefit, B_L. The probability of each shape is known to the supplier.

$$B(x, \alpha_H, \beta_H) = -\alpha_H x^2 + \beta_H x \qquad \text{with probability } v \tag{5.42}$$

$$B(x, \alpha_L, \beta_L) = -\alpha_L x^2 + \beta_L x \qquad \text{with probability } 1 - v \tag{5.43}$$

The supplier must, based on the knowledge it has, design a *menu of contracts* where each contract specifies a volume, x, and a payment, y, it will require in order to provide that volume. The maximization problem of the supplier will then be to maximize the expected profits of the contract menu.

In the case with only two possible benefit curves, the menu of contracts will need to consist of two contracts. These will be defined by (x_H, y_H) and (x_L, y_L). The maximization problem for the supplier becomes

$$\max_{(x_H, y_H);(x_L, y_L)} E[\pi_{S,A3}] = v(y_H - C(x_H) - (1 - v)(y_L - C(x_L)) \tag{5.44}$$

In each scenario the profit of the buyer must be at least equal to its reservation profit.

$$-\alpha_H x_H^2 + \beta_H x - y_H \geq \pi_{B,H}^- \tag{5.45}$$

$$-\alpha_H x_L^2 + \beta_L x - y_L \geq \pi_{B,L}^- \tag{5.46}$$

Incentive compatibility constraints are introduced in order to make sure that the buyer will be honest about its benefit. This is ensured through constraints (5.47) and (5.48).

$$-\alpha_H x_H^2 + \beta_H x_H - y_H \geq -\alpha_H x_L^2 + \beta_H x_L - y_L \tag{5.47}$$

$$-\alpha_L x_L^2 + \beta_L x_L - y_L \geq -\alpha_L x_H^2 + \beta_L x_H - y_H \tag{5.48}$$

The buyer with a high benefit is able to obtain a utility above its reservation profit by pretending to have a low benefit. Therefor the supplier has to give up an *information rent* in order to make the buyer be honest about its benefit curve. In the optimization model the profit of the supplier, which is to be maximized, can be formulated as the value chain profit less the information rent.

In order to simplify the presentation of the model we express the information rent paid to the buyer types as the following

$$U_H = -y_H - \alpha_H x_H^2 + \beta_H x_H \tag{5.49}$$

$$U_L = -y_L - \alpha_L x_L^2 + \beta_L x_L \tag{5.50}$$

Further, we define the difference between the value coefficients of the buyers as

$$\Delta\alpha = \alpha_L - \alpha_H \tag{5.51}$$

$$\Delta\beta = \beta_H - \beta_L \tag{5.52}$$

Using these expressions the optimization problem for the supplier can be expressed with $(x_L, U_L); (x_H, U_H)$ as variables. The model becomes

$$\begin{aligned}\max_{(x_L,U_L);(x_H,U_H)} \pi_{S,A3} =& v(-\alpha_H x_H^2 + \beta_H x_H - a x_H - b(1-t)x_H) \\ &+ (1-v)(-\alpha_L x_L^2 + \beta_L x_L - a x_L - b(1-t)x_L) \\ &- vU_H - (1-v)U_L\end{aligned} \tag{5.53}$$

subject to

$$U_H \geq \pi^-_{B,H} \tag{5.54}$$

$$U_L \geq \pi^-_{B,L} \tag{5.55}$$

$$U_H \geq U_L + \Delta\alpha x_L^2 + \Delta\beta x_L \tag{5.56}$$

$$U_L \geq U_H - \Delta\alpha x_H^2 - \Delta\beta x_H \tag{5.57}$$

where (5.54) and (5.55) are the participation constraints and (5.56) and (5.57) are the incentive compatibility constraints.

In order to solve the optimization problem it is necessary to identify the binding constraints of the optimal solution. The buyer with a high benefit has the opportunity to act as a buyer with a low benefit and receive a greater profit, but the reverse will not be a possibility for the buyer with a low benefit. Therefore the incentive compatibility constraint of the high benefit buyer will be binding, but not that of the low benefit buyer. Furthermore, the option for the high benefit buyer to imitate the low benefit implies that the participation constraint of the high benefit buyer is always satisfied, and that constraint will not be binding in an optimal solution. Thus, we are left with two binding constraints, (5.55) and (5.56). U_L and U_H can then be substituted into the objective function as

$$U_L = \pi^-_{B,L} \tag{5.58}$$

$$U_H = \pi^-_{B,L} + \Delta\alpha x_L^2 + \Delta\beta x_L \tag{5.59}$$

By solving the first order condition and using the definitions of U_L and U_H, (5.49) and (5.50), the optimal solution is found. The resulting menu of contracts is given as

$$x_H^* = \frac{\beta_H - a - b(1-\theta)}{2\alpha_H} \tag{5.60}$$

$$y_H^* = -\alpha_H (x_H^*)^2 + \beta_H x_H^* - \Delta\alpha (x_L^*)^2 - \Delta\beta x_L^* - \pi_{B,L}^- \tag{5.61}$$

$$x_L^* = \frac{v\beta_H - \beta_L + (1-v)(a + b(1-\theta))}{2(v\alpha_H - \alpha_L)} \tag{5.62}$$

$$y_L^* = -\alpha_L (x_L^*)^2 + \beta_L x_L^* - \pi_{B,L}^- \tag{5.63}$$

The profit of the supplier in the two scenarios can easily be found, and the expected profit will depend on the probability of each scenario, v and $1-v$.

$$\begin{aligned} E[\pi_{S,A3}] =& v(y_H^* - a(x_H^*)^2 - b(1-\theta)x_H^*) \\ &+ (1-v)(y_L^* - a(x_L^*)^2 - b(1-\theta)x_L^*) \end{aligned} \tag{5.64}$$

By adopting a non-linear contract approach the supplier is able to motivate the buyer to be honest about its true benefit. In order to do this the contract menu must be designed in a sub-optimal way, leading to a value chain profit that is lower than that for complete information. However, the supplier is expected to achieve a higher profit with a non-linear contract than with a profit sharing contract or a two-part linear contract.

Chapter 6

Contract Design for Conditional Reprofiling

The previous chapter was concerned with contract design in the case of scheduled reprofiling. Conditional reprofiling will require more complex contracts. In this case the DSO will potentially have to pay the aggregator twice, first for the reservation of the flexibility and second if the flexibility is to be activated. This way of trading flexibility is different from how most goods are sold, because the buyer does not necessarily receive the volume it has paid for, or reserved, which will be a more appropriate term in this case.

A CRP service would be beneficial for a DSO, as this would allow them to hedge against forecast errors, which are very common due to the large variations in power consumption. An important difference between the contracts for CRP and SRP is that it is only the CRP contracts that take into consideration that there is uncertainty linked to when the flexibility will be needed. This will in many cases be a more realistic portrayal of the buyer's situation, and it will lead to a lower value chain profit compared to the ones calculated using the contracts presented in the previous chapter.

For an aggregator there is a higher risk associated with providing a CRP service. In order to offer CRP the aggregator depends on suppliers of flexibility with a high responsiveness. As mentioned in Chapter 2 this can primarily be provided by households and, to some extent, businesses. The downside of these loads is that they are less reliable sources of flexibility than for instance a large factory. This increased risk of default would probably need to be reflected by higher prices for CRP than SRP. However, there is a possible upside for the aggregator as well. The reserved flexibility that is not activated by the DSO can potentially be sold in other markets for flexibility, and thus the aggregator has the opportunity to "sell the flexibility twice".

6.1 Ways to Offer CRP

CRP can be offered by the aggregator in many different variations, with varying possibilities for the DSO. This section will present some relevant forms of CRP. The different forms have been proposed and named by the author of this thesis, in lack of literature where different forms of CRP already had been defined.

Binary CRP

The simplest form of CRP will be a *binary* approach, where the DSO is only allowed to decide between activating all or none of the reserved volume of flexibility. This means that the DSO will be charged with the initial reservation fee, and will be subjected to an additional cost if it chooses to activate the flexibility.

Continuous CRP

The most flexible form of CRP is a *continuous CRP*. This entails that the DSO chooses how much of the reserved flexibility it wishes to activate, and will pay for that amount in addition to the initial reservation fee. This will imply that a contract for continuous CRP must specify an activation unit price.

A simplification of a continuous form would be a *discrete CRP*, where the DSO can choose between different fractions of the reserved amount to activate. A discrete CRP with only two possible fractions, 0 or 1, will equal the binary CRP.

6.2 Contract Design

This section will suggesti how a supplier of flexibility can design a contract to offer a CRP service to a buyer. The contract will be formulated in general terms with an unspecified supplier and buyer, but will discuss the contract from the perspective of an aggregator designing a contract to offer a DSO.

The author has chosen to use the two-part linear contract prsented in chapter 5 as a starting point, as this is regarded a simple and efficient contract in the case of full information. The contract will first be presented for a continuous CRP service and then be altered to fit a binary CRP service.

In order to design such a continuous CRP contract the following constants and variables would need to be defined.

Variables to be determined by the supplier:

- L Lump sum
- w Unit reservation cost
- t Unit activation cost

Variables to be determined by the buyer:

- x Volume of flexibility to reserve

Other variables:

- y The volume that will need to be activated where y is a stochastic variable in the interval $[0,x]$ with some known probability function $f(y)$.

Constants:

α, β Value coefficients

a, b Cost Coefficients

θ Willingness to supply

The corresponding profits of using such a contract form would be given as

$$\begin{aligned} E[\pi_{S,CRP}] &= E[L + wx + ty - ay^2 - b(1-\theta)y] \\ &= L + wx + \int_0^x f(y)(ty - ay^2 - b(1-\theta)y) \quad dy \end{aligned} \tag{6.1}$$

$$\begin{aligned} E[\pi_{B,CRP}] &= E[-L - wx - ty - \alpha y^2 + \beta y] \\ &= -L - wx + \int_0^x f(y)(-ty - \alpha y^2 + \beta y) \quad dy \end{aligned} \tag{6.2}$$

To design the optimal contract of this form would be complicated. A simplification would be to perform a discretization of the y and use a scenario approach where one defines a set number of scenarios with an activated volume, y, and a probability of that specific scenario. This thesis will present a contract for the simplest case of such a scenario approach, which will be a contract for a binary CRP service.

6.2.1 Binary CRP Contract Under Complete Information, B1

The following will present a contract design that is similar to a two-part linear contract, but it accounts for the possibility for the buyer to choose if it wishes to activate the reserved volume of flexibility or not. Because it is a contract for a binary CRP service the buyer can only choose between activating *all* or *none* of the flexibility. The author has named the contract form a *binary CRP contract*. For simplicity, the contract will be evaluated for a case of complete information only.

With a binary CRP contract the supplier offers the buyer a fixed lump sum payment, L, a unit reservation price, w, and a unit activation price, t. The buyer will in turn select a volume of flexibility, x. The probability of the flexibility being activated is given as v.

The maximization problem for the supplier becomes

$$\max_{w,t,L} E[\pi_{S,B2}] = L + wx + v(-ax^2 - b(1-\theta)x + tx) \tag{6.3}$$

Note that the supplier will be guaranteed the lump sum and reservation profit, regardless of activation, but the activation price and the cost of flexibility only apply if the flexibility is activated by the buyer. As in the cases of Chapter 5, the inclusion of a lump sum payment will allow the supplier to set unit prices to maximize the value chain profit, and then use the lump sum to extract all the profit less the buyer's reservation profit.

The value chain profit is given by

$$E[\pi_{VC,B2}] = v(-\alpha x^2 + \beta x - ax^2 - b(1-\theta)) \tag{6.4}$$

Since the expected value chain profit is the same as in Chapter 5, except it is scaled by v, the optimal value of x remains the same.

$$x^*_{VC} = \frac{\beta - b(1-\theta)}{2(a+\alpha)} \tag{6.5}$$

For simplicity it is assumed that whenever the buyer activates the flexibility it achieves the benefit of the full amount of flexibility. The buyer's maximization problem is then given as

$$\max_x \pi_{B,C3} = -L - wx + v(-\alpha x^2 + \beta x - tx) \tag{6.6}$$

Solving the first order condition for x will give the volume chosen by the buyer as

$$x^*_{B,B2} = \frac{(\beta - t) - \frac{w}{v}}{2\alpha} \tag{6.7}$$

To optimize its profit the supplier must set w and t so that

$$x^*_{B,B2} = x^*_{VC} \tag{6.8}$$

$$\frac{(\beta - t) - \frac{w}{v}}{2\alpha} = \frac{\beta - b(1-\theta)}{2(a+\alpha)} \tag{6.9}$$

This gives the following relationship between w and t.

$$w = v(\frac{\alpha(b(1-\theta) - \beta)}{a+\alpha} + \beta - t) \tag{6.10}$$

As long as the relationship between w and t is according to 6.10, their actual values will not affect the expected value chain profit or the total expected amount paid by the buyer to the supplier. Neither will they affect the value of L. The lump sum will be determined by setting $E[\pi_{B,B2}] = \pi_B^-$ and will be given as

$$L = -wx + v(-\alpha x^2 + \beta x - tx) - \pi_B^- \tag{6.11}$$

Since w and t are set to induce a specific x, L is independent of those two. In this way it can be said that the supplier will find w by determining a value for t. How t is set will, as mentioned, not alter the expected profits of the parties. However, it will affect how the payments from the buyer to the supplier are divided between being paid up front and after a potential activation of the flexibility. Analyses performed by the author in excel showed that when t is increased w will decrease and the up front payment decreases.

It is likely that the supplier will wish to receive as much as possible of the payment up front and the buyer will wish to postpone the payment. This is among other things due to the time value of money, and this will become more important if the time between the reservation payment and the activation payment is long. Other motives for the buyer to wish to postpone the payment until after activation can be tied to its liquidity.

As v increases, so does the value chain profit, and thus the profit of the supplier. This is intuitive, because the more likely it is that the DSO will need to activate the flexibility, the higher the expected benefit will be. The case where $v = 1$ will yield the same result as the two part linear contract under full information from the previous chapter.

Determining v would be a complex calculation for the DSO. It would have to consider the probability of errors in its forecasts and evaluate when it would be more profitable to utilize the flexibility than accepting the costs of grid congestion. In this example the probability of activation is assumed known to both parties, but would probably be private information to the DSO, just as α and β.

6.3 SRP Combined with CRP

As explained in Section 2.3.2 there is a difference in how well different loads are suited for SRP and CRP. Also, even though industrial suppliers are the best suited suppliers for SRP because they can provide large volumes of flexibility, one can also use businesses and households for this purpose. However, most industrial suppliers will not be able to supply CRP, because that will interfere too much with their production. This implies that an aggregator will generally be able to supply larger amounts of flexibility for SRP than CRP. In order to offer CRP services the aggregator must have access to a substantial amount of households and businesses.

It can be a good solution for an aggregator to offer both CRP and SRP services. This way an aggregator could use its suppliers to provide the type of flexibility they are best suited for and thereby achieve an efficient utilization of its supplier portfolio. This will also benefit the DSO which will be able to create an optimal mix of the two services. The DSO is likely to want to buy SRP to reduce power consumption that will incur with high certainty, and CRP could be used as a buffer in case the consumption proves to be higher than expected.

In this way the aggregator may be able to increase its sales and obtain a higher profit by offering both SRP and CRP services. In return the DSO will reduce its risk of buying too much or too little flexibility.

Chapter 7

Case Study - TrønderEnergi Nett

The purpose of this case study is to provide numerical examples of how flexibility contracts may work in practice. Also, this case study is an attempt to reveal the potential value an aggregator and a DSO can obtain from postponed investments in the grid due to a reduced peak load. This chapter will evaluate the suggested contracts for a specific planned investment by TrønderEnergi Nett. The author has in cooperation with TrønderEnergi identified a geographical area that will be suitable for a study on residential DR. The residential area used for the case study is Storhaugen, located near the centre of Trondheim.

7.1 TrønderEnergi Nett

TrønderEnergi Nett is one of the largest DSOs in the area of Trønderlag. It is responsible for the regional grid in the county of Sør-Trønderlag and the distribution grid in nineteen municipalities. In total they supply ~140 000 consumers and their grid consists of 49 transformer stations and ~4500 substations. TEN is a vertically integrated company in TrønderEnergi, which also acts as a retailer and a generator.

7.1.1 The Reference Rate

I order to use the NPV model to valuate a postponed investment, it is necessary to identify a suitable discount rate. The discount rate is meant to represent the time value of money, and will differ from firm to firm. TEN usually utilizes the NVE reference rate when considering future investments. [10]

The NVE reference rate is determined yearly by the NVE and is used in calculating the income cap for each DSO. NVE states that it regulates the DSOs so that they on average experience a payoff equal to the reference rate, and that is the discount rate that will be used in this case study. The reference rate for 2014 has been used and this was set to 6,61 %.[20]

7.2 Storhaugen

For the case study on Storhaugen the author will estimate how much the cost of a specific investment can be reduced by postponing the investment using residential demand response. All historical data concerning the consumption at Storhaugen has been provided by TrønderEnergi Nett, and are included in Appendix A.1. Where calculations are based on estimates or assumptions made by TEN analysts, this will be stated.

7.2.1 Consumption

At Storhaugen, TEN supplies a residential area of approximately thirteen thousand end consumers, primarily household consumers. As can be seen in Figure 7.1, household consumers constitute the majority of both number of consumers and yearly energy consumption. The other consumers are mainly commercial buildings such as various office and business spaces. The yearly energy consumption for Storhaugen was ~220GWh in 2014 and the energy consumption has increased over time. For the purpose of future calculations, the number of households at Storhaugen is set to 12 500.

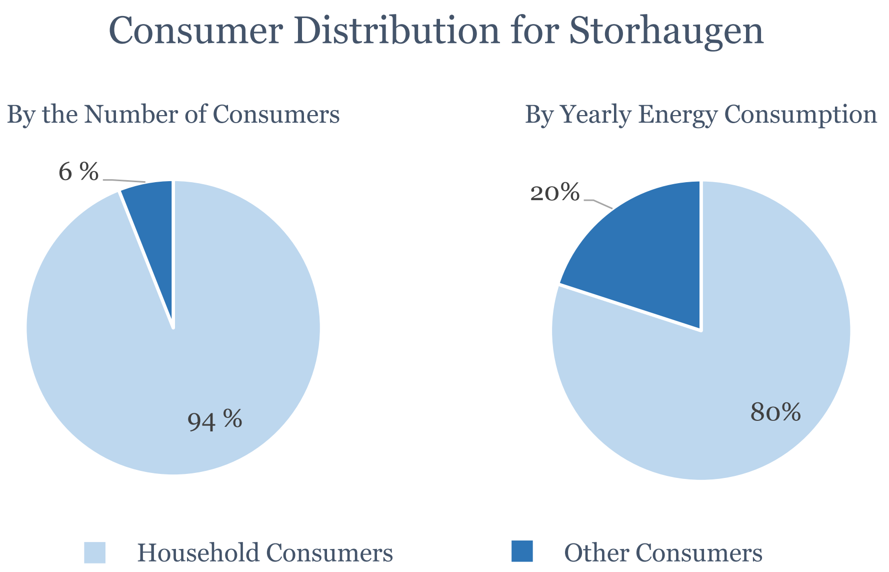

FIGURE 7.1: A graphical representation of the consumers at Storhaugen

The load curve for an average day at Storhaugen is assumed to follow a standard household consumption pattern with peaks in the morning and evening, when people are home and awake. [21] This is illustrated in 7.2. There has been an increase in the peak load over the past years and the maximum power load experienced the past years is on 63MW. This peak load equals a power consumption of approximately 4kW per household at Storhaugen.

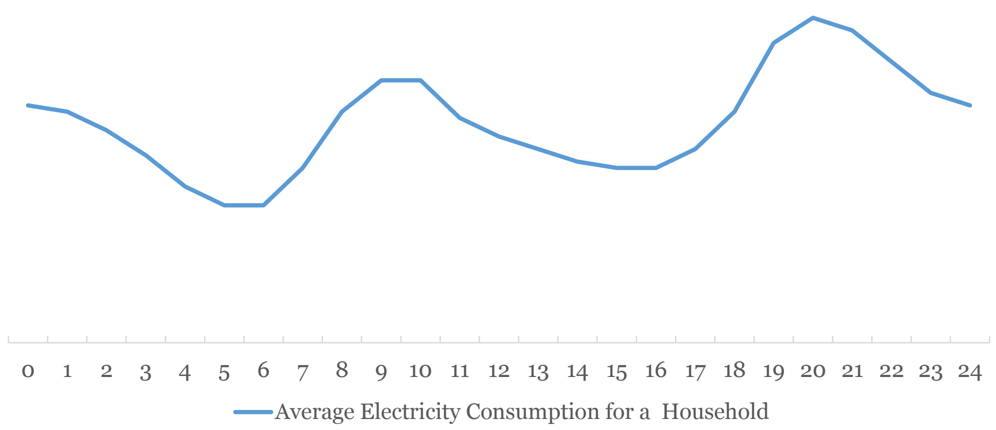

Figure 7.2: The electricity consumption of an average household throughout a regular day

7.2.2 Load Capacity

Storhaugen is supplied by a transformer station consisting of three transformers with a load capacity of 20MW each, implying a total load capacity of 60MW for Storhaugen. Some of the substations at Storhaugen are also connected to neighbouring transformer stations at Flatåsen, and this is used to reduce the load on the Storhaugen station in times of peak load.

As the yearly peak load is currently of 63MW, Storhaugen is run at overcapacity. The only reason TEN has been able to postpone investments so far has been due to the ability to use excess capacity from the Flatåsen transformer station.

7.2.3 Consumption Development and Planned Investments

Previous forecasts done by TEN for the time period 2014 to 2030 assumed no increase in the peak load at Storhaugen. This estimate however, is being revised by analysts in TEN as this is not considered a realistic development. [21]

As mentioned, the planning of grid investments is a complex task as there are many ways of handling a transformer at overcapacity. Still, TEN estimates that if the peak load at Storhaugen follows their revised forecasts, there will be a need to increase the capacity of the Storhaugen station on 2018. An increase in capacity will require upgrading at least one of the three transformers at Storhaugen. Upgrading one transformer from 20MW to 25MW will have a cost of approximately 5 MNOK. [21]

7.3 Estimation of the DSO's Value Coefficients

The value coefficients of TEN will be derived through estimating how long given amounts of flexibility can postpone the investment at Storhaugen of 5 MNOK. By adjusting peak load forecasts with the available flexibility, it is possible to estimate how much one can postpone the investment of upgrading the transformer station at Storhaugen. The estimation is made using a linear growth forecast in the peak load and setting a fixed peak load cap that determines when the investment will be made. This will make it simple to determine how long a given amount of flexibility can postpone the investment compared to if flexibility is not utilized at all. The Figure 7.3 visualises how this method is used. For the sake of the following calculations, it is assumed that the upgrade will need to be made in the year the forecasted peak load at Storhaugen passes 65MW.

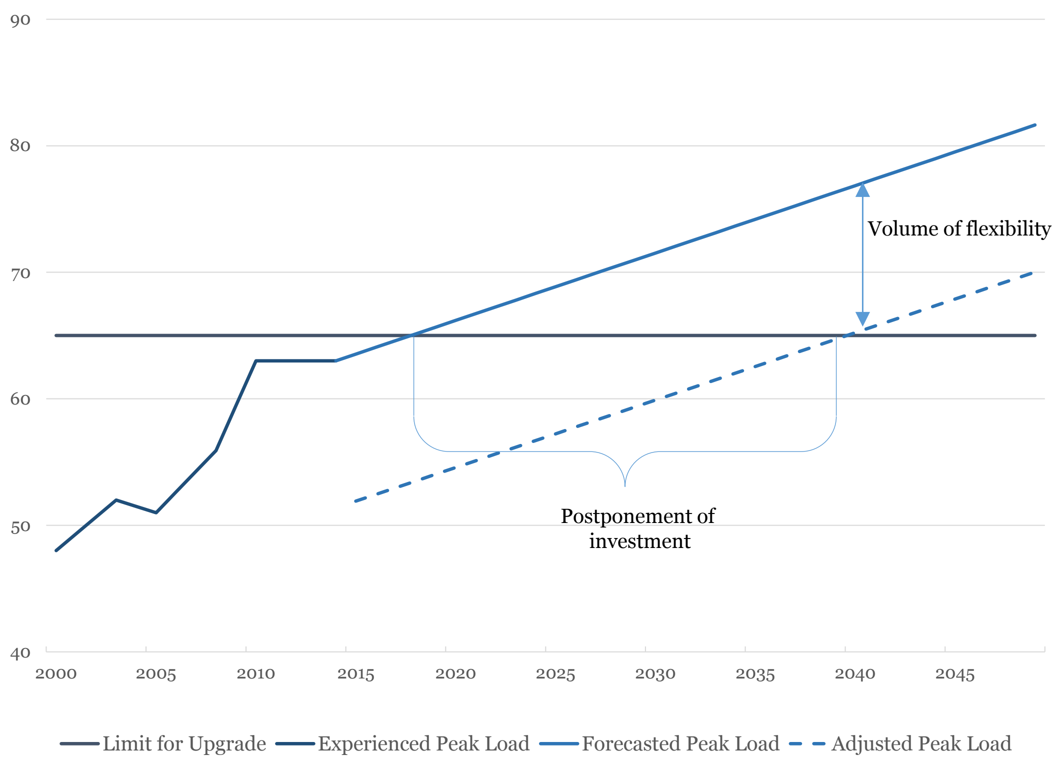

FIGURE 7.3: A visualization of the estimation of postponed investments

Due to the linear growth forecast the relationship between years of postponement and the amount of flexibility was also linear, and it was approximated that the number of years of postponement was given as $n(x) = 0.002x$. Since the investment of 5MNOK could not be divided, the full investment was postponed, implying that $\rho(x)$ from the NPV model was equal to 1. After determining the postponement for given amounts of flexibility, the postponements are valued using the NPV-model and weighted for how many hours of flexibility it is assumed to be needed. This will be determined by how many hours in a year the consumption is expected to be above grid capacity. The benefit coefficients obtained from this estimation is presented in Table 7.1. All calculations are presented in Appendix A.2.

Estimated α	Estimated β
0.0002	6.9731

TABLE 7.1: Value coefficients for TEN at Storhaugen

Reservation Profit

In addition to the value coefficients it will be necessary to determine a potential reservation profit of the DSO. The way the value of flexibility is determined by comparing the costs of upgrading the TS at Storhaugen to that of utilizing DR. The model does not take into account the possibility of extending grid lines to connect Storhaugen to other transformer stations with excess capacity. This option can be represented using the reservation profit. The costs of such an extension to Storhaugen have not been explored in this thesis and the reservation profit is set somewhat randomly. Its purpose is primarily illustrative. For the SRP contracts the hourly reservation profit is set to 10 000 NOK, which equals a yearly reservation profit of 730 000 NOK. In the CRP contract the reservation profit is set lower, because the expected value chain profit of this case is lower due to the contract taking uncertainty in demand into account. The hourly reservation profit for the CRP contract is set to 5000 NOK.

SRP Contracts	CRP Contract
10 000 NOK	5 000 NOK

Table 7.2: Hourly reservation profits for TEN at Storhaugen

7.3.1 Modeling Uncertain and Asymmetric Information

For the cases of uncertain and asymmetric information the intervals for α and β have been given as symmetrical intervals round the estimated values of α and β with an interval radius of 10% of the estimated value. This indicates a relatively low uncertainty for each value coefficient, but as the uncertainty concerns two independent coefficients, the resulting sample space is vast. The values for the upper and lower bounds on α and β are the same for uncertain and asymmetric information, but they are represented through different notation. Table 7.3 presents the boundaries of α and β for the uncertain information scenario and Table 7.4 for asymmetric information.

	Alpha	Beta
Lower Bound	$\underline{\alpha} = 0,00018$	$\underline{\beta} = 6,27579$
Upper Bound	$\bar{\alpha} = 0,00022$	$\bar{\beta} = 7,67041$

TABLE 7.3: Range of the value coefficients with uncertainty of 10%

	Alpha	Beta
Low Benefit	$\alpha_L = 0,00022$	$\beta_L = 6,27579$
High Benefit	$\alpha_H = 0,00018$	$\beta_H = 7,67041$

TABLE 7.4: Range of the value coefficients with uncertainty of 10%

Furthermore, in the case of uncertain information, this thesis has presented two approaches to setting the lump sum payment in a two-part linear contract. The two approaches differ in how they regard the buyer's attitude towards risk. Section 5.2.3 explains why an aggregator may be thought of as a risk averse, and under what assumptions this should be done. However, for the results presented in this chapter TEN is considered to be risk neutral. This is because it is thought of as a profit maximizing firm, which will engage in several flexibility contracts. Furthermore, it is not reasonable to assume that the saved cost of expanding their grid lines to Storhaugen compared to reinforcing the TS is known to TEN without uncertainty. Therefore, an expected profit higher than their reservation profit will suffice for them to accept a contract.

7.3.2 Estimation Errors

The value coefficients are based on several simplifications and assumptions that may be sources of error. Some of these will be explained in the following.

The most important simplification that has been made when estimating the benefit curve of TEN is that it does not consider the fact that for each additional year the investment can be postponed there will be one more year where TEN will need to purchase flexibility. The benefit curve modeled in this thesis will imply that the postponement will be achieved by purchasing flexibility only for a year. This is a highly inaccurate representation of reality. However, it would be very complex to create a valuation model that considers the aforementioned fact, especially because it would have to consider the time value of money. In spite of the flaws of the benefit curve estimated in this thesis, it is believed that the results are indicative of the potential profits. The yearly value resulting from the simplified benefit curve will in fact be representative of the total value of the postponement that can be extracted over the number of years it is possible to postpone the investment. Furthermore, the results will still be adequate in order to compare the efficiency of the different contract types.

The way the benefit coefficients are calculated assumes that in all the hours the grid runs at overcapacity it is overloaded with an amount equal to the amount of flexibility x. This is a rough assumption made for simplicity and in reality the overload will range from very small volumes and at the maximum equal the overload of the peak load.

The estimations have been based on there being 73 hours a year where flexibility is needed. This number has been based on there being 5% of the days in a year with peak-load, and each of these days the loads last for 4 hours. The hourly value coefficients will be greatly affected by changing the number of days with peak load per year, but the total value of the flexibility traded will still be the same.

The forecasts of peak load are sources of uncertainty. The peak load is assumed to grow linearly, but the growth could possibly be more rapid due to energy efficient technology, such as an expected increase in the use of electric vehicles. This is not considered by the linear forecast model. Also the modeling of when it will be necessary to upgrade the load capacity of Storhaugen was simplified. This would not only depend on the development of the load at Storhaugen, but also the development of the load at Flatåsen, as this area is used to relieve the load at Storhaugen. The need for investments in one area is heavily influenced by the neighbouring areas and investments made in these. Thus it is not correct to set a precise peak-load limit for when the investment at Storhaugen will be necessary. This is not considered in the simulations performed in this paper.

Finally, the savings caused by postponed investments in the grid are considered a direct earning for the DSO. In reality reduced costs do not necessarily equal increased earnings for the DSOs due to the income cap. Therefore, in order to provide a more accurate benefit curve it would be necessary to analyse how the reduced costs will affect the income cap in order to find the net value for the DSO.

7.4 Estimation of the Aggregator's Cost Coefficients

Chapter 4 presented the method used in this thesis for how to model the cost curve of an aggregator. The aggregator at Storhaugen is modeled as being comprised of 12 500 households, and the remaining consumers at Storhaugen have not been considered. The resulting cost coefficients are presented in Table 7.5 and calculations are found in Appendix A.2. The θ is assumed to equal 0.5 because the aggregator is comprised of a large amount of suppliers with an expected θ of 0.5.

Estimated a	Estimated b	θ
0.00006	0.1282	0.5

TABLE 7.5: Value coefficients for the aggregator at Storhaugen

7.4.1 Estimation Error

The cost curves have been simulated using CENS-rates and scaling them for different volumes of flexibility supplied. The scaling has been decided by the author, and the resulting cost coefficients were highly affected by the scaling. The cost coefficients are exposed to error both from the assumption that CENS-rates will be comparable to flexibility costs and the scaling factors that were set.

The aggregator has been modeled to have access to all 12 500 households at Storhaugen. This is a very optimistic assumption, but it has been made in order to reveal the full potential of utilizing residential demand response in the area.

An error that was pointed out in Section 7.3.2 was that this thesis does not consider a growth in energy efficient loads such as EVs. An increased use of EVs could decrease the cost of flexibility for households, because the load is considered a storable load that would probably be a cheap load to use for DR.

7.5 Results

The following will present the results from the Case study. The previously presented estimates for the cost curve of the aggregator and the benefit curve of TEN have been used to evaluate the contracts presented in Chapter 6 and 7. By using the numerical results the author will assess which contract type the aggregator should choose for each information scenario. Both the results from the hourly contract will be presented, and numbers representing the total profit that can be extracted over the period the investment is postponed.

7.5.1 Complete Information

Table 7.6 presents the volume of flexibility supplied and the resulting profits from the contract types evaluated for the case of complete information. As mentioned, the profit sharing contract and the two-part linear contract will under complete information provide optimal solutions for the value chain. Even though these results are unlikely to be achievable in reality, they can function as a benchmark to assess the efficiency of contracts in other information scenarios.

	Profit Sharing	One-Part Linear	Two-Part Linear
Volume [kW]	13 287	7 510	13 287
Aggregator Profit	27 539	25 943	35 898
TEN Profit	18 359	11 279	10 000
VC Profit	45 898	37 222	45 898

Table 7.6: Hourly contracts between an aggregator and a grid company with complete information

The results show that the volume that optimizes the value chain profit is 13 287 kW, which corresponds to approximately 1kW of flexibility supplied per household. With an average consumption of approximately 4 kW per household during times of peak load, the volume supplied seems reasonable. For the profit sharing contract the supplier's share is set to 60%, both for the complete information and uncertain information scenario. Because this information scenario does not entail any uncertainties, the aggregator should opt for the contract that maximizes its own profit. The results show that the two-part linear contract gives the aggregator the highest profit by far, and so this is the contract the aggregator should choose.

Best Contract	Total Aggregator Profit [NOK]	Total TEN Profit [NOK]
Two-part Linear	2 620 579	730 000

Table 7.7: Total profits of the contract parties under complete information

The values in Table 7.6 are based on hourly contracts, and the total profit for the value chain using the two-part linear contract is given in Table 7.7.

7.5.2 Uncertain Information

Under uncertain information, decisions made by the aggregator and TEN will be based on expected values. They will therefore act as in the case of complete information, but the resulting profits will be dependant on the true benefit of flexibility. It is likely that the true value coefficients will differ from their expected values and the uncertainty will cause a loss of profit. This loss will be greatest when the true value coefficients deviate the most from their expected values. Table 7.8 presents the deviations between the aggregator's profits under uncertain information and complete information when the benefit of flexibility is at its lowest ($\bar{\alpha}$ and $\underline{\beta}$) and highest ($\underline{\alpha}$ and $\bar{\beta}$). The same numbers are presented for the value chain in Table 7.9.

	Supplier's Deviation From Complete Information [%]	
	Low Benefit	High Benefit
Profit Sharing	-5	-3
One-Part Linear	33	-25
Two-Part Linear	45	29

Table 7.8: Deviation in supplier profit from complete information

	VC Deviation From Complete Information [%]	
	Low Benefit	High Benefit
Profit Sharing	-5	-3
One-Part Linear	10	-12
Two-Part Linear	-5	-3

Table 7.9: Deviation in value chain profit from complete information

The numbers presented in Table 7.8 and 7.9 show how the uncertain information causes a loss of profit compared to if the contract parties were fully informed. An interesting observation is that with a one-part linear contract and a low benefit both the aggregator and the value chain will achieve a higher profit under uncertain information than under complete information. As the one part linear contract does not provide an optimal contract for the value chain, it is possible for the uncertainty to cause a better one-part liner solution than if there was complete information.

To evaluate which contract type should be chosen, the author will compare the mean profits of the contracts for the case with the lowest possible value and the highest possible value. In addition to a measure of the profit, it is also necessary to evaluate the risk, or variance, of the contracts for the aggregator. Therefore the difference between the mean and the extreme points is also given. Table 7.10 gives the mean profit and the variance in a percentage of the profit for the contracts to be considered.

	Mean Hourly Profit	Variance in % of mean
Profit Sharing	27 539	56
One-Part Linear	25 943	0
Two-Part Linear	35 898	0

Table 7.10: Mean hourly profit and variance of contracts under uncertain information

Due to the formulation of the contracts and the information situation, both the one-part linear and the two-part linear contract provide the aggregator with profits that are independent of the actual benefit of the grid company. Since the true benefit is unknown to the grid company as well, and it makes its decision of the quantity to buy before the true benefit is revealed, and therefore the aggregator's profit, is independent of the true benefit. In this way, the linear contracts lay all the risk from uncertain information with the grid company. With the profit sharing contract, the risk is divided between the two actors, but the mean profit for the aggregator is substantially lower. The two part linear contract is clearly the most profitable contract for the aggregator. Since the grid company is assumed to be risk neutral, it will be willing to bear the risk from uncertain information.

Best Contract	Total Aggregator Profit [NOK]	Total TEN Profit [NOK]
Two-part Linear	2 620 579	730 000

Table 7.11: Total profits of the contract parties under complete information

The expected profits from the two-part linear contract is listed in 7.11. Note that the values are the same as in the complete information scenario, but in this case there is uncertainty linked to the profit of TEN.

7.5.3 Asymmetric Information

When considering the case of asymmetric information, a different set of contract forms has been assessed. The non-linear contract is introduced and it differs from the linear contracts in that it does not specify a unit price. Furthermore, it is made on a scenario based approach. In this thesis the scenario approach has been simplified so that the benefit of the DSO is assumed to either take its highest possible value or its lowest possible value. The resulting non-linear contracts from this approach is presented in Table 7.12.

	Supplied Volume, x	Payment from TEN to aggregator, y
High Benefit Scenario	21 128	55 358
Low Benefit Scenario	9 263	29 257

TABLE 7.12: Hourly non-linear contracts for asymmetric information

In the scenario of high benefit the volume supplied is 21 128kW, which equals a flexibility supplied of approximately 1,7kW per household. This is a high volume but is still considered realistic with a power consumption of 4kW per household in times of peak load.

In order to evaluate the different contracts, the same procedure as for the uncertain information will be used. Table 7.13 shows the average profit and the deviation from the average profit for the three relevant contracts.

	Mean Hourly Profit	Variance in % of mean
Profit Sharing	20 671	0
Two-Part Linear	21 912	5
Non-Linear	24 393	6

TABLE 7.13: Mean hourly profit and variance of contracts under asymmetric information

Reviewing the numbers immediately show that the profit sharing contract is the least profitable option. In this case the DSO will always give an impression of having a low benefit, and thus the profit of the aggregator is independent of the actual benefit of the buyer. This option always leaves the supplier with the profit resulting from a low benefit. Comparing the two-part linear contract with the non-linear contract shows that there is a correlation between profit and risk. The non-linear contract offers the highest profit with the highest variance. The two part linear offers a lower profit with a slightly lower variance. The aggregator is considered to be a risk neutral profit maximizing actor, and the best contract for the case of asymmetric information is evaluated to be a non-linear contract. The expected profit from using a non linear contract is given in Table 7.14.

Best Contract	Total Aggregator Profit [NOK]	Total TEN Profit [NOK]
Non Linear	1 780 674	1 326 830

Table 7.14: Expected total profits of the contract parties under asymmetric information

7.5.4 Binary CRP Contract Under Complete Information

The results of the CRP contract is presented separately as it is not comparable to the other contracts. A CRP contract is not presented as a stand alone option that will exlude the use of SRP contracts. As mentioned in Chapter 6, a CRP contract can be offered in addition to an SRP contract in order to fully utilize the aggregator's supplier portfolio.

For the results presented for the CRP contract the probability of activation, υ, has been set to 0,7 and the number of hours in a year with reserved flexibility is 73. This means that it is expected to be $0,7 * 73 = 51,1$ hours of activated flexibility in a year. The results under these assumptions are presented in Table 7.15. It is apparent that the optimal volume of flexibility supplied equals that of the SRP contract under complete information. Furthermore, the calculations show that $\pi_{VC,B1} = \upsilon * \pi_{VC,C3}$. This is to be expected considering the similarities between the proposed CRP contract and the two-part linear contract.

x [kW]	Aggregator Profit [NOK]	Value Chain Profit [NOK]
13 287	27 129	32 129

TABLE 7.15: Hourly results of the CRP contract when $v = 0,7$

The contract is able to consider the uncertainty connected to the need for flexibility at different times. A rough assumption made by the SRP contracts is that the grid company will know with complete certainty all times it will be in need of flexibility and the exact amount it will need. The binary CRP contract is more suited for how things will be in reality, when there will be many times when the grid company may suspect that they will need flexibility, but will not be sure. A CRP approach to flexibility is believed to be more practical in these cases. The CRP contract is therefore important in order to provide flexibility in a way that will also be optimal in real life.

Sensitivity Analysis of t

As explained in Chapter 6, the value of t and w will not affect the profits of the contract parties as long as their relationship is as given by (6.10). However, they will affect how much of the payment from the DSO to the aggregator is made in advance of and after the activation time. In the calculations performed in this thesis w has been expressed as a function of t, and it is possible to perform a sensitivity analysis to show how different values for t will alter the distribution of the payment between being prepaid and postpaid. Table 7.16 shows the resulting values of w and the percentage of the payment that is prepaid for different values of t.

t	w	Percentage Prepaid
0,5	0,81	86,8
1,5	0,11	60,3
3	-0,94	20,6

TABLE 7.16: Sensitivity analysis of t

The sensitivity analysis supports the statement from Chapter 6 that increasing values of t will give lower values of w and a lower share of prepaid payment. It has also been mentioned that it is likely that the aggregator will wish to receive as much as possible of the payment up front and the DSO will wish to postpone the payment due to the time value of money and liquidity.

When the value of t becomes too large, w will become negative. Similarly, imposing a too high w would result in a negative t value. This is probably going to be undesirable for the aggregator, as this could result in a payment going from the aggregator to TEN. The aggregator should set the values of t and w in order to fit the needs of both it self and the DSO. For the numbers presented in this case study a t of 1,5 would give a balanced relationship between the prepaid and postpaid payment.

7.5.5 Summary of the Results

A brief summary of the results from the case study will be presented in the following. The purpose of the case study was to get an indication of what contract types will be best for the aggregator in different information scenarios. Table 7.17 presents the SRP contracts the aggregator is advised to choose for all information scenarios and the expected total profit they will yield for both the aggregator and TEN. The resulting calculations indicate that the investment of 5MNOK can be postponed for up to 26 years, which explaines the high values of teh total profits. The total profits of the SRP contracts have been rounded off to the closest hundred thousand NOK, for the sake of readability.

Information Scenario	Best Contract	Total Aggregator Profit [NOK]	Total TEN Profit [NOK]
Complete	Two-part Linear	2 600 000	730 000
Uncertain	Two-part Linear	2 600 000	730 000*
Asymmetric	Non-linear	1 700 000*	1 300 000*

TABLE 7.17: Summary of the results of SRP contracts

Numbers marked with * in Table 7.17 indicate that the profit is based on expected values and will be subject to uncertainty. The result summary clearly shows how the information asymmetry act in the benefit of TEN, allowing it a larger share of the value chain profit. Thus, TEN has an incentive to keep private information private. The value chain profit is also reduced due to information asymmetry, because the aggregator will chose a sub-optimal contract for the value chain in order to maximize its own profit.

	Total Aggregator Profit [NOK]	Total TEN Profit [NOK]
Binary CRP Contract	1 980 405	365 000

Table 7.18: Summary of the results of CRP contracts

The resulting profits from the binary CRP contract is given separately in Table 7.18. The CRP contract is only assessed for a complete information scenario for illustrative purposes. The profits are considerably lower than for the SRP contract with complete information because the CRP contract accounts for the uncertainty in when the flexibility is needed. The way the uncertainty has been modeled gives less hours where the flexibility is activated, and this causes the lower profit.

7.6 Discussion

This chapter has done a review of potential contracts for trading DR between an aggregator and the grid company of TrønderEnergi. Overall, the results from the case study indicate that the value of postponed investments in the grid can be substantial. If TEN is able to achieve similar results in other areas of the grid, it could accumulate large cost reductions for the firm. As the DSOs are in a low degree compensated for investments connected to upholding existing parts of the grid, these types of cost reductions are especially valuable.

The chapter has performed numerical analyses in order to decide which contract the aggregator should choose in different information scenarios. In reality, none of the suggested scenarios will be completely accurate to describe the information situation between the aggregator and the DSO. The case of asymmetric information is believed to be the closest representation of reality, because the DSO is likely to be better informed of how consumption in the grid will develop and how they will plan their investments. Still, the DSO will also have some uncertainty linked to their benefit of flexibility due to the complexity of the grid and investments in it. The author believes that a non-linear contract type is theoretically the best suited to handle the information situation, but it is more likely that a two-part linear approach will be used in practice due to being simpler.

The CRP contract presented in this thesis is believed to be better suited for trading flexibility in cases of uncertain demand, which is likely to occur frequently for a DSO. The CRP contract developed thesis has been for the case where either none or all of the reserved flexibility is activated. Further research should be focused on how contracts can facilitate continuous CRP services, allowing the buyer to choose how much of the reserved amount to activate.

The contracts proposed in this thesis favour the aggregator, primarily because the aggregator is the one designing and offering the contracts. However, the reservation profit set by the author functions as a representation of the bargaining power of the DSO. It is possible that the reservation profit has been set too low and that the distribution of the profit should be adjusted. Especially under uncertain information, the DSO takes on a lot of risk in order to possibly receive a relatively low profit compared to that of the aggregator.

A consequence of the longevity of the postponements is that the DSO will be dependant on long term contracts. If repeated short term contracts are used it may lead to a hold-up problem that gives the aggregator a large bargaining power and can push up the price of flexibility. This is because as the DSO uses flexibility to postpone an investment the overall consumption in the grid will increase over time and evantually the DSO will not be able to run a functioning grid without using DR. If the aggregator chooses to increase its prices, the DSO must accept the higher prices because performing the postponed grid reinforcement will take time.

The DSO will risk incurring a large loss from congestion in the grid by rejecting the contract. As a result, the DSO must accept the aggregator's increased prices, at least until it is able to secure a better alternative. In order to avoid such a situation the DSO will most certainly wish to engage in long term contracts.

Simplifications and Sources of Error

It is important to mention that the simulations are based on many simplifications. Firstly, all calculations are based on an assumption that DR is already fully in place at Storhaugen and that the aggregator has access to all households. This is not the case, but it is meant to give an indication of the results one could achieve in the future with a DR initiative.

As emphasised in Section 7.3.2, the method for estimating the value coefficients of the DSO was highly simplified. The simplification is so large that the author does not believe the hourly profits presented in the case study are representative of reality. However, when the hourly profits are summed over the entire year, the resulting profit will be representative for the total profit it would be possible to extract over the entire relationship between the aggregator and the DSO, which will last until the investment in question is finally made. Using the suggested approach to estimate the benefit curve will not be sufficient in order to decide the DSO's willingness to pay for flexibility on an hourly basis. Future research should be conducted in order to create a method that is able to do this.

In the simulations, it is assumed that flexibility can be used to reduce the load in all times of peak load. This is seen as a reasonable assumption considering that peak loads currently occur seldom and only for a short period of time. The results presented in this case study indicate long postponements of investments. As one evaluates postponed investments further into the future, the assumption that the estimated amount of flexibility can be used over all periods of overload will become less reasonable. As the peak loads rise they are also likely to last for a longer period of time and occur more often, especially if the increase is caused by a general increase in electricity consumption. An increase in the number of hours with activated flexibility would result in higher costs than those presented in this case study, and so the results presented in this case study are believed to overestimate the postponement of the investment.

Potential Barriers

It is important to discuss factors that may stand in the way of trading flexibility between an aggregator and a DSO in the way that is proposed in this thesis. A concept that is likely to be introduced in Norway with the AMI roll-out is that of power based grid tariffs. These are meant to encourage consumers to reduce their consumption at times of peak load. If the power based grid tariffs achieve this goal on their own, the DSO would not need to purchase flexibility. However, the demo projects presented in Section 2.3.4 indicate that power based grid tariffs have a low effect on customer's consumption due to several factors. These include that the Norwegian power consumers don't fully comprehend the difference between energy consumption and power consumption, and they have a highly inelastic demand due to the low electricity prices in Norway. It is therefore believed that an aggregator could still contribute to increase the consumers' willingness to adjust their consumption, especially by directly controlling some loads on the consumer's behalf.

As the actors in the power industry, and especially the DSOs, are heavily regulated by the NVE it is necessary to ensure that the trading of demand response is facilitated by the regulations. This thesis has not investigated if current regulations stand in the way for the business model of an aggregator.

Summary

One should be careful when drawing conclusions from the results presented in this paper. Due to the simplifications that have been presented throughout this text, the author believes that the costs of the aggregator have been underestimated and the value for the DSO have been overestimated. The costs of the aggregator are overestimated because they do not include the profit the aggregator must give up to its suppliers or the operating costs of the aggregator. The value of demand response for the DSO is believed to be overestimated because the estimations do not consider that flexibility will be needed more frequently the longer the considered investment is postponed. As a result, the profits presented for Storhaugen in this case study represent an upper limit to what it would be possible to achieve. Still, the potential values presented in this case study are considerable. Even though they need to be subject to some adjustments, they indicate a high value of demand response. The author wishes to express a belief that residential demand response can have a significant value to both a DSO and an aggregator.

Chapter 8

Conclusion

As the power consumption is expected to continue to increase in future years, it will cause challenges for the distribution grid. In much of the literature on the area demand response is presented as an alternative to expensive grid reinforcements. This thesis does not view demand response and grid reinforcements as separate alternatives, but as methods that should be used in combination. As grid reinforcements are associated with high costs, any postponement or reduction of these will have great value. The purpose of this paper has been to give a contribution to quantifying the value that can be extracted from using demand response to postpone investments in the distribution grid.

As an approach to this, the thesis has explored how contracts can be offered from an aggregator of demand response to a DSO. In order to evaluate the contracts the author has estimated the cost and benefit curves of the aggregator and DSO respectively. The thesis presents existing contracts and derives the optimal contracts for different information scenarios. Existing contracts are suitable for scheduled reprofiling services, but cannot be used to offer a conditional reprofiling service. The author has developed a new contract form in order to facilitate a conditional reprofiling service. The thesis shows how a contract can be designed to charge for first reserving a volume of flexibility, and secondly for the potential activation of it. Although the contracts presented have not taken the time frame of the contracts into account, this thesis has emphasised that a contract offered to a DSO should be a long term contract.

The derivation of optimal contracts have been made on a general basis. Therefore, the results from Chapter 5 and 6 are applicable for any supplier of flexibility offering a contract to a buyer of flexibility. The only requirements are that the cost and benefit curves are assumed to follow the polynomial shape that has been suggested, and that the contract participants are profit maximizing actors.

Through a case study, this paper evaluates the suggested contracts for a specific residential area supplied by TrønderEnergi Nett. The results suggest that for SRP services the two-part linear contract will be the best option when contracting under complete information and uncertain information, while the non-linear contract is optimal for asymmetric information. The author believes that the information scenario experienced in reality will be a combination of asymmetric information and uncertain information. However, it is likely that a two-part linear contract will be utilized due to its simplicity compared to the non-linear contract.

The author wishes to express a firm belief in the necessity of CRP services in addition to SRP services. CRP is believed to be better suited for trading flexibility in cases of uncertain demand, which is likely to occur frequently for a DSO. The CRP contract is therefore important in order to provide flexibility in a way that will also be optimal in real life. Therefore the CRP contract presented in this text is an important contribution to the literature concerning trading of demand response. The CRP contract developed by the author of this thesis has been for a simple CRP service where either none or all of the reserved flexibility is activated. Further research should be focused on how contracts can facilitate continuous CRP services, allowing the buyer to choose how much of the reserved amount to activate.

The findings and simulations conducted in the case study indicate that the theoretical value of postponed investments from residential demand response is considerable, and that the investment in question can be postponed for a long period of time. The length of the postponement and its value is likely overestimated due to the simplifications performed throughout the thesis, but the author still believes the value of demand response for a DSO to be significant. Considering the possibility that one can achieve similar results in other areas of the grid, demand response could accumulate large values for both the aggregator and the DSO.

Appendix A

Appendix

A.1 Raw Data

The raw data provided by TrønderEnergi is given in the following file:

- 0.1 Raw data from TronderEnergi - Consumption and Customers at Storhaugen.xlsx

A.2 Calculations

The calculations behind the results presented in this thesis are presented in the following files:

- 4.1 Cost curves of flexibility suppliers.xlsx
- 7.1 Postponed investments.xlsx
- 7.2 Benefit curve of TEN.xlsx
- 7.3 Evaluating contracts.xlsx

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