NTNU – Trondheim
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Science and Technology

Business Models for Extracting the Value of Flexibility in Electricity Systems

A Contractual and Market Based Approach

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Industrial Economics and Technology Management
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4. Bedømmelse

Kandidatene skal ha *individuell* bedømmelse ☐
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Preface

This thesis concludes our Master's degree in *Managerial Economics and Operations Research* and *Investment, Finance and Financial Management* under the Department of Industrial Economics and Technology Management at the Norwegian University of Science and Technology. It was written during the spring of 2014.

The main topic of the study was proposed to us by our supervisors in the Fall 2013. The thesis is based on the authors interest for the energy market, and we hope that our analyses and discussions can support future decision making processes and shed light on some of the market opportunities of demand side flexibility in the future energy market. The working process has been very educational and exciting as the subjects have (to our knowledge) previously not been addressed.

First of all we would like to thank our supervisor at the department, Asgeir Tomasgard, for both his time and guidance, keeping the work on the right track. Huge thanks should also go to Stig Ø. Ottesen for introducing us to important people in the research field and his informative advising. We would also like to thank Therese Troset Engan and Jan Andor Foosnæs at NTE Nett AS, Virginia Hyde at Statnett R&D and finally Eilert Bjerkan at Enfo Consulting AS for their time and helpful information.

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Abstract

The Nordic electricity system faces several challenges, and demand side flexibility will be a key factor for securing reliable and efficient electricity supply. The aim of this thesis was to elaborate both contractual and market-based business models for releasing potential of demand side flexibility. Opportunities for several participants on the demand side as well as the supply side were emphasized. The thesis attempted to evaluate various business models both from the perspective of each individual participant and the whole society. In order to analyze factors impacting the business models, costs and benefits of flexibility were quantified. Further, illustrative studies of each business model were performed to highlight the theoretical analyses. An aggregator was introduced to explore how an intermediary party affects the overall value creation of flexibility as well as the allocation of this value. Finally, the thesis proposed future solutions for employing sufficient flexibility to the electricity systems.

The analyses indicated that the various business models have important characteristics required to manage different challenges in the trading of flexibility. Bilateral contracts enable trade of this resource at an early stage where few buyers and suppliers participate in addition to provide tailored solutions to solve specific problems in the electricity system. However, from a socio-economic perspective bilateral trading often results in sub-optimality as each individual participant designs contracts by maximizing own profit. Local flexibility markets enable sufficiently supply and demand and increase the overall efficiency. Nevertheless, several barriers must be overcome to facilitate trading in markets. Both trading approaches are vulnerable to dominating actors which is a potential problem in flexibility markets. The illustrative studies implied that grid companies have significantly higher benefits of flexibility than retailers and wind power producers, which exclude these two buyers from trading. This diminishes the released potential of flexibility. A large aggregator changes the divisions of power in the system and acts as a driving force to retrieve supply of flexibility. By doing so, the aggregator can facilitate trading for additional buyers as the grid companies have limited demands of flexibility. The results implied several business opportunities for the aggregator where a combined model can ensure optimal exploitation of his flexibility portfolio. Comprehensive load scheduling models are required to find an optimal allocation. In order to realize the whole potential of demand side flexibility, both contractual and market-based models might be required.

Sammendrag

Det nordiske kraftsystemet står overfor flere utfordringer, og fleksibilitet på etterspørselssiden vil være en nøkkelfaktor for å sikre pålitelig og effektiv strømforsyning. Målet med denne masteroppgaven var å utdype både kontrakts- og markedsbaserte forretningsmodeller for å realisere potensialet til sluttbrukerfleksibilitet. Muligheter på både tilbud- og etterspørselssiden ble vektlagt. Masteroppgaven studerte ulike forretningsmodeller både fra perspektivet til hver enkelt aktør og for samfunnet som helhet. For å analysere faktorer som påvirker forretningsmodellene, ble kostnadene og gevinstene av fleksibilitet kvantifisert. Videre ble det utført enkle, numeriske beregninger for å underbygge de teoretiske analysene. En aggregator ble innført for å utforske hvordan en tredjepart kan påvirke den samlede verdiskapingen av fleksibilitet, samt fordelingen av denne. Masteroppgaven foreslo til slutt fremtidige løsninger for å utnytte fleksibiliteten optimalt.

Analysene viste at de ulike forretningsmodellene innehar viktige egenskaper som kreves for å håndtere ulike utfordringer ved handel av fleksibilitet. Bilaterale kontrakter muliggjør handel av denne ressursen på et tidlig stadium der få kjøpere og leverandører deltar, i tillegg til å tilby skreddersydde løsninger for å løse spesifikke problemer i kraftsystemet. Likevel vil bilaterale kontrakter ofte resultere i sub-optimalitet sett fra et samfunnsøkonomisk perspektiv der hver enkelt deltaker designer kontrakter ved å maksimere egen profitt. Lokale fleksibilitetsmarkeder muliggjør tilstrekkelig tilbud og etterspørsel av fleksibilitet og øker den totale effektiviteten. Likevel må flere barrierer overkommes for å tilrettelegge for handel i fleksibilitetsmarkedet. Begge handlemåtene er sårbare for dominerende aktører, og kan være et problem i energimarkedet. De numeriske beregningene antydet at nettselskapene har betydelig høyere gevinst av fleksibilitet enn strømleverandører og vindkraftprodusenter, noe som vil forhindre disse kjøperne fra å delta i markedet, slik at det utnyttede potensialet av fleksibilitet reduseres. En aggregator endrer maktbalansen i systemet og fungerer som en pådriver for å hente ut tilgjengelig fleksibilitet. Dermed kan aggregator tilrettelegge for flere kjøpere ettersom nettselskapene har begrenset behov og derav etterspørsel av fleksibilitet. Resultatene viste flere forretningsmuligheter for aggregator der blant annet en kombinert modell kan sikre optimal utnyttelse av fleksibilitetsporteføljen. Omfattende lastplanleggingsmodeller vil være nødvendige for å sikre en optimal allokering av porteføljen til en aggregator eller en kjøper av fleksibilitet. Både kontraksbaserte og markedsbaserte modeller er nødvendige for å hente ut hele potensialet av sluttbrukerfleksibilitet.

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Chapter 1

Introduction

The Nordic electricity system is undergoing significant changes. Stakeholders in the energy sector must find new ways of operating their businesses to meet challenges as aging infrastructure, increasing integration of energy production from intermittent sources, rising energy consumption and new technology influencing how electricity is consumed today. In Norway, the use of electrical vehicles is rapidly increasing, which concerns the operators of the distribution grids as they face high irregular consumption peaks from charging. The changing consumption patterns of end-users require the electrical grid to be dimensioned for high peak load capacity, occurring only a few hours in a year.

Electricity is a special type of commodity as it cannot easily be stored. Hence, the electricity system must be balanced continuously, meaning demand must equal supply at all time. Flexibility is needed in order to maintain balance in the future electricity system. In the present system flexibility is provided by large producers, but recently the focus has been shifted towards the consumption side and its ability to deliver flexibility. Demand side flexibility has been introduced as a possible solution to the above mentioned challenges, and by providing the right incentives that induce end-users to engage in demand response programs, a variety of problems among different actors in the electricity system can be solved. Demand side participation requires smarter networks, thus smart grid technology is vital to enable comprehensive interactions. Increased demand side flexibility holds substantial potential of benefits for the whole energy system. By exploiting flexibility, grid companies and Transmission System Operators, henceforth referred as TSO, can ensure continuous power flow and maintain a reliable power supply, while producers of intermittent energy sources or retailers can reduce financial risk by lowering costs associated with imbalances. From the perspective of an aggregator, as a new market entrant, demand side flexibility can provide important business opportunities and thus a potential of gaining high profits.

As the complexity of the future energy system is increasing, new arrangements between the market actors are needed [10]. The aim of this thesis is to present various ways in which demand side flexibility can be traded, and investigate how the full potential of flexibility can be released in order to deliver benefits to all actors in the electricity system. Theoretical frameworks will be presented and the results analyzed while simultaneously linking the study to reality. Both a contractual and market-based approach will be investigated in order to suggest novel business models that can solve problems arising and at the same time be profitable for the market participants. Future solutions for trading flexibility will be proposed including an aggregator possessing incentives to facilitate the changes required. This work highlights both how single actors can exploit flexibility to maximize individual profits, and how market-based solutions can maximize the total socio-economic gain. Illustrative examples will be presented throughout the whole thesis to support the discussions.

Previous research mainly focuses on new technology and how to provide economic incentives for end-users to participate in demand side flexibility programs. The studies often emphasize how grid companies and TSOs can exploit flexibility. So far, less focus has been on solutions including all actors in the electricity system and how they can gain from demand side flexibility. This thesis studies the electricity system as a whole, and by doing so, great knowledge about various business opportunities is obtained. Usually only one trading method is considered, but here both contractual and market-based solutions will be studied, as well as the trade-off between these in a combined business model.

In order to limit the scope of the thesis, only the Norwegian electricity system is considered. However, the main findings can be applied to electricity systems in general and might even serve a greater value to some of them. The interactions in the electricity market are complex and thus a simplified value chain will be analyzed. For instance, the TSO and grid companies face many similar challenges associated with operating the grid, and for this reason only grid companies are emphasized[1]. Dynamic electricity and grid tariffs have previously been suggested to induce end-users in demand response programs. These pricing schemes are not within the scope of this thesis, instead additional incentives for suppliers and buyers of flexibility will be introduced. Selected contract types will be investigated in order to determine how actors can exploit the value of flexibility by engaging in contractual relationships. The chosen contracts hold different properties and serve as good examples on how various information scenarios impact the contract design. It should be emphasized that the numerical calculations performed are for illustrative purposes only. However, the trends in the calculations serve as good indications of the principals in general. Complete calculations can be found in attached Excel-files. If otherwise stated, the calculations are based on an hourly time-frame, which means that all prices and profits are calculated per hour. It should be stressed that the hours studied are peak load hours with high demand of flexibility, and thus the calculations are not representative for all hours in a year. A snapshot of the situations will be studied, and hence the flexibility is measured in kWh/h or kW as denoted in this thesis.

[1]Previous research has paid most attention to the TSOs and how they can benefit from demand side flexibility

The thesis is divided into seven main chapters. Chapter 2 provides a brief presentation of the Norwegian power market followed by a description of the term flexibility as well as identifies potential buyers and suppliers of flexibility. In Chapter 3, cost and benefit functions of flexibility for buyers and suppliers are derived and estimated in order to support decision making processes. Further, Chapter 4 and 5 present a theoretical framework of trading flexibility in contracts and markets respectively by studying a simplified value chain. Both chapters include simple numerical calculations and discussions on how these models can be applied to the electricity system. Chapter 6 introduces an aggregator and based on previous analyses elaborates different business models for flexibility. Finally, Chapter 7 concludes the thesis.

Chapter 2

The Norwegian Power Market

The Norwegian power market has changed considerably in recent decades. In 1991 an Energy Act was introduced to encourage increased competition in those parts of the energy sector that could not be regarded as natural monopolies. Nevertheless, there is little doubt that the energy market is about to change even more. Smart Grid technology brings along several opportunities that can change the whole value chain of todays market and flexibility from the demand side will play a key role in this change. It is expected that the future will bring more actors and new functionalities into the market. Existing roles will change, and new services and market opportunities will arise. The classic grid companies and retailers are likely to be complemented by new types of actors, like aggregators and other service providers. Companies participating in the energy sector today can broaden their commercial range of offerings by taking on new roles, but they may also face increased competition from new actors entering the market.

In order to analyze business models that extract and utilize the value of demand side flexibility, present market mechanisms as well as both existing and new actors is presented. The primary intention of this chapter is to give the reader an overview of the Norwegian power market and present how flexibility is introduced to this market. The first section gives a description of the present market design. Section 2.2 elaborates the term *flexibility* in more detail, while Section 2.3 presents possible suppliers and buyers of flexibility. Finally, Section 2.4 gives a brief overview of related research. Major parts of the theory presented in this chapter is based on work previous work by the authors given in [4].

2.1 Market Design

Electricity production are based on a range of different energy sources, from non-renewable resources as coal and gas, to renewable resources as wind, solar and hydro. Some production sources are possible to control, like hydro power or gas fired power plants, whereas intermittent energy sources are not. In Norway 99 percent of the energy production comes from hydro power [29] and hence, electricity contribute to the largest share of the energy consumption in Norway. The electricity is transported by the transmission network to substations located close to end-users. Grid companies are responsible for the local grid and provide electricity to end-users. Since building several distribution networks would not be socio-economic profitable, they are in a position of natural monopolies. Retailers, or power suppliers, buy electricity through the spot market and re-sell it through the retail market by offering the end-users a range of different contracts; fixed-price, variable-price or spot price. The retailers are responsible for the terms of power delivery including the price of electricity paid by the end-users. End-users can choose between retailers charging them for electricity, but not between grid companies charging the network tariff.

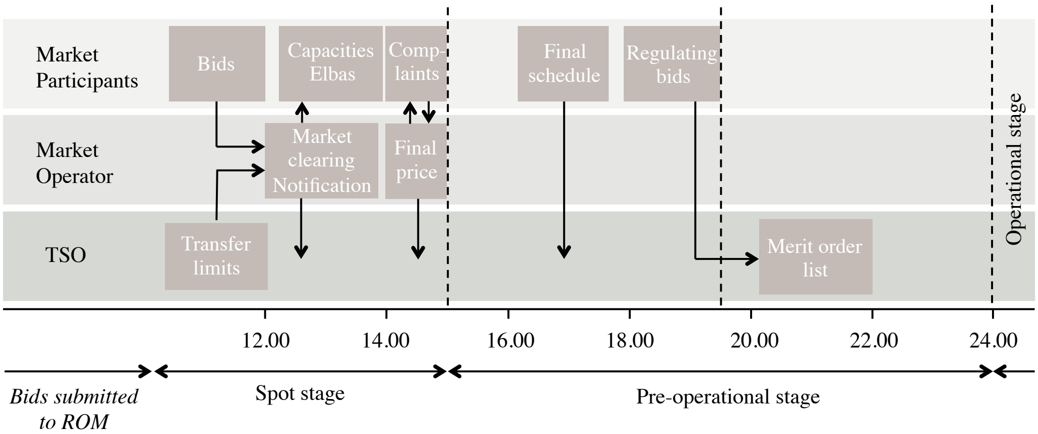


Figure 2.1: Bidding sequence in the Nordic power market.

Electricity differs from other commodities by having certain characteristics. One of the main challenges is that the electrical system has to be in balance at all time, which means that production and consumption have to coincide in every second. An unbalanced electrical system can cause real damage and if the unbalance continues over a longer time period there is a risk of system break down [10]. In order to provide enough power in the electricity system at all time there has to be a sufficient amount of available power production and flexibility in the system. The large production of electricity as well as the fact that electricity generally have to be consumed as it is generated[1] make the Nordic power market complex, and large volumes are traded daily. Sufficient reserves of electricity are important to secure reliability in the system. The power market consists of multiple market places and market participants, and it operates over different time horizons from long-term to short-term, until real-time. Figure 2.1 illustrates the Nordic power market design including the time frame.

In order to overcome the challenge of balancing the whole electricity system at any time three electricity markets exist at an overall level: a day-ahead market, an intra-day

[1]Electricity is difficult to store in large quantities and storage are not yet economical efficient.

market and an ancillary service market. In the day-ahead market, *Elspot*, electricity is traded for each hour of the following day. If the market players are not able to realize the volumes traded day-ahead, bids can be placed in the intra-day market, *Elbas*, until one hour before the hour of operation. Elbas is based on continuous auctioning, and prices are set based on a first-come, first-served principle. So far, the turnover volumes in Elbas are relatively small, but this market is becoming increasingly important as more renewable power enters the grid. In the delivery hour, ancillary services provided by the *Balancing Market* are activated to compensate for any system imbalances. The largest turnovers in the Nordic system are in the day-ahead market and the Balancing Market for regulating power [5]. When describing new business models for exploiting the value of flexibility in electricity markets it is most interesting to study the markets where it is assumed that the flexibility is valued the most, and hence the focus in this thesis will be on the day-ahead market and the reserve markets.

2.1.1 The Spot Market

Nord Pool Spot runs the leading power market in Europe and is the market operator of both the day-ahead and the intraday market. Nord Pool Spot is responsible for both physical and financial trade in the Nordic market. Today around 370 companies from 20 countries trade in the spot market and in 2012 the total turnover was 432 TWh [23]. All participants at Nord Pool Spot have to pay an annual fixed fee of 15 000 EUR. In addition the variable fee for trading in Elbas is 0,11 EUR/MWh and the corresponding fee for Elspot is 0,04 EUR/MWh [22]. Nord Pool Spot is geographically divided into different areas indicating that the grid has transfer capacity limits, and based on these limitations different area prices will occur to reflect the regional market conditions. The system price serves as a reference price for the financial power trade and is calculated by aggregated supply and demand for the Nordic system, assuming no transfer limitations in the grid.

The main activity of Nord Pool Spot is operation of the short-term physical electricity market. *Elspot* is Nord Pool's auction based day-ahead market and the main arena for trading power in the Nordic region. Today there are around 360 buyers and sellers, called members, on Elspot and most of them trade every day, placing a total of around 2000 orders for power contracts on a daily basis [20]. As the Market Operator, Elspot is responsible for receiving bids for sales and purchases of electricity. There are three different types of orders that can be placed: single hourly orders, block orders and flexible orders. The members can decide to use one or a combination of the order types. The deadline for submitting bids for power delivered the following day is at noon. The power price is then determined by matching the hourly supply and demand for each price area, as illustrated in Figure 2.2. Once the market prices have been calculated and announced to the market around 12:30 pm, all trades are settled. The power contracts are physically delivered hour by hour according to the contracts the next day.

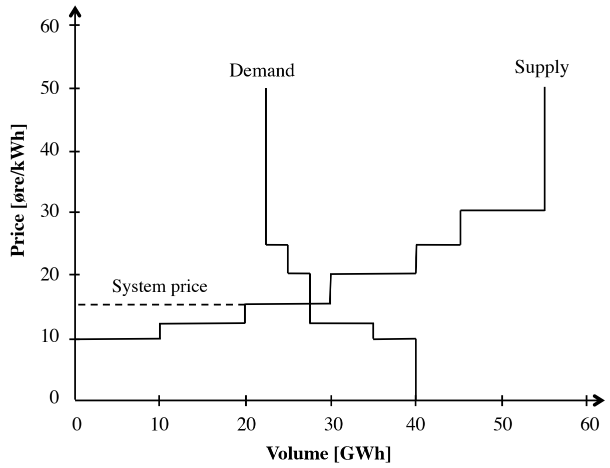


Figure 2.2: Market clearing in Elspot.

2.1.2 The Balancing Market

The Balancing Market is operated by Statnett, as the TSO in Norway, and serves as a tool to balance power generation and load at any time during the hour of operation. The Balancing Market is thus a collection of regulating objects to compensate for any imbalance between production and demand during the operating phase. Participants in this market are electricity producers and large consumers that can easily adjust their production and/or consumption in a short time note. The TSO's expenses for regulating power are financed via the balancing power traded with the balance responsible party that caused the imbalances.

The Balancing Market is operated in two phases, a bidding phase and a calculating phase. During the *bidding phase* the participants, both supply side and demand side, place bids stating hourly volume and price of upward regulation[2] or downward regulation[3]. Bids to the Balancing Market for the following day are to be submitted before 7:30 pm. The minimum quantity is 10 MW and the bidder must be able to provide the offered quantity within 15 minutes [30]. The regulating price is determined in the operational hour by the TSO by activating the bids in merit order as shown in Figure 2.3. The highest activated bid determines the balancing price. The upward regulating price is equal to or higher than the spot price, and the downward regulating price is equal to or lower than the spot price. When the operational hour has passed, all metered data are collected and the imbalances for all participants are determined in the *calculating phase*. The individual participant is charged or credited for his power imbalances, based on the prices in the Balancing Market.

[2]Increased generation or reduced consumption

[3]decreased generation or increased consumption

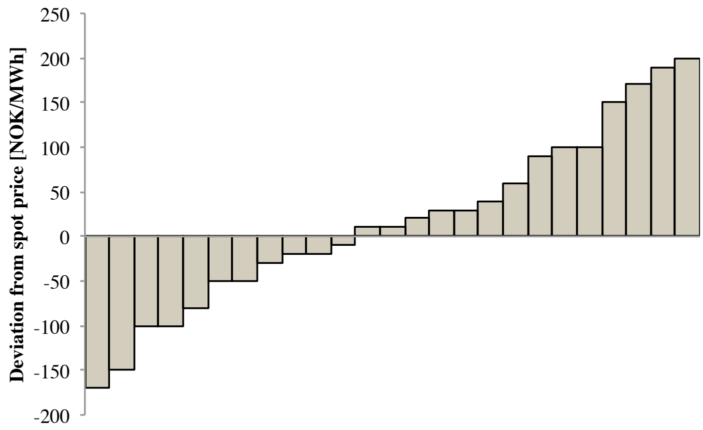


Figure 2.3: Upward and downward regulating prices in the Balancing Market. Adapted from [35].

2.1.3 The Reserve Option Market

The *Reserve Option Market* (ROM) was introduced to the Norwegian power market when the balance became narrower and the balancing reserves were not sufficient to cover the capacity needed in the Balancing Market [35]. The Reserve Option Market makes sure that there are always large enough reserves available to cover possible shortness of power by offering payments for availability of reserves. This is a capacity market where the suppliers are paid an option price to guarantee participation in the Balancing Market with a predefined volume of power. The need for ensuring sufficient upward regulating power in the Balancing Market has so far mainly occurred during the winter season in Norway[4]. Power from both generation and demand side flexibility can be submitted in the Reserve Option Market. The participants submit hourly bids on price and volume of flexibility in consumption or production. These bids must be linked to their corresponding price area. The reserves should be available on a certain time of the day and the minimum volume is set by the requirements in the Balancing Market. All the bids within one region are awarded at the same price through a price clearing process where the option price is determined as the price of the last offer accepted. A market participant with an option contract is obliged to make the reserved quantity available by bidding into the Balancing Market [12].

Two different products are traded in the Reserve Option Market. The products are called *ROM-season* and *ROM-week*. In ROM-season the options are traded with a duration of the entire season, meaning that the submitted power must be available in the Balancing Market during the whole ROM-season. Options in ROM-season should be traded before the startup of the first ROM-week, usually around October 1. The prices

[4]Specifically October through April

in ROM-season have increased the last seasons.

The duration of options in ROM-week are one week in lieu of the whole season. Bids on this product have to be submitted within Friday at noon before the week of operation. The results, i.e. power and option price, are announced at 2 pm the same day. Accepted power have to be available in the Balancing Market during the whole period of the option.

2.2 Flexibility in Electricity Systems

Flexibility in the electricity systems will be a key factor to both meet rising demand and at the same time have large enough reserves to maintain system reliability. This section will explain how the term *flexibility* is defined and used in this thesis and why flexibility in electricity systems is needed.

2.2.1 Definition of flexibility

Flexibility in electricity systems is described as flexible production and consumption of electricity and can be provided by either the supply side or the demand side. Several parameters are used to characterize flexibility in electricity systems including the amount of power modulation, the duration, the rate of change, the response time and the location [10]. Most of the flexibility today is provided by the supply side and a few large industry consumers, while the demand side is treated as price takers with inelastic demands that should be met. New technology and restructured electricity systems enable the demand side to provide flexibility to the system. In 2000 the the potential for demand side flexibility in Norway was estimated to 4 000 MW in the heavy industry sector and about 1 700 MW in the residential sector, which in total amounts to around 20 % of the peak load [12]. However, technology alone is not enough to bring along the changes that are needed. Most of the demand side flexibility is still unreleased potential. Future challenges for the system require more available flexibility, and thus flexibility from the demand side should be exploited to efficiently operate the electricity system and increase the competition. In order to do so, electricity consumers' behavior must change. The focus in this thesis will therefore be on flexibility from the demand side. Further in the thesis, *flexibility* is defined as flexible consumption or production only from the demand side. Hence, flexible generation of electricity offered by power producers is not included in the term flexibility here.

2.2.2 Demand side flexibility

The main objective of demand side flexibility is to improve the overall efficiency of the whole energy system [10]. The demand side can offer flexibility to the markets in several ways. For instance the demand side can react to spot prices in the spot market, or they can activate flexibility resources for balancing purposes and ancillary services. Flexibility can be provided by reducing and increasing as well as shifting consumption or production[5] when needed. Consumers with generation available is often referred to *prosumers*[6], meaning that they are both consumers and producers. A common term for consumers providing flexibility is *demand response*. [33] defines demand response as:

> *Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.*

To encourage the market to respond when need for flexibility arises, efficient price signals in the form of both dynamic grid tariffs and real-time pricing of electricity is crucial. The price of electricity will reflect the costs of supplying electricity under such price signals and will make the real cost transparent to the demand side. Thus the benefits of participating with flexibility become visible for suppliers. The most important incentive for end-users to be willing to provide flexibility is expected cost savings and economic gain, and proper price signals will induce economic incentives. The price signals have different characteristics in Elspot and the Balancing Market. In the Balancing Market, the flexibility is initiated by call from the TSO when steady frequency deviation occurs in real time operation. On the other hand, flexibility in the spot market is initiated by the 24-hour price setting for the day ahead [12]. The authors, and other researchers[7], believe that price signals provide insufficient economic incentives for small suppliers to activate flexibility. This thesis will propose additional economic incentives to suppliers in the form of payments from either a contractual relationship or from flexibility markets.

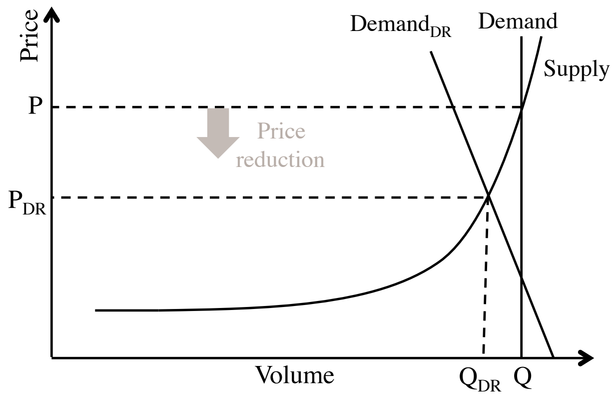


Figure 2.4: Elasticity of electricity demand. Adapted from [1].

[5]Some consumers have small scale production installed which can be switched on or off.

[6]In the following, end-users will be referred to as suppliers of flexibility. It is not explicitly defined whether they have available generation or not. If it is necessary for the analysis the two terms will be separated.

[7]For instance [8].

If the electricity system succeeds to offer sufficient incentives to end-users and they provide flexibility, the elasticity of demand will increase. [27] explains that the elasticity of demand is given by the flexibility of consumers to change demand in response to changes in price or other monetary incentives. [17] uses microeconomic theory to state that consumers of electricity, like consumers of all other commodities, will increase their demand up to the point where the marginal benefit they derive from the electricity is equal to the price they have to pay. Pilot studies in Norway carried out by [13] have shown a significant demand side response in high price periods, which means that there is certain demand side price elasticity when the conditions are right and the right incentives are given.

As illustrated in Figure 2.4 the spot market face steep bid curves in peak load periods, and there is a danger that price setting can fail in an extreme shortage situation. An elastic demand curve can lower the market price significantly, and only a small price dependent load reduction will result in a substantial drop in price. [13] states that sufficient flexibility in peak hours will reduce not only the high prices, but also the average price over time.

2.3 Suppliers and Buyers of Flexibility

The present value chain in the electricity system consists of buyers of electricity on one hand, and various power actors on the other. This thesis will analyze a value chain for the commodity flexibility in lieu of electricity, where flexibility can be traded as a virtual resource. In this value chain the end-users are the suppliers rather than buyers as in the traditional electricity value chain. Grid companies, the TSO, retailers and producers of renewable energy sources are potential buyers of flexibility. The value chain as seen in Figure 2.5 will be explored throughout this thesis. First, the value chain is analyzed without any intermediary party between the buyers and suppliers. Further, an aggregator as an intermediary will be introduced. As the name indicate, an aggregator aggregates flexibility bought from the suppliers and resell the flexibility to the various buyers either through contracts or markets.

2.3.1 Suppliers of flexibility

There are several ways to classify suppliers of flexibility. Three different types of suppliers are considered based on their activity and typical electricity load profile; industrial suppliers, commercial business suppliers and household suppliers. Each segment of suppliers[8] represents different load profiles and thus different potential for demand response. The flexibility potential is greatest in electrical appliances that need significant power and are used for large periods of time. Thus, thermal appliances often represent large potential of flexibility. In the Nordic countries the electricity consumption peaks take place during the coldest hours of the year, and thermal appliances are thus important.

[8]Notice that suppliers of flexibility also are *consumers* of electricity.

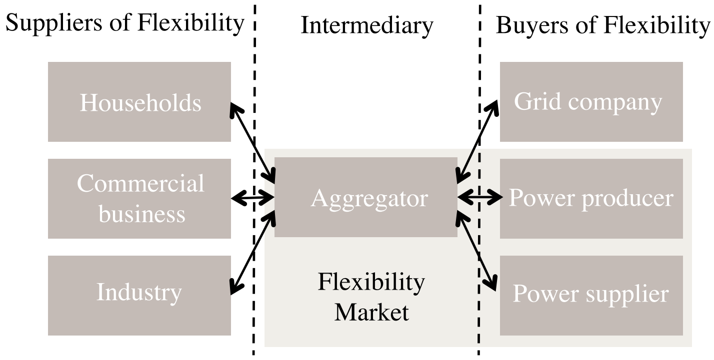


Figure 2.5: Value chain for flexibility.

Each segment's potential for providing flexibility is defined by their electricity load profiles which is briefly described in the following. Figure 2.6 shows the share of total consumption in Norway for each segment [3].

Industrial consumers are typically large actors with high electricity consumption, especially in energy intensive industry. They are often able to switch their production patterns to take advantage of low electricity prices in off-peak hours. Similarly, many of them have power generation units or heat facilities that enable them to respond to high electricity prices. Unlike the other groups of consumers, many industry actors are active participants in the electricity market today. They buy and sell electricity in the spot market, as well as placing bids of flexible load in the Balancing Market. Large industry consumers already have incentives to exploit the full potential of flexibility in order to make their business less dependent on energy prices, reduce their costs and increase their competitiveness in front of their competitors.

Commercial business consumers represent service industries like offices, schools, stores, and hotels and make up around 20 % of total electricity consumption in Norway. Heating and cooling are the main sources of consumption for this segment. Thus commercial buildings can be seen as storage resources [9]. The buildings can often be pre-heated and pre-cooled efficiently, and this flexibility could be exploited. Large commercial businesses usually have control and management systems for heating and cooling, which an aggregator or the business itself can exploit to manage demand response. Commercial businesses with large refrigerating appliances have significant potential of flexibility as refrigerators provide storage solutions. A few incentive-based programs for securing reserves exist in Norway today for this segment, but only for large commercial consumers.

Household consumers represent private consumers. Energy consumption in households depends on several factors, like members in the household, outside temperature, living space and the economy of the household. The energy is used for space heating, water heating and electricity specific consumption, i.e. lights and electric appliances. Electricity accounts for around 80 % of the total energy consumption in households. Thermal appliances with ability to store energy such as water heaters represent the appliances with largest potential, while the potential of other equipments, such as washing machines, is smaller and less reliable [10]. Many barriers, making it hard for households to provide flexibility, exist today as well as very low economic incentives. These must be removed in order to release the potential of flexibility. Additionally, households need further development of home automation and smart housing to enable flexibility.

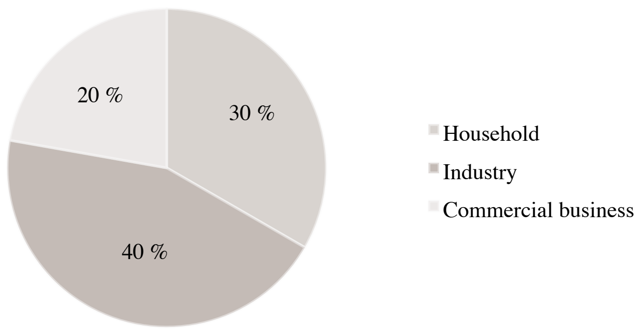


Figure 2.6: Share of total consumption for each consumer segment.

Micro-generation refers to a wide variety of energy sources, like river or pumped storage power plants, photovoltaic, wind, biogas or small cogeneration installations [10]. Small-scale decentralized generation of electricity is expected to expand in the future, and also small electricity consumers can become prosumers. This will increase the potential to provide flexibility among suppliers, but will also impose challenges to the distribution grids which have to be addressed by the grid companies.

2.3.2 Buyers of flexibility

Various market actors with diverse and often contradictory interests are acting within the energy market, and they may all have an interest in demand side flexibility. The primary players requesting flexibility are the System Operators, i.e. the TSO and grid companies. It is also believed that other actors as retailers and producers of renewable energy can exploit flexibility to reduce volume risks and imbalance costs. In this thesis the buyers of flexibility include grid companies, retailers and producers of wind power. The role of the TSO will also be described, however this actor is not included in the analyses as the TSO holds many of the same interests as grid companies but at a central level. Few of the existing market participants are utilizing the potential of the flexibility today, but some grid companies and the TSO have bilateral agreements with large flexible consumers or industrial consumer to shut down the production or switch to different energy sources, as oil or gas, if the load exceeds certain limits.

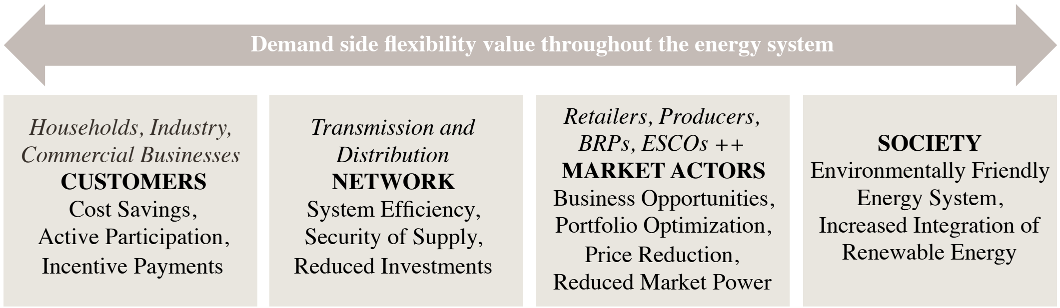


Figure 2.7: Value of demand side flexibility. Contents adapted from [10].

When describing the need for flexibility it is important to distinguish between power and energy. Power, given in watts, is defined as the instant flow of energy in the power system and does also describe the electrical size of a component or a system. Energy, measured in watt-hours, is the amount of energy produced or consumed during a certain period of time, and the basis for the present electricity tariffs for end-users[10]. For a grid company it is exclusively flexibility in terms of power that is required on a local basis. For other market actors such as retailers, aggregators, balancing responsible parties, TSOs and ESCOs that act on a more global level, the location of the consumers are of less importance and not relevant to their activities as long as the system is stable.

Grid companies are responsible for the distribution network and transportation of electricity from suppliers to customers, and are also responsible for investments to connect customers to the grid as well as to maintain and extend the grid capacity when necessary. They operate on a local or regional basis, and act like natural monopolies ensuring system reliability and stability at all time. The key dimension for grid planning and operation is the peak load, whereas the volume of transported energy is of less importance. Today's electricity grids are not dimensioned for the future changes in the energy system like increased use of electrical vehicles, changing behavior of consumers and a larger share of decentralized production [10]. High consumption peaks require expensive reinforcements of what are often the less utilized parts of the network. For grid companies flexibility has the potential to optimize the operation and planning of distribution networks. By decreasing demand in peak load hours the grid company can achieve lower costs, enhance security of supply, increase system reliability and contribute to sustainable energy development through facilitating the low carbon technology roll-out. Flexibility can also be valuable in terms of postponed or replaced network reinforcements. As the grid company faces local challenges, like congestion on a certain line or substation, only end-users connected to that node can offer adequate flexibility to solve the problem. Hence, only a limited number of grid users can supply flexibility[10]. It is expected that grid companies have to play a more active role in the electrical system in the future, and it will be necessary to increase the use of real time monitoring and advanced controlling equipment in the distribution grid as the electricity system changes. The authors believe that flexibility and smart grid technology will be vital for the grid companies to cope with the present and future challenges.

The *TSO* operates the national grid and is the overall system responsible party for each country or control area. The TSO is also the market operator of the ancillary service markets and hence responsible for maintaining balance between production and consumption in the delivery hour. Like grid companies, the TSO faces challenges as insufficient capacity and short lifetime in the transmission networks and in a worst case scenario the risk of blackout is present. By exploiting flexibility the transmission network security can be improved including network congestion, and voltage and frequency stability during outages. Additionally, the transmission capacity can be optimally utilized and peak load in hours with high consumption can be reduced. This will increase the reliability of supply and reduce costs associated with losses in the grid. Also large grid investments can be reduced and postponed. As the market operator of the Balancing Market, the TSO can activate flexibility for balancing purposes and ancillary services. Most of these benefits are hard to value in financial terms, but an alternative valuation can be derived from cost savings due to improvement in network security.

Retailers are companies that sell electricity to the end-users. There are many retailers operating in a competitive market today. The retailers buy electricity either on the Nordic power exchange or directly from production companies. When placing bids on expected consumption in Elspot, the retailers might face imbalance costs if the real consumption deviates from the submitted bid, in other words a volume risk is present. By utilizing demand side flexibility these imbalance costs can be reduced. In many countries the electricity prices are very volatile and the retailers face price risks. In these countries, flexibility can reduce both risks associated with price variations and volume. By including flexibility in the submitted bids in Elspot and react to spot prices, the elasticity of demand will increase and the average spot price of electricity will decrease.

The *power producers* generate and sell active power. Electricity production from intermittent energy sources as wind, solar and wave is not predictable and controllable to the same extent as hydro power and energy from fossil fuels. Hence producers have to base their production bids on forecasts. Hence, producers of renewable energy is more exposed to imbalance costs than other producers due to unpredictable and frequently deviations from production forecasts. Flexibility can be utilized to reduce these imbalance costs. As hydro power counts for 99 percent of the electricity production in Norway, imbalance costs are not a major problem and additionally the regulating prices are low. However, in other countries this challenge is more prominent and it is expected to change in the Nordic system as well with the increasing integration of production from wind power. When considering the role of a power producer in this thesis, a producer of wind power will be studied.

2.3.3 Aggregator

A new and possibly essential role in the future electricity system is the aggregator. An aggregator will be especially important for small suppliers, facilitating them to sell their flexibility. Aggregators act as intermediaries between suppliers who provide the flexibility and the procurers of this flexibility. On one hand the aggregators handle flexibility at the retail level by offering innovative solutions that are interesting for the suppliers and on the other they aggregate individual flexibility in sufficiently large volumes for it to be traded in a market or through contracts with buyers. In the present system very few actors has taken on the role as aggregators, and there is no clear definition of which services this role can offer. Examples of proposed services are controlling equipment and software to manage loads, consulting services within energy efficiency and demand response, management of power production, market entrance for other actors and a fully allocation of energy where different loads is controlled directly by the aggregator. In order for the aggregator to offer innovative services it might be necessary to specialize in one specific service, for instance recharging electric vehicles or controlling heat pumps, with their business models solely concentrating on the special properties of selected technologies [8]. If aggregators specialize in few services, a large number of aggregators can exist in the market which will increase competition. This thesis will present some of the business opportunities of flexibility addressed to aggregators.

Several possible actors can take the role as aggregators. Existing actors in the power market can include an aggregator role in their businesses. The aggregator can also be a third-party actor, for instance a consulting company or an IT service company. If the aggregator does not have balance responsibility, a decrease or increase of electricity consumption or production might lead to imbalances for the retailer of the relevant supplier of flexibility. Thus, the balancing responsible party or the retailer would be affected by actions of other participants if their customers, i.e flexibility suppliers, are involved. This externality must be addressed in some way, for instance by regulating aggregators or through operating permits of flexibility [10]. Retailers have many incentives to adapt this role. They are already balance responsible parties and are established participants in existing markets. Retailers also operate in an competitive environment, and new flexibility services may give them competitive advantages. Another advantage is that retailers already manage customer portfolios. Hence, they have an advantage compared to a new unknown actor offering aggregator services. Through experience from participation in the power markets, the retailers have achieved great knowledge about price trends and revenue possibilities. Regardless of whom taking the aggregator role, it needs to be ensured that the actors providing flexibility services act in a way that do not hinder the security of supply or the safety and data privacy of the suppliers [10].

2.4 Previous research

Most of the previous research related to future changes of the power market concentrate on the technological aspects. In contrast there has been less focus on the interactions between participants of demand side flexibility and how this resource can be extracted as well as allocate the value efficiently in the value chain. In recent years more attention has been paid to demand side flexibility. Large power actors and Governments have started to realize the importance of this resource in the future energy system, and proposed guidelines on how flexibility should be extracted and implemented in the system. In [8] the TSO in Denmark and the Danish Energy Association propose a Smart Grid concept which can be used to mobilize and activate flexible electricity consumption and production from small customers and recommend how this concept should be implemented. In May 2014 GEODE published a report [10] stating the vital role of demand side flexibility for the future success of the Distribution System Operators across the European Union. Some researchers and academics have studied various methods of trading flexibility as well as to activate the resource from small suppliers. Most of these studies can be categorized into two main groups. The first group focuses on contract design between flexibility participants, while the other group has a market-based approach for flexibility.

2.4.1 Contract design between flexibility agents

The major part of the study in this group design contracts between the procurers of flexibility and the suppliers, with the main focus on how to engage suppliers as flexibility participants. Fahrioğlu and Alvarado [2] employ a mechanism design approach for designing incentive compatible contracts between a utility and its customers, where the suppliers reveal their private information about costs. The strength of this approach is that the asymmetry of information is addressed. Nevertheless, only a subset of possible buyers and suppliers of flexibility is considered and potential intermediary parties are not taken into account. [16] presents a contract design framework that enables demand side resources to participate in ancillary services markets. They exploit mechanism design as well to design incentive compatible and individually rational contracts in the presence of asymmetric information. The model analyzes the effects various contract design parameters have on the cost and amount of flexibility procured.

2.4.2 Market-based approach of flexibility

Some studies have shifted the focus towards trading in markets. The authors in [28] use mechanism design to discover supplier categories and determine the adequate incentives for each case and implement this in the unit commitment model of existing electricity markets. The strength of this model is that it considers the relationship between flexibility, the daily market price of electricity and the generation. However, this study only include flexibility in existing markets and does not evaluate benefits of other market solutions of flexibility. The authors in [14] and [15] propose a separate flexibility market where all buyers and suppliers can participate. Both papers treat flexibility as a public good, an argues that this leads to efficient allocations in a socio-economic view. These two papers will be described in more detail in Chapter 6.

2.4.3 Combined studies of flexibility

In this thesis studies from both groups will be combined in order to analyze if a larger share of the potential for demand side flexibility can be utilized. Both value and costs of flexibility will be quantified in order to find efficient solutions for trading flexibility. Possible bilateral contracts between aggregators and buyers will be designed, a subject that is not previously studied as far as the authors know. The thesis will not only concentrate on grid companies as procurers of flexibility as most previous research, but will consider several possible buyers and suppliers to extract the full value of flexibility. Market-based and contractual solutions will be evaluated from both the perspective of each single participants and the total social benefit of flexibility.

Chapter 3

Cost and Benefit Functions of Flexibility

Many studies have been carried out about benefits of flexibility, and most of them clearly state that there indeed exists several benefits of exploiting this resource as described in Chapter 2. However, distributing the benefits and costs fairly across all players is a challenging task that need to be studied in more detail. In order to distribute the value and cost of flexibility they first have to be quantified. This chapter defines functions for quantifying costs and benefits of flexibility for suppliers and buyers, respectively, as well as explain the shape of these functions. The parameters are estimated in order to be used in illustrative examples in the next chapters. Additionally, a description is given on how decision makers can use sophisticated empirical data to estimate these parameters more accurately. The chapter also explains how these functions can be modeled as individual supply and demand curves and used in the market clearing of a flexibility market. The market demand and supply curves are obtained by horizontally summing all the individual demand and supply curves.

Several assumptions with stressing are made in this chapter. The benefit and cost function are constructed on an hourly basis and only applies to hours with peak load consumption and hence hours with high demand for flexibility. High demand results in high flexibility prices which clearly affect the illustrative studies. The numerical values found in this chapter will be used for illustrative examples when studying contractual and market-based business models of flexibility. The estimates are based on data from various sources, and are scaled to adapt the cases and scenarios studied here. The estimates often rely on average values and represents average actors in Norway. These approximations will clearly affect the numerical results throughout the thesis.

3.1 Cost Function for Suppliers of Flexibility

Costs of supplying flexibility are hard to quantify as a large share of the costs vary with individual preferences and are not always of the monetary art. This section will derive a cost function for flexibility and propose a guideline for how the parameters in the cost function can be quantified.

3.1.1 Factors influencing the cost

The cost of supplying flexibility for end-users depends on several aspects. First of all, the amount of load shifted or reduced will obviously affect the cost and will vary depending on which load the suppliers are required to shift or reduce. If the amount of the curtailment is low the suppliers employ the cheapest loads for demand response. As the amount increases, more expensive loads have to be reduced or shifted. [32] presents an overview of different categories of load:

- Inflexible load: no flexibility, the load must be met at any time, e.g. alarms, lights, base load. Inflexible load is consumption in which the end-users value too high to reduce of shift.
- Reducible load: can be reduced, it is accepted that only parts of the load is met. The reduced volume will not be met at a later time. A loss in comfort may occur, and thus a corresponding cost, e.g. dimmed lights, ventilation systems.
- Flexible/portable load profile: can be moved in time, but the load profile is kept. Can be moved both forward and backward in time, e.g. washing machines, industrial processes.
- Flexible/portable volume: can be moved in time, and the load profile can be changed as long as the total volume is covered. Can be moved both forward and backward in time, e.g. batteries, heat loads and charging of electric vehicles.

Costs of various loads are illustrated by alternative prices in Figure 3.1. Electrical water heaters and other heating systems with storage capacity can be considered as relatively cheap flexibility, while base loads which are relatively inflexible have very high alternative prices. By shifting load connected to washing machines, dryers or dishwashers in households, or heating or cooling systems in office buildings, an alternative cost of reduced comfort will apply. Flexibility with high alternative price can typically be time shift of production processes for factories.

Second, the cost differ for each individual end-user since they have individual preferences regarding load reduction or load shifting and hence depend on the supplier type. Finally, the duration and timing of the curtailment will also influence the cost. The cost will typically increase the longer the load has to be reduced. Further in this thesis, the cost will only depend on the supplier type or the preference of the supplier and the volume of flexibility supplied in order to simplify the cost function. The duration of the curtailment is fixed to one hour.

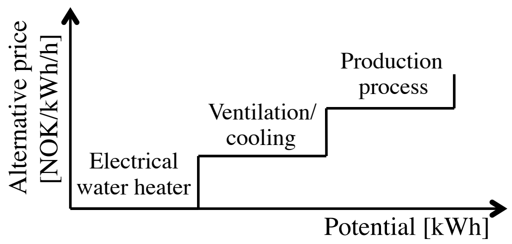


Figure 3.1: Cost of various electricity loads. Adapted from [13].

3.1.2 Cost function and supply curve

The cost of supplying flexibility can be described through the suppliers' cost functions. The cost functions will differ between the various supplier segments[1] based on their expected cost of providing a certain amount of flexibility, but the shape of the curve remains the same for all suppliers. The cost $C_s(\theta_s, x_s)$ of curtailing x_s kW to a supplier of type θ_s is assumed given by

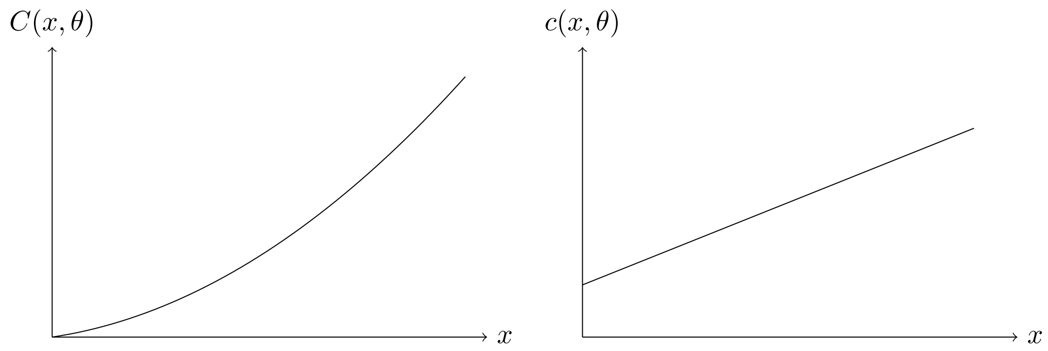
$$C_s(\theta_s, x_s) = a_s x_s^2 + b_s(1 - \theta_s)x_s \qquad \forall s \in S \tag{3.1}$$

Here θ_s is a continuous variable describing the supplier type or the supplier preference parameter. This parameter can be explained as the *willingness* for each supplier type to curtail or shift load. For households, θ_s reflects private preferences of providing flexibility and includes loss of comfort and privacy. For industry and commercial businesses θ_s can describe the inconveniences of shifting production schedules or reducing comfort and work effort. Higher values of θ_s imply higher willingness. a_s and b_s are cost coefficients and are assumed equal for all supplier types in the same segment. The term $-b_s x_s \theta_s$ makes sure that various values of θ_s lead to different values of the marginal cost for the supplier. Additionally, as θ_s increases the marginal cost decreases. Thus, the cost function implies that the supplier with the lowest θ_s will have the highest marginal cost and hence the lowest marginal benefit. For the sake of simplicity, the probability distribution of θ_s, $F(\theta_s)$, will be modeled as a uniform distribution where θ_s is a random variable in the interval [0, 1]. This probability distribution is known to both the buyer and the suppliers, but the value of θ_s is suppliers' private information and is unknown to the buyer.

The shape of the cost function is illustrated in Figure 3.2a. The cost function is strictly convex and the marginal cost is positive and linearly increasing with the amount of flexibility. Intuitively, this shape can be explained by the different costs of various loads. When the supplier delivers only small amounts of flexibility the supplier can reduce or shift the loads with lowest cost first. As more flexibility is reduced loads with higher cost

[1]As defined in Subsection 2.3.1 the suppliers are divided in households, industry and commercial businesses.

have to be curtailed, thus increasing the cost. The same reasoning apply for the marginal cost, which will increase as more expensive loads are interrupted, i.e. the amount flexibility x_s is high. When the amount of flexibility supplied is so high that inflexible loads have to be interrupted, the cost increases rapidly as seen in the figure. The cost will increase until all loads have been curtailed. An exponential function can be a more suitable description of the costs as the cost will increase more rapidly when converging towards the maximum load available. For mathematical convenience the function stated in (3.1) will be employed in further analyses.



(a) Cost function of flexibility **(b)** Supply curve of flexibility

Figure 3.2: Shape of the total and marginal cost function of supplying flexibility.

If the flexibility is traded in a market, the individual supply curve can be derived from the derivative of the cost function $\frac{\partial C_s(x)}{\partial x}$ for a given supplier type θ which corresponds to the marginal cost of suppling flexibility. The supply curve indicates the relationship between the price of the flexibility and the supplied volume. The supply curve for an individual supplier s is

$$c_s(x_s) = 2a_s x_s + b_s(1 - \theta_s) \qquad \forall s \in S \tag{3.2}$$

The total aggregated supply curve is found by horizontally summing the individual supply curves for each supplier.

$$c_{agg} = \sum_{s=1}^{S} [2a_s x_s + b_s(1 - \theta_s)] \tag{3.3}$$

3.1.3 Quantifying costs

Besides the technical ability, the engagement of a supplier to provide flexibility to the system depends on his individual *preferences* regarding the costs and benefits associated with this supply. Quantifying costs of flexibility can be challenging both because of the individual influence of providing flexibility and the fact that they are hard to measure. Additionally, not all costs associated with supplying flexibility are of the monetary art. Monetary costs could for example include lost production, higher costs for moving production in time or start-up costs, while non-monetary costs include loss of comfort, loss of privacy and other individual costs. Non-monetary costs arise especially for households. The total socio-economic cost of supplying flexibility can exceed the private cost of every supplier due to the complexity of the electricity system. Flexibility can for instance impose imbalance costs or reduced sale of electricity for the producers. From a socio-economic perspective all costs should be considered. However, for simplicity only the private costs will be taken into account in the analyses.

[18] presents the results of comprehensive surveys held to reveal the cost of energy not supplied (CENS) for electricity consumers. A similar approach with surveys can be employed to estimate the cost of providing flexibility among potential suppliers. Several methods can be used in the surveys to estimate private costs including [18]:

- *Direct Worth* a method utilized to reveal the respondents direct costs as a consequence of supplying a given amount of flexibility from different loads.
- *Willingness-to-pay* used to map the respondents willingness to pay for not reducing or shifting different loads.
- *Willingness-to-accept* map the compensation the respondents require to supply flexibility.

The survey should employ at least two of the methods in order to improve the estimate. After the surveys are collected, the data should be processed. The cost parameters could be normalized in order to compare the costs within a supplier segment. By so doing, the average of the costs within a segment could represent the cost function for the whole segment. Some common normalization factors are yearly electricity consumption and maximal effect. The advantage of surveys is that they can be customized to find specific information. There are some drawbacks as well, including high costs and use of resources and other common problems typically involved with surveys [18].

3.2 Numerical Estimates of the Cost

The numerical values of the cost coefficients are the basis for the illustrative studies throughout this thesis. They are employed in both the maximization problem when designing contracts and in the market clearing of flexibility markets. This section will present the estimation methods and the assumptions for calculating cost coefficients for various suppliers as well as the results. In addition to each segment's cost function, an aggregated cost function representing a large supplier and the market supply curve, respectively, are presented as they will be employed in calculations later on.

3.2.1 Estimates of costs for individual suppliers

The numerical estimates for the cost coefficients are based on the rates of CENS found through surveys in [18]. Both Direct Worth and Willingness-to-pay were used in the surveys, and the rates represent the average of the replies from the two methods. The rates employed in the estimation of the cost coefficients are shown in Table 3.1 and are given for a power interruption of one hour. Unlike power interruptions, supplying flexibility is voluntarily and notified in advanced. Moreover, only a share of the supplier's entire load are curtailed. Consequently, the rate of CENS are scaled down in the calculation of the cost coefficients. When small amounts of flexibility are provided the cost constitutes a minor share of the CENS. As more flexibility is provided and expensive loads are reduced the cost of providing flexibility converges towards the scaled CENS. The average consumptions are calculated from data in [3]. Appendix A.2 illustrates various amounts of flexibility curtailed and the corresponding estimated cost of providing this flexibility for the three supplier segments. Based on these values regression analyses are performed to find the cost coefficients for each segment and the results can be seen in Table 3.2. The regressions are conducted with a fixed willingness parameter $\theta = 0,5$. For simplicity, it is assumed that these numerical values of the coefficients holds for all values of θ. In reality they will deviate if θ changes and new regressions should be performed for each θ. Complete calculations can be found in the attached Excel-file[2].

Table 3.1: Input data for estimating costs for suppliers of flexibility.

	Avg. consumption [kWh]	CENS [NOK/kWh]
Industry	278	33,7
Commercial business	23,18	55,8
Household	2,71	8,6

As the results indicate, household suppliers have the lowest unit cost of providing flexibility. However, a single household has relatively small amounts of flexibility due to the low consumption compared to an industry or commercial business supplier. Thus, a large number of household suppliers are required to obtain sufficient volumes of flexibility, which may be costly. Additionally, household suppliers have to install automation systems before they can participate whereas large commercial and industry suppliers often have controlling systems installed already. For an aggregator or a buyer there will be a trade-off between lower unit costs and large number of suppliers as well as the reliability of each supplier type. Note that the duration of the curtailment is fixed to one hour, and hence does not take costs of curtailment in subsequently hours into consideration. If the duration was two hours instead, the cost would probably increase by more than the additional cost for one hour as implied here. This is not taken into account in the thesis.

[2] *3 Cost Functions.xlsx*

3.2.2 The aggregated supply of flexibility

For further calculations a fictive large supplier is needed to match the demand of one buyer. The large supplier can be seen as an intermediary party with aggregated flexibility. In the illustrative study the aggregated portfolio consist of 15 industry suppliers, 150 commercial businesses and 2 000 households. In order to find the aggregated cost coefficients for this supplier all the individual cost functions are horizontally summed and the results are illustrated in Table 3.2.

When studying a flexibility market the aggregated market supply can be found by horizontal summation of the supply curves of each individual supplier providing flexibility to the market. It is assumed that the total market supply includes flexibility from 120 industry suppliers, 1 000 commercial businesses and 10 000 households. The share of households are relatively low as it is assumed that these suppliers have less incentives to participate in the near future. Estimates of the aggregated market supply are indicated in Table 3.2. The size of this market corresponds to a small local market.

Table 3.2: Cost coefficients for various suppliers [NOK/(kWh/h)].

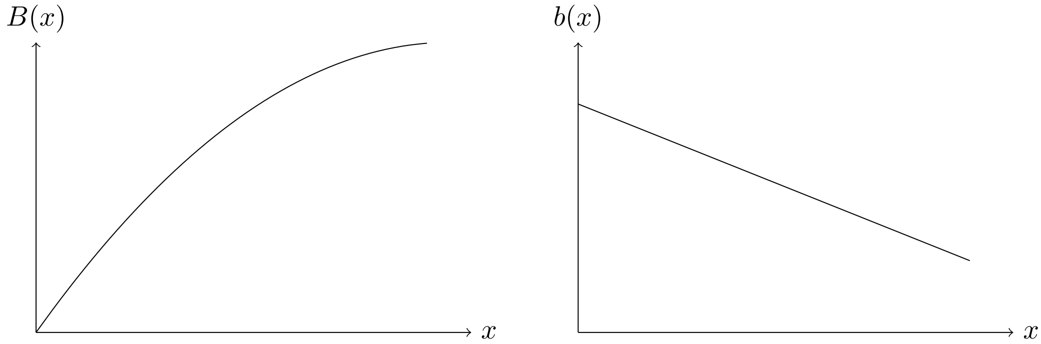
	a	b
Industry	0,04148	0,68950
Commercial business	0,82830	1,2000
Household	0,74320	0,09843
Large supplier	0,00030935	0,2243
Supply curve	0,000057	0,26996

3.3 Benefit Function for Buyers of Flexibility

The value of flexibility for the different actors in the power market can be described through their benefit functions. The benefit functions will differ between the buyers based on the expected benefit of having a certain volume of flexibility available in the hours when its needed. It is assumed that the benefit $B_j(x_j)$ for buyer j of having x_j kW of flexibility available in a certain hour is given by

$$B_j(x_j) = -\alpha_j x_j^2 + \beta_j x_j \qquad \forall j \in J \tag{3.4}$$

where α_j and β_j are the valuation coefficients for buyer j. These coefficients can be determined by performing quantitative analyses of the buyers' benefits from different volumes of flexibility available. Notice that the benefit represents net benefit and does not take into account the costs of buying the flexibility. Calculating benefits of flexibility are not simple and entails estimating the financial value of flexibility actually delivered



(a) Benefit function of flexibility   **(b)** Demand curve of flexibility

Figure 3.3: Shape of the total and marginal benefit function of procuring flexibility.

to the power system. Without an accurately estimation method, it will be challenging to justify the improvements related to the exploitation of flexibility.

The shape of the benefit function is illustrated in Figure 3.3a. Notice that the function is strictly concave. The marginal value of the flexibility is positive and decreasing with the available volume of flexibility. The shape of the function can be justified based on the assumption that the benefit will increase when the volume of available flexibility increases until the maximum volume of flexibility required is reached. In other words, the share of the reduced investment cost or reduced imbalance cost will increase as more volume of flexibility is available. The decreasing marginal value can be explained by the fact that a small amount of flexibility is sufficient to postpone and reduce large costs, while large volumes of flexibility are needed less frequently. This is shown in Figure 3.4, in which illustrates that having a moderate amount of flexibility can cover the majority of the needs. For a grid company it can be a matter of small margins to avoid congestion, and for a producer of wind power or a retailer the deviations from scheduled production and consumption are normally moderate.

When the flexibility is available through a market, the demand curve for flexibility can be derived from the derivative of the benefit function, $\frac{\mathrm{d}B_j(x_j)}{\mathrm{d}x_j}$, given in equation (3.4). Hence, the demand $b_j(x_j)$ of buyer j for x_j kW flexibility is

$$b_j(x_j) = -2\alpha_j x_j + \beta_j \qquad \forall j \in J \tag{3.5}$$

By horizontally summing the demand curves of all the buyers total demand for flexibility is determined as

$$b_{agg} = \sum_{j=1}^{J} [-2\alpha_j x_j + \beta_j] \tag{3.6}$$

Notice that when looking at the demand for flexibility through a market perspective it is assumed for simplicity that there are no restrictions on transfer capacity in the grid so that only one market for flexibility exists. Figure 3.3b shows the demand curve for flexibility.

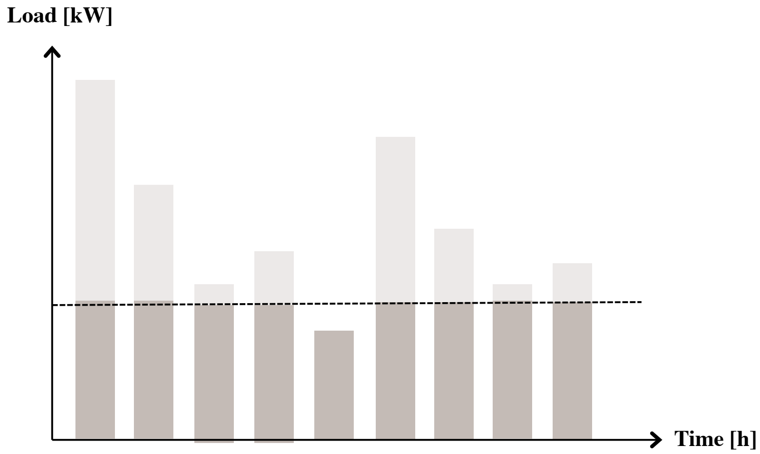


Figure 3.4: Justification of the shape of the benefit function.

3.3.1 The value of flexibility for a grid company

[12] states that the largest benefit of flexibility for a grid company is reduced and postponed investments in lieu of capacity expansion. In addition, costs associated with operational reliability C^R and cost of energy not supplied C^{ENS} can be reduced. The benefit $B_G(x)$ for a grid company by reducing a planned investment I and postponing it in $n(x)$ years when having x kW flexibility available in the hours it is needed is given by

$$B_G(x) = I - (1 - \rho(x))I - \frac{\rho(x)I}{(1+i)^{n(x)}} + \Delta C^{ENS} + \Delta C^R \tag{3.7}$$

Here $\rho(x)$ is the percentage share of the investment that can be postponed, i is the interest rate, ΔC^{ENS} is the reduced cost of energy not supplied and ΔC^R is the reduced cost associated with operational reliability. The first term I represents the planned investment, the second term $(1 - \rho(x))I$ is the investment that cannot be reduced, while the third term $\frac{\rho(x)I}{(1+i)^{n(x)}}$ is the present value of the share of the investment that can be postponed and the two last terms represent the reduced costs of reliability and CENS. The expression states that for each investment, ρ and n are dependent on the volume of flexibility, x, available. If a grid company is planning an investment to increase the capacity of the grid, this investment can be reduced, postponed or even eliminated by having access to a certain volume of flexibility in hours with need, securing a capacity within the given limits.

To simplify the calculations in this thesis ΔC^{ENS} and ΔC^{R} are neglected, but these parameters should be included if the model is used for operational decisions. The demand of flexibility for a grid company can be calculated based on expected congestion in the grid related to a planned investment. A larger volume of flexibility available increases the share of the investment postponed, and can be postponed for a longer time period. At the same time a greater volume of flexibility will decrease the risk of postponing investments. Through simulations of the load capacity required in transmission lines or a transformer one can determine the required volume of flexibility needed to reduce a certain investment cost. By studying empirical data and using forecasting models the relation between the share of investment reduced, the number of years the investment can be postponed and the volume of flexibility can be found.

3.3.2 The value of flexibility for a producer of wind power

For a wind power producer, or other producers of energy from intermittent sources, flexibility can compensate for costs associated with irregular production and deviations from scheduled production. When the actual power production deviates from scheduled production[3], the producer faces imbalance costs. Table 3.3 presents the different costs occurring for a wind power producer based on the direction of the regulating volume and the system balance. This is known as the two-price model.

Table 3.3: Two-price model for regulating costs in the Balancing Market.

Actors balance	System balance	
	Surplus $\sigma_h = 1$	**Shortage** $\gamma_h = 1$
$x_h^A > x_h^S$	$P_h^{SPOT} - P_h^{DOWN}$	0
$x_h^A < x_h^S$	0	$P_h^{UP} - P_h^{SPOT}$

When actual production x_h^A deviates from scheduled production x_h^S the producer of wind power will face imbalance costs based on the volume of deviation and the system balance. If actual production is higher than scheduled production, the producer receives spot price when the system is in shortage or downward regulating price if the system is in surplus. Consequently, in the first case the price for the excess production equals the spot price, and no loss incurs. In the latter, the producer only receives downward regulating price for the excess production, and hence faces a lost revenue. When actual production is lower than scheduled production, the producer pays spot price when the system is in surplus or upward regulating price when the system is in shortage. Here the producer has to pay spot price or upward regulating price to cover the production

[3]Here it is assumed that scheduled production equals the volume bid into Elspot

deviations and can resell it for spot price, thus facing a loss in the latter situation. In hours with system balance, the upward and downward regulating prices are equal to the spot price, and the power producer will not incur imbalance costs, or lost revenue. The cost or lost revenue given in NOK/MWh caused by production imbalance P_h^{BAL} in hour h is given by

$$P_h^{BAL} = \begin{cases} (P_h^{SPOT} - P_h^{DOWN})\sigma_h & \text{if } x_h^S < x_h^A \\ (P_h^{UP} - P_h^{SPOT})\gamma_h & \text{if } x_h^S > x_h^A \end{cases} \qquad \forall h \in H \tag{3.8}$$

where P_h^{SPOT}, P_h^{DOWN} and P_h^{UP} is the spot price, the downward regulating price and the upward regulating price in hour h respectively. The binary variables σ_h and γ_h are equal to one if the system is in surplus or shortage respectively. To ensure that the system is in either shortage, surplus or balance, the following restriction is added

$$\sigma_h + \gamma_h \leq 1 \qquad \sigma_h, \gamma_h \in \{0,1\} \qquad \forall h \in H \tag{3.9}$$

If both σ_h and γ_h are equal to zero the system is in balance and no imbalance cost occurs. In the case of deviations from scheduled production, the volume of regulating quantity needed in each hour x_h^R is defined as

$$x_h^R = \begin{cases} x_h^A - x_h^S & \text{if } x_h^S < x_h^A \\ x_h^S - x_h^A & \text{if } x_h^S > x_h^A \\ 0 & \text{otherwise} \end{cases} \qquad \forall h \in H \tag{3.10}$$

This expression declares the regulating quantity which is always positive or equal to zero when there no deviation occurs. Finally, the hourly benefit $B_P(x_h^F)$ of reduced imbalance costs for a producer of renewable energy when having x_h^F MW flexibility available in the specified hour is

$$B_P(x_h^F) = \begin{cases} P_h^{BAL} x_h^R & \text{if } x_h^R \leq x_h^F \\ P_h^{BAL} x_h^F & \text{if } x_h^R > x_h^F \end{cases} \qquad \forall h \in H \tag{3.11}$$

If the available volume of flexibility is equal to or higher than the regulating volume required, the benefit is simply calculated as the regulating volume multiplied with the cost or lost revenue from imbalance. On the other hand, if the available volume of flexibility is less than the needed regulating volume, the benefit is given by the profit from the available volume of flexibility. Notice that the benefit is given on an hourly basis and that it includes both costs and lost revenues.

By having a certain amount of flexibility available at all time the yearly imbalance costs are assumed to be reduced by a given percentage share. The greater volume of flexibility available, the greater reduction of the imbalance costs can be achieved. Hence, the benefit function is characterized by the shape in Figure 3.3a. The maximum volume of flexibility required is estimated to be a percentage share of total installed capacity, given by [11]. It is difficult to predict imbalance costs, but by studying historical data, wind forecasts and obtaining knowledge about expected deviations from scheduled production it is possible to calculate an estimate of the benefit of flexibility. However, it should be emphasized that if the regulating prices are lower than the price of flexibility the producers will not benefit from procuring flexibility. Another issue for producers is the fact that average electricity prices are expected to decrease when introducing flexibility to the system, hence reducing the overall income.

3.3.3 The value of flexibility for a retailer

Like the wind power producer, a retailer faces imbalance costs due to volume risk in the daily market but the volume and frequency of the deviations from the original consumption or production schedule differs, and thus the size of the imbalance costs. Flexible load can be exploited to reduce the imbalance cost associated with the deviation in scheduled and actual consumption. The imbalance costs occurring for different directions of regulating volume and system balance, the one-price model, are presented in Table 3.4. The retailer can also use flexibility to avoid buying electricity in expensive peak load hours by bidding elastic demand curves.

Table 3.4: One-price model for regulating costs in the Balancing Market.

Actors balance	System balance	
	Surplus $\sigma_h = 1$	**Shortage** $\gamma_h = 1$
$x_h^A > x_h^S$	$P_h^{DOWN} - P_h^{SPOT}$	$P_h^{UP} - P_h^{SPOT}$
$x_h^A < x_h^S$	$P_h^{SPOT} - P_h^{DOWN}$	$P_h^{SPOT} - P_h^{UP}$

When the actual consumption x_h^A exceeds scheduled consumption x_h^S, the retailer pays downward regulating price when the system is in surplus and upward regulating price when the system is in shortage. In the first case the retailer faces a revenue from buying the extra electricity at a lower price. In the latter the retailer suffers a loss due to paying a higher price for the extra consumption than if the bid was accurate. If the actual consumption is lower than the scheduled consumption the retailer receives upward regulating price when the system is in shortage and downward regulating price when the system is in surplus. Here the retailer paid spot price for the electricity and can resell the unused electricity facing a revenue or a loss. The cost or possible lost revenue P_h^{BAL} in NOK/MWh associated with the regulating volume is given by

$$P_h^{BAL} = \begin{cases} (P_h^{DOWN} - P_h^{SPOT})\sigma_h + (P_h^{UP} - P_h^{SPOT})\gamma_h & \text{if } x_h^S < x_h^A \\ (P_h^{SPOT} - P_h^{DOWN})\sigma_h + (P_h^{SPOT} - P_h^{UP})\gamma_h & \text{if } x_h^S > x_h^A \end{cases} \qquad \forall h \in H \tag{3.12}$$

The variables are presented in the previous subsection. Notice that when actual consumption is less than scheduled consumption and the system is in shortage, the retailer face a revenue equal to $(P_h^{UP} - P_h^{SPOT})$ per MWh, likewise when actual consumption is higher than scheduled consumption and the system is in surplus the retailer faces a revenue equal to $(P_h^{SPOT} - P_h^{DOWN})$, and hence these situations are described as a negative costs. Equation (3.9) ensures that the system is in either surplus, shortage or balance, and the regulating quantity is given by (3.10).

The hourly benefit for the retailer $B_R(x_h^F)$ of having a volume of x_h^F MW of flexibility available is calculated from

$$B_R(x_h^F) = \begin{cases} P_h^{BAL} x_h^R & \text{if } x_h^R \leq x_h^F \\ P_h^{BAL} x_h^F & \text{if } x_h^R > x_h^F \end{cases} \qquad \forall h \in H \tag{3.13}$$

This can be interpreted in the same way as for the wind power producer. Demand forecasts for retailers are based on seasonally factors, weather and consumption patterns. With the increased use of electrical vehicles it is likely that future consumption will be more unpredictable, and higher imbalance costs will occur.

3.4 Numerical Estimates of the Benefit of Flexibility

The numerical calculations of the benefit for buyers of flexibility are based on hourly gain obtained by having a given volume of flexibility available in the certain hour. Large amounts of data have to be analyzed by using an appropriate estimation method to quantify the benefits. In some cases the buyer do not know the benefit obtained by exploiting flexibility and the calculations will have to be based on expected values of costs, gains and number of days flexibility is required. The approach for computing the valuation coefficients for each buyer consists of three steps:

1. Formulate an expression for the benefit of the buyer based on expected reduced costs by having a certain volume of flexibility available in the given hour
2. Calculate the benefit for different volumes of available flexibility
3. Find the valuation coefficients by fitting an analytical function, $B(x)$, to the previous obtained benefit values

3.4.1 Estimates of benefits for individual buyers

To estimate the valuation coefficients for a grid company data about yearly investments costs is based on numbers from [34]. The estimates are made for an average grid company in Norway. Only the share of investment connected to capacity expansion in the grid is considered. It is assumed that overload occurs in 5 percent of the days each year and that the duration of the problem is 5 hours, leading to an estimated hourly investment cost of 285 000 NOK. Notice that this cost only applies to the hours where flexibility is needed. The calculated benefit is sensitive to the input parameter. For instance, by assuming that flexibility is needed more frequently the hourly benefit will decrease significantly. The input data is presented in Table 3.5. The regression analysis to determine the valuation coefficients for a grid company is based on the numbers in Appendix A.2, whereas the value gain is calculated from (3.7). For simplicity ΔC^{ENS} and ΔC^{R} are neglected.

Table 3.5: Input data for estimating valuation coefficients for the grid company.

Total yearly investment cost [NOK]	26 000 000
Hourly investment cost [NOK]	284 931
Interest rate	5 %
No. of days with overload in a year	5 %
No. of hours with overload each day	5
No. of hours with overload	91

The estimation of valuation coefficients for a wind power producer examines a producer with a total installed capacity of 150 MW and expected maximum production deviations of 10 % of total installed capacity [11]. The accuracy of the production schedule is based on bids placed in Elspot 24 hours before actual production. It is assumed that the producer do not participate in Elbas to correct the production schedule closer to the hour of operation. The input data for the calculations is presented in Table 3.6.

Table 3.6: Input data for estimating valuation coefficients for the wind power producer.

	Present	Future
Total installed capacity [MW]	150	150
Day-ahead deviation	10 %	10 %
Yearly imbalance cost [NOK]	4 000 000	8 000 000
No. of hours with deviation in a year	35 %	35 %
Average hourly imbalance cost [NOK]	1 380	2 609

The yearly imbalance cost is scaled down from the estimated calculations in [4][4]. By assuming that the producer of wind power faces production deviations in 35 % of the hours in a year, an average hourly imbalance cost is calculated for these hours. The benefit curve differs from one day to another due to varying imbalance costs, and hence an average day is studied with a maximum deviation of 7,5 % of installed capacity. The

[4]An error in the calculations was detected in the original project work, but this error was corrected before the value of imbalance costs was obtained.

share of the costs to be reduced depends on the available volume of flexibility in the given hour. The calculations include both a present and a future scenario with doubled regulating costs for the producer and the retailer. It is assumed that only the regulating prices will change, and not the frequency of the deviations. The valuation coefficients derived from the regression analysis for both scenarios are presented in Table 3.8.

In reality a wind power producer is able to perform a significantly more accurate calculation of the imbalance costs. The value gain associated with the regulating volumes should be studied in more detail to justify the benefit of flexibility in this case. Especially the frequency of large regulating volumes occurring should be compared to the frequency of impacts of lower regulating volumes. By aggregating the imbalance costs for different seasons, prices, system balances and volumes of deviation, a whole year can be simulated.

The calculations for a retailer is similar to the wind power producer but rely on different assumptions and values. The yearly imbalance costs used as the basis of the calculations are obtained from [4], and serve as a pessimistic bound[5]. As the regulating prices often are equal to the spot price, it is assumed that imbalance costs only occur in 25 % of the hours during a year, independent of the number of hours with consumption deviation. A retailer with a total load of 250 MW[6] has an average deviation of 1,8 % of total load [4]. When estimating the benefit of flexibility a deviation of 0,9 percent of total load in the given hour is assumed. This assumption clearly affects the results, but is assumed to be a reasonable assumption weighing up for the high estimate of yearly imbalance costs. The input data is given in Table 3.7. The hourly imbalance costs in the hours with consumption deviations are calculated, and the share to be reduced as well as the corresponding benefit are presented in Appendix A.2.

Table 3.7: Input data for estimating valuation coefficients for the retailer.

	Present	Future
Total load [MW]	250	250
Day-ahead deviation	1,8 %	1,8 %
Yearly imbalance cost [NOK]	5 000 000	10 000 000
No. of hours with deviation in a year	25 %	25 %
Average hourly imbalance cost [NOK]	2 283	4 566

As the Table 3.8 clearly indicates, the grid company has significantly higher hourly benefit than the retailer and wind power producer. The size of the gaps between the benefits are highly dependent on the approximations and assumptions made. However, research imply that grid companies have large potentials of flexibility and it is realistic that the

[5] High imbalance costs.
[6] Corresponding to he size of Trondheim Kraft

grid company for this reason has higher benefit than the other buyers. Since the benefits for retailers and producers of intermittent energy sources rely on the electricity prices which is low today, they have larger potential in the future with possibly larger variations in prices. This is illustrated with larger valuation coefficients for both actors in the future scenario. The entire calculations and assumptions are found in the attached Excel-file[7].

3.4.2 The aggregated demand of flexibility

In order to investigate the possibility of flexibility to be traded in a separate flexibility market, the aggregated demand function needs to be defined. Here the aggregated market demand consists of two grid companies, four retailers and four producers of wind power. The demand function is given in (3.5) and the total market demand is derived by horizontal summation of the individual demand curves. Both demand in a present and a future scenario is calculated to illustrate how the market demand changes when the benefit of different buyers increases. The valuation coefficients are presented in Table 3.8, and as can be seen from the numerical results, the grid companies are dominating the demand for flexibility, especially in the present scenario due to substantially higher benefit than the other actors. It should be emphasized that these numerical results does not reflect the real market demand, but serves as a good example of how actors with different benefits affect the market.

Table 3.8: Valuation coefficients for the buyers given [NOK/(kWh/h)].

	Present scenario		**Future scenario**	
	α	β	α	β
Grid company	0,0003774	13,44		
Wind power producer	0,00004	0,4787	0,00007541	0,9049
Retailer	0,0006103	2,371	0,001221	4,742
Aggregated demand curve	0,0001887	13,44	0,0001165	10,12

[7] *3 Benefit Functions.xlsx*

Chapter 4

Contract Design

There are various ways to trade flexibility in order to allocate the value of flexibility among the participants. This chapter describes a contractual approach, in which flexibility is traded bilaterally between a supplier and a buyer to solve a certain problem. The costs and benefits as well as the risks are allocated between the actors through a chosen contract type in a simplified value chain consisting of only one buyer of flexibility and one large supplier as seen in Figure 4.1. The large supplier is aggregated from several small suppliers as described in Subsection 3.2.2. In reality, buyers of flexibility will engage in contracts with multiple suppliers of flexibility or an aggregator in order to obtain sufficient flexibility to solve their problems. The objective of the chapter is to determine the optimal contracts in various information scenarios both theoretically and applied to the energy market.

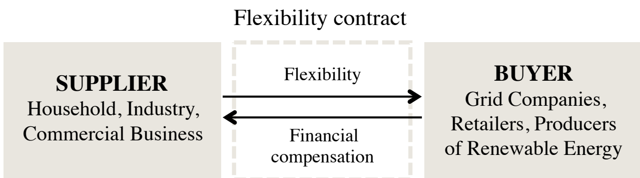


Figure 4.1: Value chain of flexibility consisting of a buyer and a large supplier.

When designing a contract, it is important to consider the lead time. Short lead time might encourage actors to strategically withhold in order to raise the price and at the same time there is no long-term financial obligations for the contractors. On the other hand, long-term agreements give more financial security which will be essential to some of the actors. For instance, a grid company may benefit from a long-term contract for delivery of flexibility if the flexibility is used to postpone investments. Additionally, the contract design will differ in the situation of a one-time offer versus a repetitive contractual relationship. This thesis focuses on contracts in general, and the lead time of the contracts and the number of contracts offered are not taken into consideration. In all contractual relationships there is a risk that the parties violate the contract terms, and hence a penalty charge should be activated if the supplier fails to deliver the contracted volume of flexibility. For simplicity the penalty is disregarded in this thesis, but should indeed be included in other contexts.

Principal-agent theory will be employed when designing contracts, in which a principal, here the buyer of flexibility, designs and offers a contract that an agent, the supplier, can accept or reject. When designing contracts, the buyer has to consider the type of contract he can offer and his available information about the supplier's cost structure of providing flexibility. A complicating factor which often leads to sub-optimal outcomes is lack of information for the buyer in the contractual relationships. Suppliers of flexibility can have private information about the their marginal cost of supplying flexibility. Buyers, on the other hand, may have private information about both their marginal costs and benefits of procuring flexibility. Both linear and nonlinear contracts are designed and analyzed in order to reach an efficient outcome under various conditions. Due to the different properties of various contract types and the different preferences among actors, multiple contracts will be studied including a profit-sharing contract, a one-part linear contract, a two-part linear contract and a nonlinear incentive compatible contract. The first section analyzes the simplest scenario with complete information. Further, uncertainty about the value of flexibility will be introduced, as well as asymmetric information about the supplier's willingness to provide flexibility.

The contract design in this chapter relies on several assumptions that is worth stressing. First, it is assumed that both the buyer and the supplier adopt an optimizing behavior and maximize their individual utility. Given the contract offered by the buyer, the supplier maximizes his own utility and chooses volume of flexibility accordingly. Second, unless otherwise stated, the buyer moves first as a Stackelberg leader. This means that the buyer will design and offer a contract to the supplier who accepts or rejects the contract. The illustrative calculations in the chapter are based on an hourly time resolution where flexibility is needed in the given peak load hour, and it is assumed that the supplier can provide sufficient flexibility to cover this demand. It is important to emphasize that the numerical results are highly dependent on the cost and benefit coefficients calculated in Chapter 3, and that the intention of the calculations is to illustrate the functionalities of the contracts in different scenarios. Only selected derivations and results will be presented in this chapter, whereas the remaining can be found in Appendix A.3. Detailed numerical calculations are given in attached Excel-files[1]. The procedure for deriving the optimal contracts is based on the work in [7].

4.1 Contracting under Complete Information

In this section it is assumed that the buyer of flexibility has complete information about the supplier's cost of providing flexibility. Hence, the buyer knows the true value of the

[1] *4 Contract Design.xlsx*

cost coefficients a and b as well as the willingness parameter θ. The benefit of flexibility $B(x)$ is also known to both parties. Under complete information, the buyer can use his knowledge about the supplier's cost structure to find the actual volume of flexibility supplied when offering different types of contracts, and hence derive an optimal contract. In reality complete information rarely occurs in contractual relationships but the analytical and numerical results in this section can serve as a benchmark for the contracts in the other information scenarios to be investigated.

The contracts to be studied under the scenario with complete information are a profit-sharing contract denoted $C1$ in the subscripts, a one-part linear contract denoted $C2$, and a two-part linear contract denoted $C3$. The procedure for deriving the optimal contract parameters is the same in all information scenarios, and thus the calculations are explained thoroughly in this section and in the following sections only the optimization problems and the derived expressions are presented.

4.1.1 Profit-sharing contract

In a profit-sharing contract the buyer of flexibility offers the supplier a percentage share $(1-\rho)$ of the joint value chain profit given by

$$\pi_{VC,C1} = -\alpha x^2 + \beta x - a x^2 - b(1-\theta)x \tag{4.1}$$

where a, b, θ, α and β are the cost and benefit coefficients of the parties. The percentage shared with the supplier depends on their bargaining power. The maximization problem of the buyer is given by

$$\max \pi_{B,C1}(x) = \pi_{VC,C1}\rho \tag{4.2}$$

whereas the maximization problem of the supplier can be written

$$\max_x \pi_{S,C1}(x) = \pi_{VC,C1}(1-\rho) \tag{4.3}$$

The optimal amount of flexibility x given in kW chosen by the supplier can be found by the derivative of (4.3) with respect to x and results in

$$x^*_{VC} = \frac{\beta - b(1-\theta)}{2(a+\alpha)} \tag{4.4}$$

As can be seen from (4.4) the optimal volume of flexibility is independent of ρ. Thus, the supplier will always choose the volume that both maximizes its own profit and the joint value chain profit. This equation also illustrates that if a buyer has large benefit of flexibility, i.e. large β and small α, the optimal volume of flexibility traded is high. Likewise this applies when the supplier have low costs, i.e. low a and b and high θ. In contrast the optimal volume of flexibility decreases with decreasing benefit or increasing costs. It is clear that under complete information a profit-sharing contract will always maximize the profit of both parties. The value chain profit as a function of the cost and benefits parameters is given by substituting the optimal volume of flexibility in (4.4) into (4.1) and equals

$$\pi_{VC,C1} = \frac{(b(1-\theta)-\beta)^2}{4(a+\alpha)} \tag{4.5}$$

Since the buyer is designing and offering the contract it is natural to assume that he has the greatest bargaining power and that he will claim the largest share of the joint profits so $\rho \geq (1-\rho)$ and thus $\pi_{B,C1} \geq \pi_{S,C1}$. In reality it is unlikely that a small supplier of flexibility, such as a single household, will have bargaining power in a contractual relationship with the buyer e.g. a grid company, and hence he will obtain only a marginal profit. In contrast a large supplier or an aggregated portfolio of suppliers will have substantial higher bargaining power and might take advantage of this in a profit-sharing contract by claiming a significantly larger share of the joint profits.

4.1.2 One-part linear contract

In a one-part linear contract the buyer offers a wholesale price w per kW flexibility to the supplier. The buyer determines an optimal contract by solving the following maximization problem

$$\max_{w} \pi_{B,C2}(w) = -\alpha x^2 + \beta x - wx \tag{4.6}$$

and finds the optimal wholesale price by investigating the supplier's maximization problem

$$\max_{x} \pi_{S,C2}(x) = wx - ax^2 - b(1-\theta)x \tag{4.7}$$

The optimal volume of flexibility x^* supplied for any wholesale price w is determined by the derivative of the supplier's profit with respect to x

$$\frac{\partial \pi_{S,C2}}{\partial x} = w - 2ax - b(1-\theta) = 0 \tag{4.8}$$

and solving (4.8) for x yields

$$x_{C2} = \frac{1}{2a}(w - b(1-\theta)) \tag{4.9}$$

The buyer now determines the wholesale price w that maximizes his profit given the optimal volume, and by substituting (4.9) into (4.6) the buyer solves the following problem

$$\max_{w} \pi_{B,C2}(w) = -\alpha\left(\frac{w-b(1-\theta)}{2a}\right)^2 + \beta\left(\frac{w-b(1-\theta)}{2a}\right) - w\left(\frac{w-b(1-\theta)}{2a}\right) \tag{4.10}$$

The optimal wholesale price is then determined by the derivative of (4.10) with respect to w

$$\frac{\partial \pi_{B,C2}}{\partial w} = -\frac{\alpha}{2a^2}(w-b(1-\theta)) + \frac{\beta}{2a} - \frac{1}{2a}(2w - b(1-\theta)) = 0 \tag{4.11}$$

Solving for w the buyer find the optimal wholesale price w^*_{C2} that should be offered to the supplier

$$w^*_{C2} = \frac{a\beta + b(1-\theta)(\alpha + a)}{\alpha + 2a} \tag{4.12}$$

Evaluating (4.12) it is obvious that buyers with large benefit of flexibility are able to offer a substantial higher wholesale price to the supplier than buyers with smaller benefit. Thus, suppliers of flexibility prefer to contract with buyers having high benefit, as grid companies, while other buyers, as retailers and wind power producers, might risk to design unattractive contracts. Additionally, suppliers with high costs require a high wholesale price compared to suppliers with low costs. Obviously, as for all contract types, the value chain profit will be low or even negative, if a buyer with low benefit, as a wind power producer, contract with a supplier having high cost, i.e. commercial businesses, and hence such contractual relationship will not be formed. In the case of a one-part linear contract the profit of the buyer is given by

$$\pi_{B,C2} = \frac{(\beta - b(1-\theta))^2}{4(\alpha + 2a)} \tag{4.13}$$

while the supplier's profit is determined by

$$\pi_{S,C2} = \frac{a(\beta - b(1-\theta))^2}{4(\alpha + 2a)^2} \tag{4.14}$$

By comparing (4.13) with (4.14) it is clear that the buyer's profit is higher than the supplier's profit as $\pi_{S,C2} = (\frac{a}{\alpha+2a})\pi_{B,C2}$ and $\frac{a}{\alpha+2a} < 1$ for all positive values of a and α. This result is not surprising since the party with the initiative to propose the contract terms, here the buyer captures the largest proportion of the value chain profit. Suppliers with low bargaining power, such as households, might obtain a higher profit from a one-part linear contract than a profit-sharing or two-part linear contract due to the degree of bargaining power. The value chain profit in the one-part linear contract is less than the optimal value chain profit given in (4.5). This results from the fact that the buyer chooses a lower wholesale price leading to a smaller amount of flexibility traded, $x^*_{C2} < x^*_{VC}$.

4.1.3 Two-part linear contract

In a two-part linear contract the buyer offers a constant unit wholesale price w per kW flexibility x and a fixed lump sum payment L to the supplier[2]. The buyer determines the contract (w, L) that optimizes his profits by solving the following problem

$$\max_{(w,L)} \pi_{B,C3}(w, L) = -\alpha x^2 + \beta x - wx - L \tag{4.15}$$

[2]In the contracts presented the lump sum payment L is defined to be paid by the buyer, but in reality the opposite will occur since the buyer is designing the contracts and will use the lump sum to extract the profit from the supplier. Hence, the value of L proves to be negative in most of the calculations.

$$\text{s.t.} \qquad \pi_{S,C3} \geq \pi_S^- \tag{4.16}$$

where π_S^- is the supplier's reservation profit and $\pi_{S,C3}$ is given by

$$\max_x \pi_{S,C3}(x) = wx - ax^2 - b(1-\theta)x + L \tag{4.17}$$

As the buyer has complete information about the supplier's cost structure he can set the inequality (4.16) to be binding. Additionally, the buyer's profit is determined by $\pi_{B,C3} = \pi_{VC,C1} - \pi_S^-$ where $\pi_{VC,C1}$ denotes the joint value chain profit given in (4.5). Thus, the maximization problem in (4.15) is equivalent to maximizing joint profits. Since L is independent of x it will not affect the supplier's decision of volume of flexibility so when the buyer offers a two-part linear contract, it is optimal for the supplier to choose the volume of flexibility that optimizes the value chain profit. The optimal lump sum L is determined by substituting (4.17) and (4.4) into (4.16), and solving for L gives

$$\begin{aligned} L^*_{C3} &= \pi_S^- - w\left(\frac{\beta - b(1-\theta)}{2(a+\alpha)}\right) + a\left(\frac{\beta - b(1-\theta)}{2(a+\alpha)}\right)^2 + b(1-\theta)\left(\frac{\beta - b(1-\theta)}{2(a+\alpha)}\right) \\ &= \pi_S^- - \frac{a(\beta - b(1-\theta))^2}{4(\alpha+a)^2} \end{aligned} \tag{4.18}$$

The lump sum is negative by definition due to (4.16) and (4.18), and hence the absolute value of L increases with increasing benefit, which means that the buyer will obtain higher profits. The optimal wholesale price w^*_{C3} equals the supplier's marginal cost for the optimal volume of flexibility in (4.4) and hence

$$w^*_{C3} = 2ax + b(1-\theta) = \frac{a(\beta - b(1-\theta))}{a+\alpha} + b(1-\theta) \tag{4.19}$$

As illustrated above, when the buyer has complete information about the supplier's cost structure it is optimal to set the wholesale price equal to the supplier's marginal cost and use the lump sum payment to extract all profits from the supplier in excess of his reservation profit π_S^-. Thus, the supplier pays a fee to the buyer to enter the contract relationship. The lump sum payment required by the buyer might decrease the incentive for small suppliers of flexibility to engage in a flexibility contract as there is already lack of incentives to induce such suppliers in providing flexibility to the electricity system. In contrast, large suppliers already aware of the value of flexibility might be willing to pay the lump sum to supply flexibility to a large buyer, and hence gain profits by doing so. The buyer profit equals

$$\pi_{B,C3} = \frac{(b(1-\theta) - \beta)^2}{4(\alpha+a)} - \pi_S^- \tag{4.20}$$

and the supplier's profit is given by

$$\pi_{S,C3} = \pi_S^- \tag{4.21}$$

Clearly the supplier profit is dependent on the balance of negotiation in the contractual relationship like in the profit-sharing contract. If the supplier has low bargaining power, he might accept a lower reservation profit than if he had greater bargaining power. It can easily be seen that the two-part linear contract optimizes the value chain profit as the sum of the profits in (4.20) and (4.21) equals the optimal value chain profit $\pi_{VC,C1}$ given in (4.5). Based on these contractual analyses a two-part linear contract is well suited for large buyers contracting with a large supplier of flexibility. When offering contracts to smaller suppliers, as households, the buyer should consider a profit-sharing contract or a one-part linear contract instead. In reality the flexibility required by the different buyers will most likely not coincide in the same hours, and hence the supplier will have the opportunity to deliver flexibility to various buyers through multiple contracts.

4.1.4 Illustrative study of complete information

The derived expressions for x, w, L and actors' profits are employed to provide numerical examples of the various contracts. Table 4.1 shows the results from the calculations in different contract types between the large supplier and a grid company. Comparing the hourly profits in the each contract, it can be seen that both the profit-sharing contract and the two-part linear contract maximize the value chain profit and yield the highest profit for the buyer if the percentage shared and the reservation profit of the supplier equal the supplier profit in the one-part linear contract. These results correspond well with the analytical analysis. In the calculations, the supplier's reservation profit is set equal to the supplier profit in a one-part linear contract and the supplier's percentage of the joint profit is 30 %.

Table 4.1: Bilateral contracts between a grid company and a large supplier under complete information.

	Profit-sharing	One-part linear	Two-part linear
Optimal volume [kW]	9 704	6 690	9 704
Supplier profit [NOK]	19 399	13 845	13 845
Buyer profit [NOK]	45 265	44 582	50 819
Value chain profit [NOK]	64 664	58 427	64 664

As stated in the previous subsections, both the optimal volume of flexibility traded and the wholesale price increases with increasing benefit in all contract types. The supplier will prefer to contract with a grid company as the calculations estimate this benefit to be significantly higher than the benefit of the other buyers. The yearly profits of the buyers shown in Table 4.2 are calculated by multiplying the hourly profit with the expected number of hours that flexibility is needed. Contracts offered by the retailer and the wind power producer might be rejected by the supplier due to the higher alternative profit by contracting with a grid company.

Table 4.2: Yearly value chain profits for various buyers of flexibility under complete information.

	Grid company	Wind power producer	Retailer
Hours with activated flexibility	91	3 066	2 190
Value chain profit	5 884 410	294 866	3 034 951

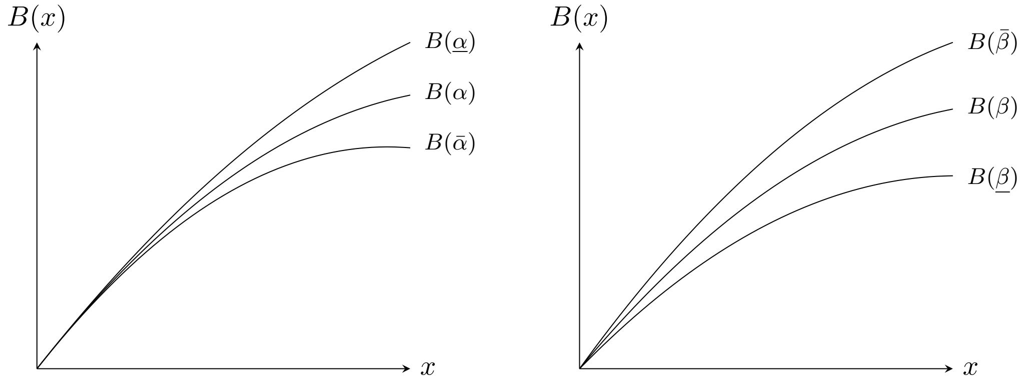
The retailer and the producer of wind power achieve low hourly profits regardless of the contract type due to their low estimated benefit caused by relatively low regulating prices in the present Balancing Market. With an increased share of renewable production from intermittent sources in the future power system, the regulating prices are expected to increase. This is illustrated in a future scenario where it is assumed that the imbalance costs are doubled. Using the future benefit in the contract calculations, the hourly value chain profits are clearly higher than in the present scenario as can be seen in Table 4.3. Hence, it is believed that it is possible to gain higher profits by utilizing flexibility for these actors in the future. As complete information rarely occurs in contractual relationships, the next sections will introduce more realistic scenarios with uncertainty and asymmetric information present.

Table 4.3: Hourly profits in present and future scenarios under complete information.

	Present	Future
Retailer profit [NOK]	1 386	3 502
Producer profit [NOK]	96	408

4.2 Contracting under Uncertainty

In reality it is reasonable to assume that the benefit of flexibility is uncertain for some actors, especially in the case of a retailer or wind power producer facing imbalance costs that might be difficult to predict. This degree of uncertainty can be removed if the contract is designed to offer flexibility when needed rather than contracting on flexibility in predefined hours. In contrast it is less reasonable to argue that the benefit of a grid company is uncertain since planned investment costs are known. However, it can be challenging to anticipate the need for flexibility based on increasing energy demand and higher peak loads in the future. In this section uncertainty is introduced to the contractual relationship between the buyer and supplier of flexibility. It is now



(a) Uncertain α **(b)** Uncertain β

Figure 4.2: Benefit functions for various valuation coefficients.

assumed that the buyer's benefit of flexibility $B(x)$ is uncertain for both parties when the contract terms are negotiated. In other words, the parameters α and β are unknown but is assumed to be uniformed distributed within a given interval. It is stated that $\underline{\beta} \leq \beta \leq \bar{\beta}$ and $\underline{\alpha} \leq \alpha \leq \bar{\alpha}$. Following from the shape of the benefit curve it is known that $B(\underline{\beta}) \leq B(\beta) \leq B(\bar{\beta})$ and $B(\bar{\alpha}) \leq B(\alpha) \leq B(\underline{\alpha})$ as illustrated in Figure 4.2.

In the event of uncertainty the buyer risks obtaining a profit deviating from the optimal profit in complete information, due to sub-optimal contract design. Under uncertainty the buyer specifies the contract terms based on expected values of the benefit, and the actual benefit is revealed after the contract is concluded. When the actual benefit of flexibility is identified, it is assumed that both parties have complete information about the benefit which is a reasonable consideration as imbalance costs can be calculated from the regulating prices in retrospect. The sequence of information is illustrated in Figure 4.3.

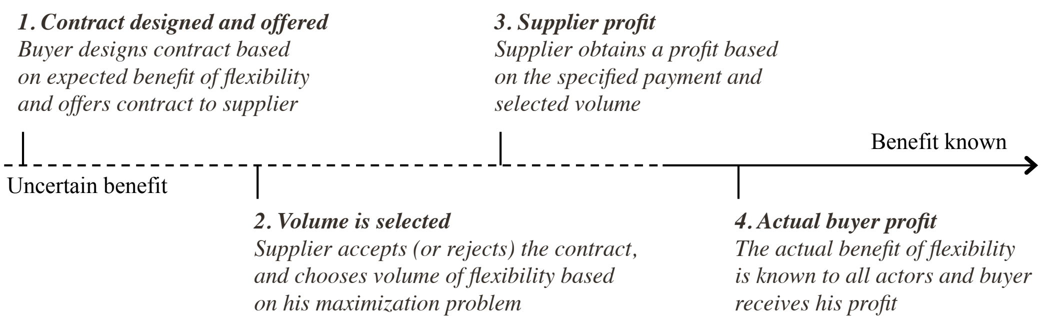


Figure 4.3: Information timeline in the contractual relationship under uncertainty.

To determine how different contract types handle uncertainty, the same contracts as in the case with complete information are studied; a profit-sharing contract denoted $U1$, a one-part linear contract denoted $U2$, and a two-part linear contract denoted $U3$.

4.2.1 Profit-sharing contract

The uncertain benefit of flexibility influences the optimal volume of flexibility traded in the contract. The supplier is offered a percentage share of the joint profits and then choose a volume of x kW based on the expected value of α and β. As stated in Subsection 4.1.1 the supplier chooses the optimal value chain volume in a profit-sharing contract and the maximization problem equals

$$\begin{aligned}\max_x E_{\alpha,\beta}[\pi_{VC,U1}(x)] &= E_{\alpha,\beta}[-\alpha x^2 + \beta x - ax^2 - b(1-\theta)x] \\ &= \int_{\underline{\alpha}}^{\bar{\alpha}} \int_{\underline{\beta}}^{\bar{\beta}} -\alpha x^2 + \beta x - ax^2 - b(1-\theta)x \quad \mathrm{dF}(\beta)\mathrm{dF}(\alpha)\end{aligned} \tag{4.22}$$

By solving the integral based on the assumption that α and β are independent of each other, and following the same procedure as in Subsection 4.1.1 the flexibility supplied is derived to be

$$x_{U1} = \frac{E[\beta] - b(1-\theta)}{2(a + E[\alpha])} \tag{4.23}$$

If the actual values of the valuation coefficients differ from their expected values it will clearly affect the value chain profit as the supplied volume was sub-optimal. Since the joint profit is divided between the parties in the contractual relationship, both parties will be exposed to the uncertainty. For the supplier of flexibility, the risk sharing in this case might lead to low willingness to accept this type of contract. Especially small suppliers, as households, are believed to be risk averse and they are not interested in undertaking financial risk as they face marginal gains by providing flexibility. The expected value chain profit is given by substituting (4.23) into (4.22)

$$E_{\alpha,\beta}[\pi_{VC,U1}] = \frac{(b(1-\theta) - E[\beta])^2}{4(a + E[\alpha])} \tag{4.24}$$

Since the benefit of flexibility is known to both parties in retrospect, the actual value chain profit obtained can be derived by substituting (4.23) into the expression for joint value chain profits in (4.1) and hence yields

$$\pi_{VC,U1} = \frac{(b(1-\theta) - E[\beta])(b(1-\theta)(a - \alpha + 2E[\alpha]) + a(E[\beta] - 2\beta) + \alpha E[\beta] - 2\beta E[\alpha])}{4(a + E[\alpha])^2} \tag{4.25}$$

The actual profits achieved by the participants depend on which extent the real values of the benefit valuation coefficients deviate from their expected values. The greatest impact on the profit occurs when the valuation coefficients deviate in the same direction, i.e. higher β and lower α or vice versa. In reality it is natural to believe that the coefficients are correlated and will always affect the benefit in the same direction, hence the matter of uncertainty will have a great impact on the profits obtained by the parties engaged in the contract. Risk averse buyers are interested in sharing the risk with the supplier, in which can be obtained in a profit-sharing contract between the supplier and buyer. . Most buyers are risk averse in varying degrees. For grid companies, sufficient flexibility is crucial for their operation of the grid as the opposite can lead to major failures. Thus, grid companies might be risk averse in the sense of not jeopardizing the reliability of the grid. Large suppliers, i.e. industry suppliers, are willing to take upon more financial risk than small suppliers like households as they face substantial higher gains from providing flexibility and are capable of covering potential losses. Consequently, it is unlikely that a supplier will engage in a profit-sharing contract under uncertainty as this is the contract type with the highest associated financial risk. If one or both parties are risk averse, this clearly impede the contractual relationship and a profit-sharing contract is not suitable.

4.2.2 One-part linear contract

In the one-part linear contract under uncertainty the buyer designs w based on the expected value of the benefit. The optimal volume of flexibility chosen by the supplier is based on the offered wholesale price, and still given by (4.9). The buyer's maximization problem is

$$\max_{w} E_{\alpha,\beta}[\pi_{B,U2}(w)] = E_{\alpha,\beta}[-\alpha x^2 + \beta x - wx] = \int_{\underline{\alpha}}^{\bar{\alpha}} \int_{\underline{\beta}}^{\bar{\beta}} -\alpha x^2 + \beta x - wx \quad \mathrm{dF}(\beta)\mathrm{dF}(\alpha) \tag{4.26}$$

Applying the same solution method as in Subsection 4.1.2 the optimal wholesale price w offered by the buyer equals

$$w_{U2}{}^* = \frac{aE[\beta] + b(1-\theta)(E[\alpha] + a)}{E[\alpha] + 2a} \tag{4.27}$$

Unlike a profit-sharing contract, this contract allocates most of the risk to the buyer. As the buyer faces uncertainty when the wholesale price is determined on expected values, he might end up with a sub-optimal contract. When the true values of the coefficients, α and β, differ from their expected values, the value chain profit will decrease compared to the case with complete information. Nevertheless, a one-part linear contract handles the uncertainty quite well for risk averse actors as the wholesale price is designed based on expected values which means that the variance is minimized. The supplier's profit is not dependent on the relation between the expected and the actual value of the benefit, and thus he does not face any risk associated with the uncertainty in this case. However, the supplier obtains a higher profit in the case of complete information if it turns out that the actual benefit was higher than the expected benefit. For small risk averse suppliers, this contract is well suited as they will not suffer from the uncertain parameters and have the opportunity to maximize profits based on the specified contract parameters.

4.2.3 Two-part linear contract

When introducing uncertainty in a two-part linear contract the buyer has to specify both the wholesale price w and the lump sum L based on expected benefit and hence the buyer's maximization problem is

$$\begin{aligned}\max_{(w,L)} E_{\alpha,\beta}[\pi_{B,U3}(w,L)] &= E_{\alpha,\beta}[-\alpha x^2 + \beta x - wx - L] \\ &= \int_{\underline{\alpha}}^{\bar{\alpha}} \int_{\underline{\beta}}^{\bar{\beta}} -\alpha x^2 + \beta x - wx - L \quad \mathrm{dF}(\beta)\mathrm{dF}(\alpha)\end{aligned} \tag{4.28}$$

$$\text{s.t.} \qquad \pi_{S,U3} \geq \pi_S^- \tag{4.29}$$

The optimal lump sum and wholesale price can be derived by using the same approach as in Subsection 4.1.3 and becomes

$$L^*_{U3} = \pi_S^- - \frac{a(b(1-\theta) - E[\beta])^2}{4(E[\alpha] + a)^2} \tag{4.30}$$

and

$$w^*_{U3} = \frac{a(E[\beta] - b(1-\theta))}{a + E[\alpha]} + b(1-\theta) \tag{4.31}$$

As in the one-part contract under uncertainty, the buyer's profit depends on how the valuation coefficients deviate from their expected values. In this contract the fixed lump sum paid to the buyer affects the allocation of risk. The deviations from optimal profit caused by uncertainty are larger in a two-part linear contract than in a one-part linear contract. Nevertheless, in most cases the two-part linear contract provides higher profits to the buyer. The supplier does not face financial risk associated with uncertainty as he choses the volume of flexibility supplied based on the specified contract terms, and always ends up getting his reservation profit like in the case of complete information, $\pi_{S,U3} = \pi_{S,C3} = \pi_S^-$. Consequently, if the supplier's reservation profit is less or equal to the supplier profit in a one-part linear contract the buyer will choose a two-part linear contract unless he is substantially risk averse.

4.2.4 Illustrative study of uncertainty

To illustrate the impact of uncertain benefit on profits and allocation of flexibility, the benefit coefficients are assumed to deviate both ways in an interval of 20% from actual coefficients. The variables and profits are then calculated for various deviations compared to the benchmark solution of the contracts in complete information.

The numerical results given in Table 4.4 show that the profit in a two-part linear contract deviates the most from the case with complete information. Figure 4.4 illustrates the actual profits for the grid company when the contract is designed based on expected values. Clearly, if the actual benefit deviates from its expected value, this has large impact on the profit. At the same time this contract type yields the highest profit for the buyer as long as the supplier's reservation profit is less than or equal to the expected profit for the supplier in a one-part linear contract, except with worst case deviation. In the worst case deviation, i.e. low β and high α, a one-part linear contract obtains the highest profits for the buyer due to the large deviation in the two-part linear contract. In the two-part linear contract the supplier has a fixed reservation profit and therefore the profit of the buyer might deviate to a greater extent from its expected value than in a one-part linear contract where only the wholesale price is designed based on expected values. Knowing this, the risk preference of the buyer decides which contract to choose. The buyer will design the contract based on his expected profits and will in most scenarios obtain higher profits with the two-part linear contract. However, a risk averse buyer will prefer a one-part linear contract with less variance, and thus more certain income.

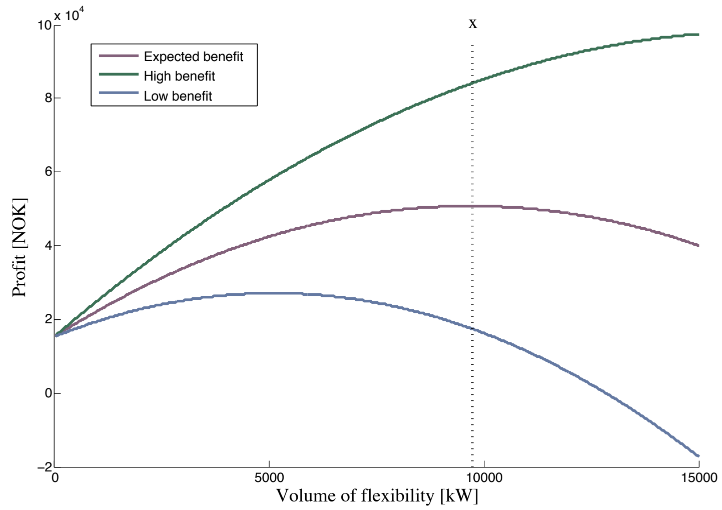


Figure 4.4: Actual profits in a two-part linear contract for the grid company with various benefits.

Table 4.4: Deviation in profit for grid company under uncertainty compared with complete information

	Deviation from complete information [%]	
	Best case	Worst case
One-part linear	5,3	12,1
Two-part linear	7,8	24,3
Profit-sharing	6,7	15,2

4.3 Contracting under Asymmetric Information

In most contractual relationships one or both of the parties have some private information about some of their parameters, e.g. costs, effort, willingness and benefit, that they have an incentive to keep private. It is now assumed that the willingness parameter θ of the supplier is private information and not known to the buyer. The probability function $dF(\theta)$ of θ is known and θ is uniformly distributed within the interval $[\bar{\theta}, \underline{\theta}]$ where $\underline{\theta}$ and $\bar{\theta}$ represents high and low willingness respectively. This asymmetric information will impact the contracts designed. The more informed agent may exploit the less informed principal, thus acting *opportunistically.* *Adverse selection* is a possible consequence of this opportunistic behavior of private information and creates a market failure by reducing the size of a market or eliminating it, thus preventing desirable transactions [25]. In this section the buyer is a Bayesian expected utility maximizer, anticipating the suppliers's subsequent behavior and optimizing accordingly within the set of available contracts.

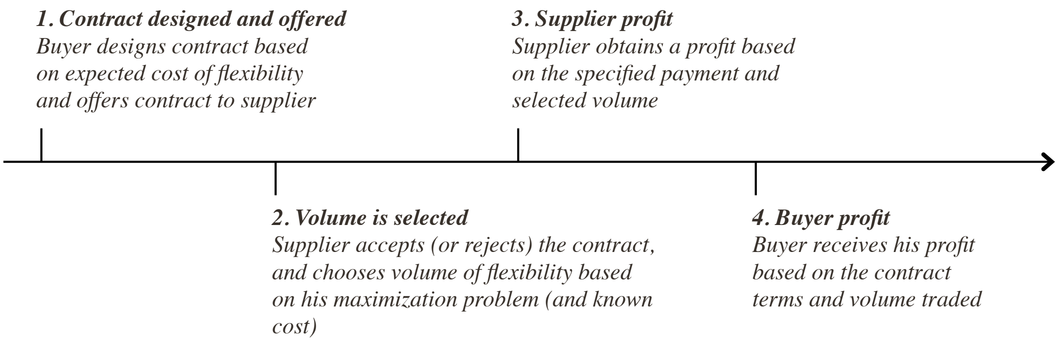


Figure 4.5: Information timeline in the contractual relationship under asymmetric information.

In the case of asymmetric information the buyer has the incentive to induce the supplier to reveal his true costs to gain higher profit. A one-part linear contract offers limited contract flexibility and hence the buyer cannot achieve this with a one-part linear contract. Additionally, the previous sections stated that both the value chain profit and buyer profit are highest in a two-part linear contract. Hence, the one-part linear contract will not be investigated in this information scenario. Most linear contracts do not handle information asymmetry in a good manner, and thus the contracts described earlier will only be examined briefly. The main focus in this section is the introduction of a nonlinear contract to deal with this challenge. The flow of information and decision stages are indicated in Figure 4.5.

The contracts to be studied in this information scenario are a profit-sharing contract denoted $A1$, a two-part linear contract denoted $A2$ and a nonlinear incentive compatible contract denoted $A3$.

4.3.1 Profit-sharing contract

Asymmetric information often leads to inefficient profit-sharing contracts. If the cost or benefit of flexibility is unknown to one of the parties, the other party might act opportunistic to increase his own profit, and hence lower the total profit of the value chain due to sub-optimality. The maximization problem under asymmetric information becomes

$$\begin{aligned} \max_x E_\theta[\pi_{VC,A1}(x)] &= E_\theta[-\alpha x^2 + \beta x - a x^2 - b(1-\theta)x] \\ &= \int_{\bar{\theta}}^{\underline{\theta}} -\alpha x^2 + \beta x - a x^2 - b(1-\theta)x \,\mathrm{dF}(\theta) \end{aligned} \tag{4.32}$$

As the supplier cost is private information, the supplier might lie about the cost and choose a volume deviating from the optimal volume for the value chain. By claiming a higher cost than the actual cost, the supplier achieves a profit equal to

$$\pi_{S,A1} = E_\theta[\pi_{VC,A1}](1-\rho) + b\Delta\theta x \tag{4.33}$$

where $b\Delta\theta$ is the additional gain from the difference between the claimed and the real value of θ. Thus, the supplier obtains his part of the expected value chain[3] profit plus a mark up. It is believed that asymmetric information will be present in contracts with small suppliers. Households can act opportunistically by easily lying about their willingness and preferences, and thus demand a higher payment for providing flexibility. Larger suppliers, as industry and commercial businesses, are not interested in violating the trust in the contractual relationship and risk not to be offered a new contract when it expires. The buyers obtain lower profits under this information scenario due to the opportunistic behavior of the supplier.

[3] Based on the expected willingness parameter.

4.3.2 Two-part linear contract

In a two-part linear contract under asymmetric information the buyer's optimization problem is written as

$$\max_{w} E_\theta[\pi_{B,A2}(w)] = E_\theta[-\alpha x^2 + \beta x - wx - L] = \int_{\bar{\theta}}^{\underline{\theta}} -\alpha x^2 + \beta x - wx - L \,\mathrm{dF}(\theta) \tag{4.34}$$

For any given w, the buyer always selects the highest L that still satisfies the supplier's individual rationality constraint given by the reservation profit for all θ. Since $\pi_S(\theta)$ is increasing in θ, this constraint holds for all θ if it holds at $\theta = \bar{\theta}$. Thus, the optimal lump sum L can be written as

$$L^*_{A2} = \pi_{\bar{S}} - \frac{a(b(1-\bar{\theta}) - \beta)^2}{4(\alpha + a)^2} \tag{4.35}$$

Substituting this expression for L into (4.34) and noting that the resulting expression is concave in w, we can solve the first-order condition for w to find that

$$w_{A2}{}^* = \frac{b(1 - E[\theta])(\alpha + a) + \beta a + ab(1 - \bar{\theta})}{\alpha + a} \tag{4.36}$$

The information asymmetry means that the buyer must offer a smaller lump sum payment than before, i.e. $L^*_{A2} \leq L^*_{C3}$, to meet the "worst-case" supplier's reservation profit requirements. To compensate, the buyer adds a markup based on how far removed the "worst-case" supplier is from the mean, to the wholesale price. In a two-part linear contract the trade-off between effort incentives and risk is evident. The buyer accepts a lower lump sum to ensure that the supplier will engage in the contract, and hence he chooses to give up a share of the profit. For the buyer of flexibility it is important that the suppliers accept the contract, as he will not obtain any profits if they do not. Hence, the buyer must ensure a sufficiently high wholesale price and a low lump sum so even the least willing suppliers will participate.

4.3.3 Nonlinear incentive compatible contract

When asymmetric information about cost structures is present, linear pricing tends to be inefficient like described above. In lieu of employing traditional linear contracts the following subsection will investigate a nonlinear contract by using *mechanism design with revelation principle* adopted from Game Theory. The idea behind mechanism design is to design an incentive structure that encourages the supplier to chose the efficient contract and by so doing reveal his true cost [2]. The revelation principle is used to simplify the problem. The model follows the same solution procedure as in [19].

For the sake of simplicity, it is assumed that the supplier's type only take two possible values. The discrete type model is sufficient to highlight the main principles arising under asymmetric information without having to handle the technicalities of a continuum of types [19]. The supplier can be either more willing $\underline{\theta}$ or less willing $\bar{\theta}$ to curtail load with respective probabilities v and $1-v$. The supplier's cost functions are given by

$$C(x,\underline{\theta}) = ax^2 + b(1-\underline{\theta}) \qquad \text{with probability } v \tag{4.37}$$

or

$$C(x,\bar{\theta}) = ax^2 + b(1-\bar{\theta}) \qquad \text{with probability } 1-v \tag{4.38}$$

The buyer designs menu of contracts with given amounts of volumes with corresponding fixed incentive payments and will compute the profit of any menu of contracts $\{(\underline{y},\underline{x});(\bar{y},\bar{x})\}$ in expected terms. Thus, the buyer's maximization problem becomes

$$\max_{\{(\underline{y},\underline{x});(\bar{y},\bar{x})\}} \pi_{B,A3} = v\left(B(\underline{x}) - \underline{y}\right) + (1-v)\left(B(\bar{x}) - \bar{y}\right) \tag{4.39}$$

As there are only two supplier types the buyer knows the two possible values of θ and their respective probabilities. The buyer must offer the supplier a utility level at least as high as the utility level the supplier could obtain outside the relationship. These constraints are referred to as the supplier's *participation constraints*. The outside opportunity utility level is set to the reservation profit of the supplier and hence the constraints are

$$\underline{y} - a\underline{x}^2 - b(1-\underline{\theta})\underline{x} \ \geq \underline{\pi}_S^- \tag{4.40}$$

$$\bar{y} - a\bar{x}^2 - b(1-\bar{\theta})\bar{x} \ \geq \bar{\pi}_S^- \tag{4.41}$$

Here y is the incentive payment to the supplier for a given volume of x delivered. This payment schedule vary with the supplier type θ. For the allocation to be efficient, *incentive compatibility constraints* have to be introduced

$$\underline{y} - a\underline{x}^2 - b(1-\underline{\theta})\underline{x} \ \geq \ \bar{y} - a\bar{x}^2 - b(1-\underline{\theta})\bar{x} \tag{4.42}$$

$$\bar{y} - a\bar{x}^2 - b(1-\bar{\theta})\bar{x} \ \geq \ \underline{y} - a\underline{x}^2 - b(1-\bar{\theta})\underline{x} \tag{4.43}$$

The incentive constraints encourage the supplier to tell the truth about his θ. In Equation (4.42) the efficient supplier's payment must be as much as he would make if he were to mimic the inefficient supplier. The volumes must generally satisfy a *monotonicity constraint*, and in this simple two-type model, adding (4.42) and (4.43) yields $\underline{x} \geq \bar{x}$. Thus, incentive compatibility alone implies that the output requested from the inefficient supplier cannot be higher than the output requested from the efficient supplier.

The asymmetry of information enables the efficient supplier to achieve a utility level above his reservation profit by mimicking the inefficient supplier. Thus, the buyer have to give up an *information rent* to the efficient supplier. The information rent to each type of supplier can be denoted by

$$\underline{U} = \underline{y} - a\underline{x}^2 - b(1-\underline{\theta})\underline{x} \tag{4.44}$$

$$\bar{U} = \bar{y} - a\bar{x}^2 - b(1-\bar{\theta})\bar{x} \tag{4.45}$$

If the efficient supplier mimic the inefficient supplier he would get $\bar{U} + b\Delta\theta\bar{x}$. Even if the inefficient supplier's utility level is set to zero, the efficient supplier can obtain a positive profit $b\Delta\theta\bar{x}$. This positive information rent is generated by the informational advantage the supplier has over the buyer of flexibility. By using the definition of the information rents, the incentive payment y can be substituted such that the new optimization variables become $\{(\underline{U}, \underline{x}); (\bar{U}, \bar{x})\}$. Substituting in the information rent and the benefit functions the economic interpretations are easier to understand. The new maximization problem is

$$\begin{aligned} \max_{\{(\underline{U},\underline{x});(\bar{U},\bar{x})\}} \pi_{B,A3} & v\left(-\alpha\underline{x}^2 + \beta\underline{x} - a\underline{x}^2 - b(1-\underline{\theta})\underline{x}\right) \\ & + (1-v)\left(-\alpha\bar{x}^2 + \beta\bar{x} - a\bar{x}^2 - b(1-\bar{\theta})\bar{x}\right) - \left(v\underline{U} + (1-v)\bar{U}\right) \end{aligned} \tag{4.46}$$

subject to

$$\underline{U} \geq \pi_S^- \tag{4.47}$$

$$\bar{U} \geq \pi_S^- \tag{4.48}$$

$$\underline{U} \geq \bar{U} + b\Delta\theta\bar{x} \tag{4.49}$$

$$\bar{U} \geq \underline{U} - b\Delta\theta\underline{x} \tag{4.50}$$

Here (4.47) and (4.48) are the new participation constraints and (4.49) and (4.50) are the incentive compatibility constraints. The maximization problem clearly states that the buyer will accept some distortions away from the optimal output of the $\bar{\theta}$-supplier in order to decrease the $\underline{\theta}$-supplier's information rent. Thus, the solution to this problem is called a *second-best* solution and deviates from the efficient first-best solution obtained under complete information, in which can be found in Appendix A.3.5. Generally, the technical difficulty of incentive problems is to determine which of the many constraints are binding at the optimum of the buyer's problem [19]. The ability the efficient supplier has to mimic the inefficient supplier implies that the efficient supplier's participation constraint (4.47) is always strictly satisfied. In addition, the inefficient supplier's incentive compatibility constraint is also irrelevant, since the difficulty comes from a efficient supplier willing to claim that he is inefficient rather than the reverse. This leaves two binding constraints at optimum, the efficient supplier's incentive compatibility constraint (4.49) and the inefficient supplier's participation constraint (4.48) leading to $\bar{U} = \pi_S^-$ as an optimal solution. Thus, $\underline{U} = b\Delta\bar{\theta}\bar{x} + \pi_S^-$ is also optimal. Substituting this into the buyer's maximization problem and solving for $(\underline{y}, \underline{x}); (\bar{y}, \bar{x})$ yields

$$\underline{x}^*_{A3} = \frac{\beta - b(1-\underline{\theta})}{2(\alpha + a)} \tag{4.51}$$

$$\bar{x}^*_{A3} = \frac{\beta - b(1-\bar{\theta})}{2(\alpha + a)} - \left(\frac{v}{1-v}\right)\frac{b\Delta\theta}{2(\alpha + a)} \tag{4.52}$$

$$\underline{y}^*_{A3} = b\Delta\theta\bar{x}^*_{A3} + a(\underline{x}^*_{A3})^2 + b(1-\bar{\theta})\underline{x}^*_{A3} + \underline{\pi}^-_S \tag{4.53}$$

$$\bar{y}^*_{A3} = a(\bar{x}^*_{A3})^2 + b(1-\bar{\theta})\bar{x}^*_{A3} + \bar{\pi}^-_S \tag{4.54}$$

Compared with the complete information setting in the Appendix, asymmetric information alters the buyer's optimization by the subtraction of the expected rent that has to be given up to the efficient supplier. This rent does only depend on the volume $\bar{x}$ of the inefficient supplier, hence the optimal output for the efficient supplier in (4.51) is equal to the optimal output in the first-best solution. The second-best output for the inefficient supplier is smaller than the first-best output, which corresponds to the buyer's trade-off between $\bar{\theta}$-output and the information rent given up.

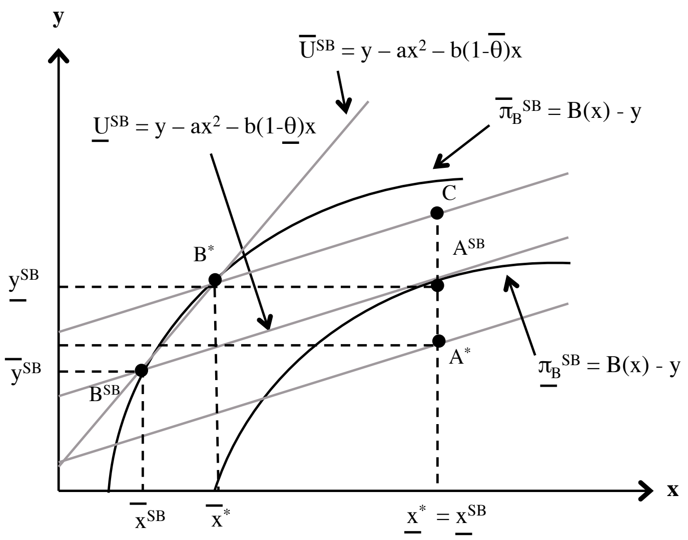


Figure 4.6: Optimal contract under asymmetric information indicated by subscript SB. Adapted from [19].

Figure 4.6 is a graphical representation of the second-best outcome. Under complete information the optimal contract is given by (A*, B*). An incentive compatible contract (B*, C) can be constructed with the same output levels by giving the efficient supplier a positive information rent. However, rather than requiring the first-best output level for the inefficient supplier, the buyers wants to slightly decrease this output in order to decrease the information rent. The optimal trade-off occurs at the second-best outcome $(\mathrm{A}^{\mathrm{SB}}, \mathrm{B}^{\mathrm{SB}})$.

The profit for the buyer is given by (4.46) with the optimal volumes of flexibility for both supplier types given by (4.51) and (4.52). The efficient supplier receives a higher profit than in complete information and is given by

$$\underline{\pi}_{S,A3} = b\Delta\theta\bar{x}^*_{A3} + \bar{\pi}_S^- \tag{4.55}$$

The inefficient supplier obtain a profit equal to his reservation profit

$$\bar{\pi}_{S,A3} = \bar{\pi}_S^- \tag{4.56}$$

In reality there will be more than two suppliers types, and the buyer of flexibility have to design and offer a number of contracts in order to minimize the disadvantage of asymmetric information. The buyer must typically design one set of menus to each of the supplier segments, i.e. households, industry and commercial businesses. Asymmetric information may be less present in some of the groups than others.

4.3.4 Illustrative study asymmetric information

Investigate how the asymmetry affects the profit of the different parties in the various contract types, It is clear that the asymmetric information is challenging for the buyer when designing the contract. Nevertheless, by choosing the right type of contract the asymmetry can be manageable. The optimal volumes of flexibility, wholesale prices, the lump-sum as well as profits are calculated for the different contract types presented. A sensitivity analysis illustrates the impact of deviating θ's from the expected value.

Table 4.5 illustrates that a profit-sharing contract performs poorly with information asymmetry present. The worst case scenario occurs if the supplier of flexibility claims that $\theta = 0,3$ while his actual $\theta = 1$. In this case the supplier will obtain a larger profit than case of complete information, while the buyer's profit will decrease. Hence, the buyer will suffer from choosing a profit-sharing contract when asymmetry occurs due to the opportunistic behavior of the supplier. As the table indicates there are small deviations in profits. This is due to the low estimated value of the cost coefficient b.

Table 4.6 shows actual profits for the grid company if θ turns out to be 0,3 or 0,7 when the expected value of this parameter is 0,5 in the design of the two-part linear and the profit-sharing contract. In the nonlinear contract the buyer knows that the actual θ is

Table 4.5: Hourly profits [NOK] in a profit-sharing contract for a grid company in a worst case scenario.

	Asymmetric information	Complete information
Buyer profit	44 960	46 029
Supplier profit	20 787	19 727
Value chain profit	65 748	65 757

either 0,3 or 0,7. The calculations confirm that the nonlinear contract extracts higher profits for the buyer independent of the suppliers actual willingness, and deals with the asymmetric information in a better way. This occurs as the supplier reveals his true willingness, and hence cost, and therefore the volume of flexibility chosen is based on his true cost. In the profit-sharing contract the supplier will always claim to have the highest cost, hence the buyer's actual profit is equal regardless of the actual willingness.

Table 4.6: Comparing actual profits [NOK] for the grid company in various contracts.

	Actual willingness	
	$\theta = 0,3$	$\theta = 0,7$
Profit-sharing	45 265	45 265
Two-part linear	49 735	49 751
Nonlinear	50 384	50 387

A small supplier of flexibility, like a household, might prefer to relate to a fixed payment for a specified amount of flexibility, like in a nonlinear contract, rather than being paid a marginal price per kWh. For this reason, and the arguments mentioned earlier, the buyer of flexibility should design a nonlinear incentive compatible contract to suppliers in order to maximize profit. This contract type will be used in further discussion and investigation of business opportunities of demand side flexibility.

Chapter 5

Separate Flexibility Market

A contractual approach of trading flexibility might be economic inefficient in many situations because competitive prices are not fully considered in the selection of suppliers providing flexibility. Contracts focus on flexibility benefits for only a subset of participants. Optimizing the benefits of flexibility individually in each contractual relationship can result in conflicts on how the flexibility is scheduled as they solve different problems. Additionally, partial approaches such as bilateral contracting result in lower returns for suppliers as they are unable to offer their flexibility to all buyers [14]. Instead of trading flexibility bilaterally between the buyer and the supplier, the flexibility can be aggregated into a virtual pool where a market operator clears the market, and buyers and suppliers of flexibility can trade. This chapter will illustrate a separate flexibility market with various forms of market imperfections. All buyers and suppliers of flexibility can access this market. The flexibility market and the participants are illustrated in Figure 5.1. For simplicity, it is assumed throughout this chapter that the geographical location of flexibility is insignificant. In reality, grid companies need flexibility to solve local problems in the distribution grid and hence demands flexibility from suppliers in a specific geographic location.

There are several approaches for clearing a market. In this thesis a price-quantity demand curve is used to represent prices at which the buyers are willing to buy flexibility of the corresponding volumes and the market operator clears the market by maximizing total market benefit. The demand curve is derived from the marginal benefit functions for various buyers of flexibility while the supply curve is defined by the marginal cost functions for each supplier both described in Chapter 3. The clearing of this market results in both a price and a volume of flexibility to be scheduled in the power system for a given hour. It is assumed that the market operator receives supply and demand based on the *true* costs and benefits of the market participants. This chapter will first analyze a flexibility market with perfect competition. Further, market imperfections in terms of monopoly and monopsony are investigated. Illustrative numerical examples will be presented in each section and the complete calculations can be found in attached

Excel-files[1].Throughout this chapter the flexibility market is assumed to be separate from the existing electricity market but is considered to operate synchronously with this market as the two resources are physically linked.

The marginal value of flexibility constitute the aggregated market demand and is denoted

$$p(x) = -2\alpha_M x + \beta_M \tag{5.1}$$

where the subscript M is used to clearly indicate that the coefficients represent aggregated valuation coefficients for all buyers. Likewise, the aggregated market supply is denoted

$$c(x, \theta_M) = 2a_M x + b_M(1 - \theta_M) \tag{5.2}$$

θ_M is assumed known information by all participants. These demand and supply curves are used throughout the chapter.

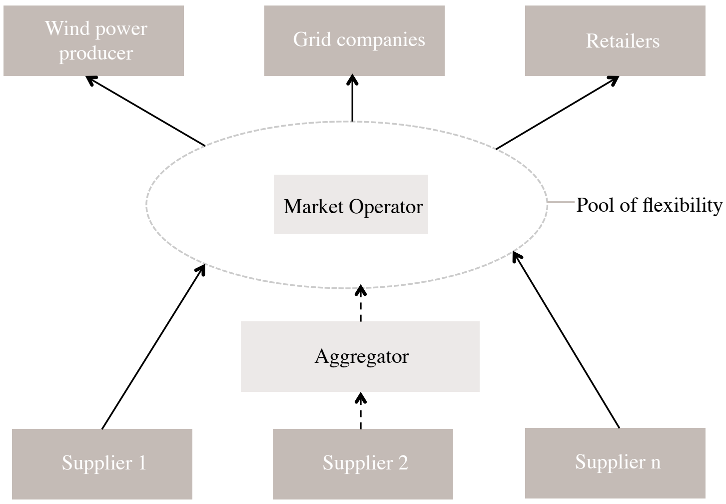


Figure 5.1: Participants and interactions in a separate flexibility market.

5.1 Flexibility Market with Perfect Competition

The first section will model the flexibility market as perfectly competitive. In economic theory, *perfect competition* refers to a market where no participants are large enough to exercise market power and affect the market price [?]. Each participant is seen

[1] *5 Separate Flexibility Market.xlsx*

as a price taker. The conditions for perfect competition are strict and few perfectly competitive markets exist. A flexibility market with perfect competition is therefore unlikely. However, perfect competition is Pareto efficient and will serve as a benchmark for other market outcomes analyzed in this chapter.

5.1.1 Market clearing with perfect competition

A market operator should facilitate the flexibility market and clear the market given the submitted demand and supply. Receiving demand and supply from all participants the market operator can clear the market by finding an equilibrium volume of x and a market price $p(x)$. Equating (5.1) and (5.2) the market clears with the following optimal output and market price

$$x^* = \frac{\beta_M - b_M(1-\theta_M)}{2(\alpha_M + a_M)} \tag{5.3}$$

$$p^*(x^*) = -\alpha_M \left(\frac{\beta_M - b_M(1-\theta_M)}{\alpha_M + a_M} \right) + \beta_M \tag{5.4}$$

This market outcome is efficient and hence a first-best solution to the market-based approach. As seen by the to equations both the volume and the market price depend on the aggregated valuation and cost coefficients. By definition, higher benefits result in higher demand. Likewise, higher costs result in lower supply. Clearly the ratio of demand and supply, and hence the benefits and costs decide the optimal market outcome. (5.3) imply that an increased benefit will increase the equilibrium volume and hence also the market price, while an increased cost will lower the equilibrium volume and price. This is consistent with microeconomic theory. Buyers' benefits are sensitive to β, and it turns out that the size of each buyer's β coefficient determines whether or not they will participate in the market. If some buyers have significantly larger β coefficients than others due to higher benefit, increasing the market price, the buyers with low β or benefit will not participate in the market as a result of a higher price than their valuation of flexibility.

Both equation (5.3) and (5.4) are similar to the optimal volume of x and the wholesale price w, respectively, in the two-part linear contract with complete information presented in Subsection 4.1.3. The contractual and market-based approach will not necessary give the same optimal price and volume owing to the fact that total demand and supply might differ in the contractual relationship and in the flexibility market. By assumption the buyer has bargaining power in the contractual relationship and will therefore extract the larger share of the value chain profit by receiving a lump sum payment from the supplier. This is not possible in a market with perfect competition where the buyer is a price taker without any market power. Unlike a two-part linear contract where the buyer can extract profit with the lump-sum, the profit when buying in the market is only given by the buyer's value of flexibility and the given payment for the volume of flexibility x he buys

$$\pi_B = -\alpha x^2 + \beta x - p(x)x \tag{5.5}$$

Higher supply of flexibility lowers the market prices. For the buyers to have large enough supply of flexibility available in a bilateral contract they have to engage in large number of contracts with suppliers, which can be costly. If the flexibility market is well-functioning with large turnover volumes, and if the participation fee and transaction costs[2] are lower than the cost of engaging in contracts, the buyer can benefit from trading in a market instead in order to secure sufficient volumes of flexibility at a lower cost. This again depends on the buyer's bargaining power in a contractual setting and his ability to exercise market power.

A supplier's profit π_S in a flexibility market only depends on the market price and his cost of supplying flexibility

$$\pi_S = p(x)x - ax^2 - b(1-\theta)x \tag{5.6}$$

Here x is the volume of flexible load that the individual supplier delivers at the given market price. For a small individual supplier, e.g. a household, without any barging power a flexibility market with perfect competition might be more efficient than a bilateral contract with a buyer. In such a market the supplier receives a rightful price for the flexibility he supplies and is able to provide flexibility to the whole range of buyers.

5.1.2 Illustrative study of perfect competition

Employing the estimated cost and valuation coefficients from Chapter 3 the equilibrium price and volume is calculated from (5.3) and (5.4). The individual participant's procured or provided volume of flexibility are derived from their demand and supply curve whereas their profits are calculated from (5.5) and (5.6). Table 5.1 illustrates prices, optimal volume of flexibility and profits in both a contractual relationship between a grid company and a large supplier with complete information and in a flexibility market. Total demand and supply are the same in both trading approaches, but it is assumed that they represent several buyers and suppliers in the market instead of two large actors as in the contract.

The numerical calculations of the benefit for grid companies are significantly higher than the benefits for wind power producers and retailers, which forces the market price above the level where these buyers can profit from trading. Thus, only grid companies will trade in this flexibility market given the estimated benefits for each buyers. With such a large gap in the benefits, this market will not be perfectly competitive since

[2] In a perfectly competitive market there are no transaction costs in the market. However, it is likely that there will be a fee for trading in the flexibility market.

Table 5.1: Comparison of a market with perfect competition and contracts under complete information.

	Market	**Bilateral contract**	
		One-part linear	Two-part linear
Marginal price [NOK/kW]	6,12	4,25	6,11
Optimal volume [kW]	9 704	6 690	9 704
Grid company			
Profit [NOK]	35 536	44 582	50 818
Large supplier			
Reservation profit [NOK]			13 845
Profit [NOK]	29 128	13 845	13 845

the grid companies have a significant influence on the market price due to their high demand. However, if the grid companies do not realize the influence they have on the price, they will still be price takers. Alternatively, they could collude to obtain lower prices than if they take the price as given. As shown in Table 5.2 these results changes when looking at a future scenario where imbalance costs for wind power producers and retailers are doubled. Then retailers' β and hence their benefits are large enough for them to participate in the market. The wind power producer on the other hand still not profit from participating in the market. This scenario illustrates a more competitive market where the market price is raised.

Table 5.2: Market outcomes in a present and future scenario with perfect competition.

	Present scenario	Future scenario
Market price [NOK/kW]	3,22	3,42
Grid company		
Optimal volume x [kW]	13 538	13 281
Profit [NOK]	69 168	66 545
Retailer		
Optimal volume x [kW]	0	543
Profit [NOK]	0	360

As the costs and benefits in these calculations are only estimates, the results will differ in practice. However, in reality some buyers will value flexibility more than other buyers, and research [12] propose that grid companies have the largest potential and thus the largest benefit. For this reason, it is unlikely that a flexibility market is perfectly competitive, and some actors, either on the supply side or the demand side will have some degree of market power. Another criteria for perfect competition is that there are no externalities. Flexibility, as a virtual resource, can affect both the costs and benefits of actors in the power market, thus externalities might exist in this flexibility market and prevent the market to be perfectly competitive. The possibility of large aggregators or buyers to dominate in a local market will exhibit entry of new participants, decreasing the market competition. The following sections will analyze two possible scenarios of market power; a large supplier or an aggregator behaving as a monopoly or one buyer capable of reducing the market price as a monopsony.

5.2 Supplier as a Monopolist

Assume that there is only one supplier of flexibility in the market. The supplier can exploit this position to increase profit. By definition, *monopoly* is the ability of an actor to profitably raise the market price of a good or service above marginal cost [**?**]. This can be a plausible scenario in the power system if the flexibility market is operated locally and one large aggregator has a portfolio consisting of flexibility from all suppliers in the geographic area supplying the local market. The following section will present the extreme case of this scenario where only one supplier has all the market power. In reality, oligopoly with a few large aggregators and suppliers is more realistic.

5.2.1 Market clearing with monopoly

Instead of equating demand with supply to obtain an equilibrium volume as in perfect competition, the supplier set the volume of flexibility where marginal cost equals to marginal *revenue* and finds the corresponding price on the demand curve as seen in Figure 5.2. Total revenue for the buyers is given by $p(x)x$ where $p(x)$ is the aggregated demand given in (5.1). By equating the marginal revenue $-4\alpha_A x+\beta_A$ with the supplier's marginal cost in (5.2) the monopoly volume x^{ml} and price $p^{ml}(x^{ml})$ becomes

$$x^{ml} = \frac{\beta_M - b(1-\theta)}{2(2\alpha_M + a)} \tag{5.7}$$

$$p^{ml}(x^{ml}) = -\alpha_M \left(\frac{\beta_M - b(1-\theta)}{2\alpha_M + a} \right) + \beta_M \tag{5.8}$$

Note that the cost coefficients in the supply curve are not aggregated since the supply only consist of the marginal cost for the monopoly supplier. The marginal revenue curve is twice as steep as the demand curve, and hence the marginal cost crosses this curve at a lower volume x, raising the price which can be seen in the expressions for x and $p(x)$. Compared to the optimal price $p^*(x^*)$ in perfect competition the first term in (5.8) has a larger denominator and hence will decrease the negative term, which in turn raises the monopoly price. The monopoly volume in (5.7) has a larger denominator than the analytical expression for the optimal volume in perfect competition, lowering the monopoly volume. These results corresponds with microeconomic theory. Given the strictly decreasing demand curve, the volume is lowered when the price increases. However, by setting a high market price, the supplier foregoes transactions with the buyers who value flexibility less than the market price, creating a *deadweight loss* from a socio-economic perspective. This loss refers to potential gains that were neither extracted by the supplier nor the buyers. The social welfare, i.e. the combined consumer and producer surplus, is lower in the monopoly market due to this deadweight loss. Efficiency in the form of total gains from trade will not be reached in a monopoly setting.

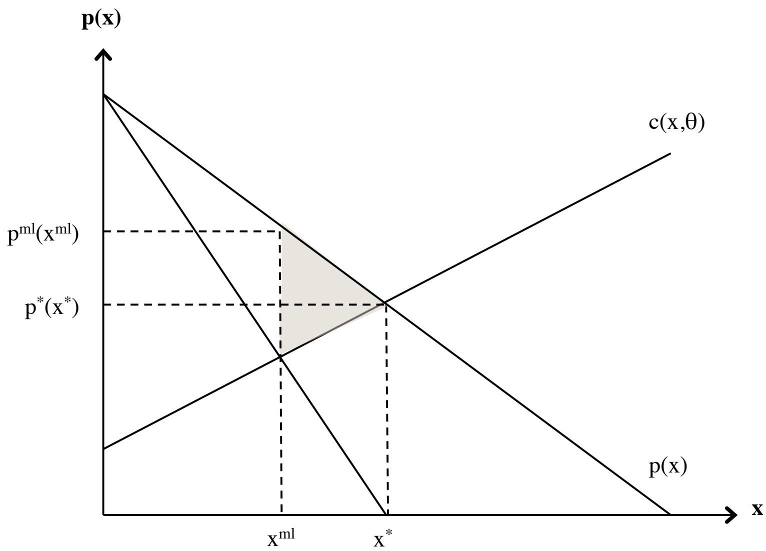


Figure 5.2: Market clearing of monopoly flexibility market.

A flexibility market where the suppliers have market power compares to bilateral contracts where suppliers' reservation profits or proportions of the shared joint profits are high due to bargaining power. Nevertheless, it is harder for one or few suppliers to exercise market power in a flexibility market compared to bilateral contracts since there tends to be more participants in a market whereas a bilateral contract only consist of two parties. Small suppliers will likely neither possess significant market power nor bargaining power.

5.2.2 Illustrative study of monopoly

Using the same aggregated market demand and supply as in the previous section, assuming that one large supplier has access to the whole aggregated supply, the monopoly price and volume are calculated from (5.7) and (5.8). The calculations shown in 5.3 illustrate the effects on market price and volume compared the benchmark scenario with perfect competition. Due to the high price in the monopolistic market, retailers will neither buy flexibility in the present nor the future scenario where their benefits are higher. These results are reasonable to assume generally as well. A monopolistic supplier will sell the flexibility to the buyers who value the resource most, and since grid companies might have larger potentials, other buyers will be extorted from the market. From a socio-economic point of view, this flexibility market is inefficient and in the long run it will be hard for the large supplier to maintain his position unless barriers hinder entry of other market participants.

5.3 Buyer as a Monopsonist

Another form of market failure arises when there is only one buyer of a good, rather than one seller as in the monopoly situation. This form of market power is called *monopsony.* As a monopsonist, the buyer is able to buy flexibility at a price below its marginal value of the resource. A flexibility buyer with monopsony power is a more likely scenario than a supplier with monopoly power. Both grid companies, wind power producers and retailers are large entities compared to individual suppliers, especially households. Thus it is more realistic that these buyers will have larger shares of the market power than a single supplier. However, this might not be true if the supply is aggregated by a flexibility aggregator which will be discussed in more detail in Chapter 6.

5.3.1 Market clearing with monopsony

A monopsonist chooses a volume x at the intersection of the demand and *marginal expenditure* curves as illustrated in Figure 5.3. Marginal expenditure is the additional cost of buying one more unit of flexibility, i.e. 1 kWh [26]. Algebraically the total expenditure curve is given by $p(x)x$ where $p(x) = c(x, \theta)$ is the market supply given in (5.2). Equating marginal expenditure $4ax + b(1-\theta)$ with the demand or marginal value, the monopsony volume x^{ms} becomes

$$x^{ms} = \frac{\beta - b_M(1-\theta_M)}{2(\alpha + 2a_M)} \tag{5.9}$$

The valuation coefficients are not aggregated as the demand is given by one buyer's marginal value. The supply curve defines the *average expendtiure* that the buyer must pay for each volume x of flexibility. The monopsony price $p^{ms}(x^{ms})$ is found on the average expenditure curve, i.e the supply curve, at the optimal monopsony volume

$$p^{ms}(x^{ms}) = \frac{a_M(\beta - b_M(1-\theta_M))}{\alpha + 2a_M} + b_M(1-\theta_M) \tag{5.10}$$

Compared to the perfect competition scenario, the monopsony volume is smaller which can be easily verified since the denominator, as with monopoly, is larger than in the expression for optimal output in perfect competition. Consequently, as the demand curve is strictly decreasing the market price in (5.10) is higher than in perfect competition.

As in monopoly the monopsony outcome is inefficient and creates a deadweight loss shown by the shaded area in Figure 5.3. The buyers are better off since his marginal expenditure is higher than average expenditure due to an upward-sloping supply curve. The suppliers are worse off since they are paid less while having the same costs of supplying the flexibility. Additionally, the market clearing volume is smaller and hence fewer suppliers are able to supply flexibility in the given hour compared to a competitive situation.

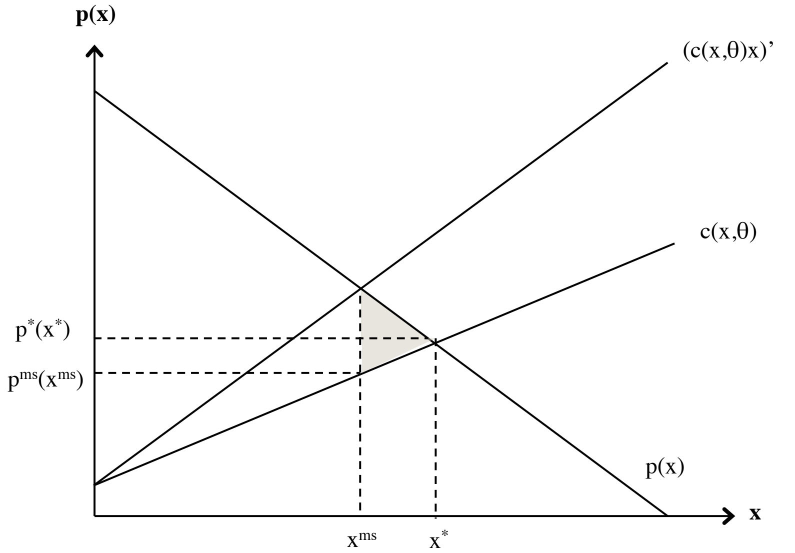


Figure 5.3: Market clearing of monopsony flexibility market.

So far in this chapter it has been assumed that the value of flexibility is known by all participants and that the true values are reflected in the market demand. However, as discussed in the previous chapter the values of flexibility may be uncertain. With uncertain benefits the demanded volume of flexibility from the buyer might deviate from the optimal volume and this will cause market failure. The buyer face a larger risk trading flexibility when the value is uncertain. Without any market power the higher risk may result in low profits for the buyer since he can not affect the market price and his expenditures could turn out higher than the value. With uncertainty present monopsony power can reduce this risk as the buyer is able to set the price below the lowest possible marginal value if this value is within a known interval. From a socio-economic perspective this will cause even larger deadweight losses, and thus a lower market benefit. This compares to a two-part linear contract as the optimal contract in Section 4.2 under uncertainty where the buyer has large bargaining power, and thus extracting highest profits even if this contract type result in largest deviations due to the uncertainty.

5.3.2 Illustrative study of monopsony

It is assumed in the market clearing that a large grid company as a monopsonist has a demand equal to the sum of the two grid companies that forms the aggregated market demand in Subsections 5.1.2 and 5.2.2. The aggregated market supply is the same as in previous calculations in this chapter. The monopsony volume and price are calculated from (5.9) and (5.10) respectively. The numeric values of the market clearing price and volume in Table 5.3 illustrates that both the price and the volume of flexibility traded is lower than the competitive output. However, the monopsony volume of flexibility is not as low as the monopoly output.

Table 5.3: Illustrative calculations of market imperfections in a flexibility market.

	Perfect competition	Monopoly	Monopsony
Volume of flexibility [kW]	27 076	15 314	21 977
Market price [NOK/kWh]	3,22	7,66	2,64

Compared to present prices in existing electricity markets the market prices illustrated in Table 5.3 are substantially higher in all scenarios. Note that the prices only apply for hours with high demand for flexibility, and as all buyers by assumption demand flexibility in the same hours, high demand hours will result in extreme prices. Additionally, these prices are calculated for extreme scenarios where only one buyer or supplier has all the market power. In reality market power will likely be shared between few large participants in the market in lieu of just one. However, prices in Elspot and in the Balancing Market are normally not higher than 2 NOK/kWh in peak hours today [21]. Thus, retailers and wind power producers who use flexibility to reduce imbalance cost, would be better off paying the imbalance cost rather than buying flexibility at the calculated prices. The calculations indicate that only grid companies will trade in the flexibility market with their estimated benefit functions. The numeric values of the prices in Table 5.3 are extremely sensitive to the benefit and cost functions derived for each participant, and as they are estimates, they should only be employed to describe the principles and not the actual possible price levels of flexibility in different scenarios. Nevertheless, it is assumed that the variation in electricity prices will increase in the future which induces more extreme prices, like in Denmark. Hence, it may be realistic to assume that flexibility prices in peak hours also will be higher in the future.

If few actors are able to exercise market power in the flexibility market in the long run it is reasonable to assume that there will be some form of regulation by competition Authorities to prevent too high or low prices and inefficient allocation of the resources. From the socio-economic view, the society are better off if the flexibility market is operated with many competitive buyers and suppliers of flexibility. In order to facilitate such flexibility markets, existing barriers should be removed and the market must enable all buyers to participate even if their demand of flexibility rely on supply from specific geographic locations as with grid companies. The latter will be analyzed in the following chapter.

Chapter 6

Novel Business Models for Flexibility

Throughout this thesis a contractual and market-based approach of trading flexibility have been presented and analyzed. Sufficient volumes of demand and supply has been taken as given. However, both demand and supply of flexibility are still uncertain in the Norwegian power market, and also in many other countries. The major part of the potential buyers do not realize the value of flexibility, hence they will not demand this resource. Like the buyers, most suppliers do not know the value of flexibility, or the costs for that matter, as they take electricity prices as given regardless of how much they consume of the good. Hence, the incentives for providing flexibility are not present yet. Most suppliers do not even have knowledge about flexibility as a resource. The smart grid technology has been widely developed in recent years which enables the use of flexibility as an additional resource in the electricity system. Nevertheless, small amounts of flexibility are exploited today. The major challenge and uncertainty regarding use of flexibility is available supply. Several changes have to be made in order to enable trading of flexibility as well as to attract suppliers to provide flexibility. Various barriers make it hard for new entrants in the power system to offer new and innovative solutions of flexibility. Many researchers believe that aggregator roles are necessary as driving forces to extract the potential of flexibility. Aggregators can both aggregate large volumes of flexibility and offer this flexibility to potential buyers, making it easier for buyers to utilize flexibility without changing their own business models.

Based on the existing challenge of small volumes of flexibility available for trading, this chapter will introduce the aggregator role as a possible solution. The aggregator has several opportunities to extract profit from flexibility. Thus various business models for an aggregator will be presented and analyzed. It is assumed that market barriers have been removed in order to arrange for trade of flexibility. All business models are based on models presented previously in this thesis. The possibility of replacing aggregators with local flexibility markets and advanced automated control systems will also be discussed. Figure 6.1 illustrates possible trading alternatives of flexibility and participants in various markets as well as the interactions in the system.

The first section introduces the aggregator in the value chain studied. Further, three business models for the aggregator will be proposed, including trading in existing markets, bilateral contracting with buyers and suppliers as well as a combined model employing both trading solutions. Subsequently, a simple model shows how local flexibility markets can solve system and reliability problems for all actors. Finally, future solutions to release the potential of flexibility as well as efficient allocation of the resource will be proposed. The chapter will consider how the theoretical models derived in this thesis could work in practice, and how they could deviate. Simple numerical examples related to each of the models are performed, and the complete calculations are found in attached Excel-files[1].

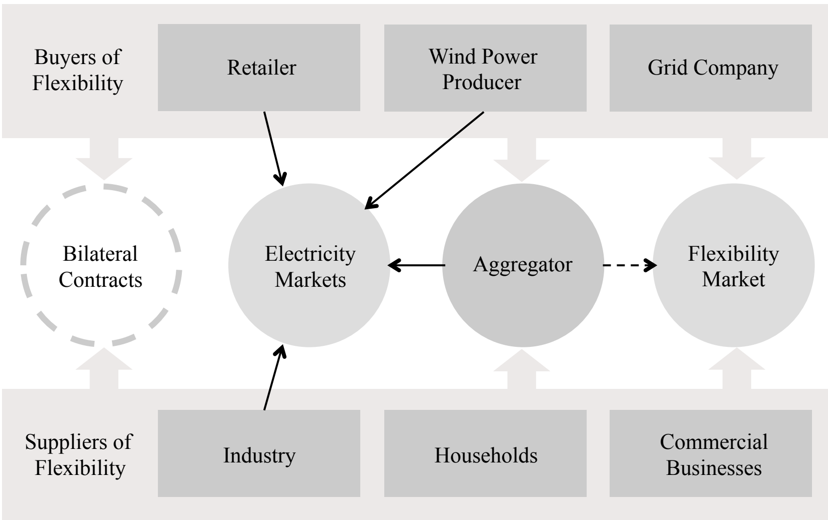


Figure 6.1: Business models for flexibility including participants and trading methods.

6.1 Aggregators' Business Opportunities

The previous two chapters has shown the importance of sufficient supply in order to reach an efficient allocation of flexibility as well as allocate the value this resource brings along. One major challenge related to releasing the potential of flexibility is to aggregate large enough volumes of flexibility from suppliers, whether it is traded in a contract or in a market. An aggregator role is proposed by many researchers in the energy business sector as a solution to this challenge. Aggregators can offer attractive solutions and new services to individual suppliers giving the suppliers sufficient incentives to provide

[1] *6 Novel Business Models.xlsx*.

flexibility. By so doing the aggregator acts as a driving force for releasing the potential of flexibility. An aggregator can offer the suppliers a payment in order to control their loads according to given restrictions. In addition the suppliers can receive reduced electricity and grid tariffs if the aggregator manages to reduce or shift load in peak load hours with high prices.

Aggregators have several possible opportunities of flexibility to build business models upon. The first step for an aggregator is to attract large flexibility portfolios, and in order to do so he has to buy flexibility from suppliers. It is natural to assume that an aggregator will form contracts with suppliers. To avoid problems with asymmetric information a nonlinear contract is suggested as the trading method and will be employed in further analysis. For a third party aggregator without any existing relationships with the suppliers this will be a time consuming process and crucial for the aggregator's long term existence.

After the aggregator has collected a flexibility portfolio he should investigate all the opportunities for selling this flexibility and find the optimal schedule to maximize profits. As suggested so far in this thesis two major trading methods of flexibility are possible. As a relatively large actor an aggregator is able to form bilateral contracts with large buyers of flexibility. Depending on the competition among aggregators and the size of the portfolio, an aggregator may have bargaining power in contracts as well as market power. Thus an aggregator can possibly utilize each trading area if there are no entry barriers. This chapter will analyze three various business models for the aggregator: selling flexibility in existing electricity and reserve markets by submitting bids of flexibility as supply, bilateral contracting with various buyers and a combined model with trading both in markets and through contracts. Moreover, an aggregator is faced with a complex maximization and scheduling problem and must deal with both the suppliers of flexibility and the buyers, as well as operate in several different markets with varying time frames. This evidently require advanced controlling systems and huge amounts of knowledge about the power system and actors participating in electricity and flexibility markets. Another complicating factor of the aggregators' problem is the large number of relationships the aggregator has to engage in with the various agents, especially suppliers. Additionally, contractual relationships are often characterized by asymmetric information as discussed in Section 4.3 , complicating the decision making and scheduling processes.

Although many researchers believe that aggregators are required in order to exploit flexibility, it is not obvious from an economic point of view why an additional party in the value chain would be efficient nor increase social surplus. Buyers could buy flexibility directly from suppliers like illustrated in Chapter 4. For instance, retailers already have customer relationships with electricity consumers and can utilize this contact and built-up trust to reduce their imbalance costs and place flexible bids in Elspot. Nevertheless, aggregating flexibility from suppliers require time and costs, and these tasks may fall outside the buyers' core businesses. An aggregator specializing in aggregating and selling flexibility may be able to do this at a lower cost. This could possibly result in a higher social surplus, as illustrated with the following simple example. If a buyer contract directly with suppliers his profit is defined as

$$\pi_B = B(x) - c(x)x - F_B \tag{6.1}$$

Here $B(x)$ is the buyer's benefit of procuring flexibility, $c(x)$ is the marginal cost for each unit flexibility he buy, i.e payments to the suppliers, and F_B is a fixed cost of aggregating supply. The aggregator's profit if he contracts with suppliers is defined as

$$\pi_A = p(x)x - c(x)x - F_A \tag{6.2}$$

where p(x) is the price for each volume of flexibility x he sells to the buyer, $c(x)$ is the marginal cost he has to pay suppliers, which is assumed equal for both the buyer and the aggregator and F_A is a fixed cost of aggregating supply. $c(x)$ is by assumption the same regardless of who is buying from the suppliers, hence suppliers' profits are equal in both value chains. Assuming that aggregator's fixed cost is lower than the buyer's, all else held equal[2], this results in a higher value chain profit and hence overall social surplus in the long run

$$\pi^A_{VC} = \pi^B_{VC} + (F_B - F_A) \tag{6.3}$$

Here $\pi^A_{VC} > \pi^B_{VC}$ following from $F_A < F_B$ where π^A_{VC} and π^B_{VC} are value chain profits with and without an aggregator, respectively. Note that Equation (6.3) do not indicate how the profits are allocated within the value chain, only the size of the overall profit is illustrated.

Even though aggregators manage to aggregate flexibility at a lower cost than the buyers, their long term existence face other threats. Sophisticated control systems can automate tasks like aggregating supply and scheduling flexibility. Supply can for instance be bid directly into a market, taking predetermined restrictions into account. With well-functioning control systems the aggregator role may be redundant in the long run. However, for such systems to exist high investments have to be made, and it is not clear who should cover these costs.

6.2 Contract Design with an Aggregator

When introducing an aggregator as a new role in the value chain this will affect the way of designing contracts and how profits are allocated between the parties compared to the situation with only a buyer and supplier of flexibility. As a new market player, it is natural to assume that the aggregator has the incentive to design and offer contracts to both buyers and suppliers of flexibility. In this section the contracts offered by aggregator are simple bilateral contracts.

[2]Both demand and supply could differ when the value chain does not consist of the same actors.

As stated in Chapter 4, the contract terms and the allocation of profit in the value chain are highly dependent on the bargaining power of the actors, and by offering the contract the aggregator might have an advantage in the contract relationship. However, the profit obtained by the aggregator depends on the reservation profits of the buyers and suppliers. The aggregator's fixed cost F_A will not affect the design of an optimal contract but is essential to determine the existence of this role in the long run.

6.2.1 Aggregator and supplier of flexibility

The contractual relationship with suppliers of flexibility is essential for the aggregator's business opportunities and is illustrated in Figure 6.2.The Aggregators' profit is highly dependent on the payment schedule of flexibility to suppliers and the volume of flexibility they manage to aggregate from the suppliers. The contracts should be designed to attract enough suppliers to aggregate a large portfolio of flexibility. An attractive contract will provide the suppliers with the right incentives to participate in such an agreement.

As mentioned in Section 6.1, a potential complicating factor in the aggregator's maximization problem is the information asymmetry. When designing contracts between an aggregator and the suppliers of flexibility, it is realistic to assume that the marginal cost and willingness of supplying flexibility is private information for the suppliers. Based on the investigation and analyses of different contract types in Chapter 4, a nonlinear incentive compatible contract is considered to be the optimal contract to deal with this challenge.

Figure 6.2: Contractual relationship between a supplier and an aggregator.

For mathematical convenience it is assumed that the aggregator only faces two types of suppliers, with high and low willingness respectively. The aggregator gain $p(x)$ per kW flexibility, either from a market or through bilateral contracts with buyers. The aggregator is assumed to be a price taker when trading in the market and hence the volume of flexibility does not influence the market price. In reality this assumption yields if the aggregator trades in existing markets with large turnover volumes or in large flexibility markets with many suppliers. The maximization problem of the aggregator when contracting with two types of suppliers is given by

$$\max_{\{x,y\}} \pi_A = v(p(x)\underline{x} - \underline{y}) + (1-v)(p(x)\bar{x} - \bar{y}) - F_A \tag{6.4}$$

subject to (7.19) to (4.43)

where the restrictions are specified in Subsection 4.3.3.

The marginal and fixed cost addressed to the aggregator's business of flexibility is uncertain. Typically, the aggregator faces large investment costs of advanced controlling systems in the beginning, and a marginal cost of each volume of flexibility he buys. The aggregator may have additional variable costs associated with trade. For simplicity it is assumed that the aggregator does not have a marginal cost of buying flexibility except for the payment to the suppliers. By using the same procedure as in Subsection 4.3.3 the following menu of contracts $\{(\underline{x}, \underline{y}), (\bar{x}, \bar{y})\}$ is offered to the supplier

$$\underline{x} = \frac{p(x) - b(1-\underline{\theta})}{2a} \tag{6.5}$$

$$\bar{x} = \frac{p(x) - b(1-\bar{\theta})}{2a} - \Big(\frac{v}{1-v}\Big)\frac{b\Delta\theta}{2a} \tag{6.6}$$

$$\underline{y} = b\Delta\bar{x} + a\underline{x}^2 + b(1-\underline{\theta})\underline{x} \tag{6.7}$$

$$\bar{y} = a\bar{x}^2 + b(1-\bar{\theta})\bar{x} \tag{6.8}$$

The aggregator's profit from contracting with one supplier equals

$$\pi_A = p(x)x - y \tag{6.9}$$

and the total profit of the aggregator can be found by summing the individual profits obtained from each supplier. The supplier profit becomes

$$\pi_S = y - ax^2 - b(1-\theta)x \tag{6.10}$$

The further investigation of new business models and opportunities for an aggregator will be based on this type of contract between the aggregator and supplier of flexibility.

6.2.2 Aggregator and buyer of flexibility

The buyers of flexibility account for a large part of an aggregator's profit. Actors with high benefits of flexibility will provide substantial revenues and hence a key issue for an aggregator is to design the right type of contract to maximize profits. It is important for the aggregator to acquire information about the need for flexibility for different buyers and by doing so, value the benefit of flexibility. In reality the information available may vary, but for simplicity it is here assumed that the benefit of flexibility is known to all parties. As shown in Chapter 4 a two-part linear contract is well suited in this scenario.

Figure 6.3: Contractual relationship between a buyer and an aggregator.

In this contractual relationship the aggregator is assumed to have a cost $c_A(x)$ of buying flexibility from the suppliers and a fixed administrative cost F_A. The value of c_A is determined by the contract type the aggregator has with the supplier of flexibility. The aggregator need to solve the following maximization problem

$$\max_{(w,L)} \pi_A = wx + L - c_A x - F_A \tag{6.11}$$

when he knows that the buyer profit is given by

$$\pi_B = -\alpha x^2 + \beta x - wx - L \tag{6.12}$$

$$\text{s. t.} \quad \pi_B \geq \pi_B^- \tag{6.13}$$

By using the same approach as in Subsection 4.1.3 the optimal hourly volume of flexibility x in kW is

$$x_{AB} = \frac{\beta - w}{2a} \tag{6.14}$$

and the aggregator will offer the following combination of lump sum[3] and wholesale price to the buyer

$$L_{AB} = -\alpha x^2 + \beta x - wx - \pi_B^- \tag{6.15}$$

$$w_{AB} = c_A \tag{6.16}$$

From this derivation it can be verified that the profits of the aggregator and buyer can be expressed as

$$\pi_A = L - F_A \tag{6.17}$$

$$\pi_B = \pi_B^- \tag{6.18}$$

Clearly, in the scenario with complete information about the buyer's benefit of flexibility the aggregator is able to extract all profits excess the reservation profit of the buyer by using the lump sum. However, in reality it is likely that a large buyer will have significant bargaining power and hence a high reservation profit. The authors believe that a grid company postponing investments by utilizing flexibility is interested in engaging in a long-term contractual relationship with the aggregator and is willing to pay a large lump sum to secure sufficient flexibility available. In contrast, retailers and wind power

[3]The lump sum is defined as a payment from the buyer to the aggregator as, by assumption, the aggregator designs the contract.

producers have more uncertain needs for flexibility and might be less willing to commit to a long-term contract and pay a large fixed sum. The wholesale price and lump sum presented in (6.16) and (6.15) respectively provides a basis for further discussion and analysis when investigating the business models for an aggregator.

6.3 Aggregator as a Participant in Existing Markets

Today, only very large consumers can participate on the supply side in existing electricity markets based on their flexible consumption volumes. Additionally, there exists market barriers and requirements for participation as high yearly fees, minimum bidding volumes and balancing responsibility. Small suppliers of flexibility, as households and other small scale industry, do not have market access, and thus an aggregator is required to realize the potential value of flexibility in the various markets. The profit obtained for the aggregator depends on the market price and the volume traded. The aggregator can choose to provide flexibility in the market either by bidding reduced load, as supply, or a price elastic demand curve. In the following subsection the first alternative is considered. The cost of flexibility is specified by the bilateral agreement between the aggregator and the supplier, here in terms of a single household. To get an impression of the realized profits the hourly profits are aggregated to a yearly profit for both parties. The aim of this section is to investigate in which markets the aggregator will gain from trading. The markets to be studied are Elspot, the Balancing Market and the Reserves Option Market and the aggregator's business model solely ofcus on trading in one of these. Other markets as Elbas and the Secondary Reserves Market are not included in this analysis but could be interesting to study in further research. Especially the Secondary Reserves Market might provide high returns due to high prices and large volumes.

6.3.1 Elspot

As Elspot is a day-ahead market, the market participants might face imbalance costs if they fail to deliver or consume the submitted volume. For an aggregator these costs can occur if the actual volume of flexibility deviates from the volume bid in Elspot. One of the main market barriers for entry of an aggregator in Elspot is the minimum volume requirements and the fixed yearly participation fee. Additionally, the aggregator must have balance responsibility, or cooperate with a balance responsible party. The aggregator will likely also face high annual costs of hourly metering [5].

The market clearing in Elspot is done by the SESAM calculation and is based on an application of the social welfare criterium in combination with market rules [24]. SESAM is maximizing the value of the objective function subject to physical constraints. The simplified objective function, the social welfare ciriterium, is given by

$$max \sum_{n} \left\{ \int_{0}^{d^a} D^a(x)dx - \int_{0}^{s^a} S^a(y)dy \right\} \tag{6.19}$$

Here, a represents an area, d^a is demand in area a and D^a is the demand function in area a, s^a is supply in area a and S^a is the supply function in area a and n is the number of areas. The model expresses that social surplus, consumers' utility minus producers' cost, shall be maximized subject to minimal requirements about volumes, area balance, transmission capacities, maximal transmission ramp rates, accepted bids and price difference between areas.

In Elspot, the flexibility can either be included as elastic demand curves, or in the supply curve by reducing load. These situations are illustrated in Figure 2.4 in Chapter 2 and Figure 6.4 respectively. When the flexibility is handled as supply, the aggregator compete against other power producer about delivering flexibility. It is believed that the cost of flexibility will be equal to or lower than the spot price. Today end-users have indirectly access to Elspot through their retailer. A retailer undertaking the role of an aggregator can use the flexibility to bid price elastic demand curves in Elspot. The increased elasticity of demand will lead to lower price variations, and additionally decrease the market clearing price for electricity.

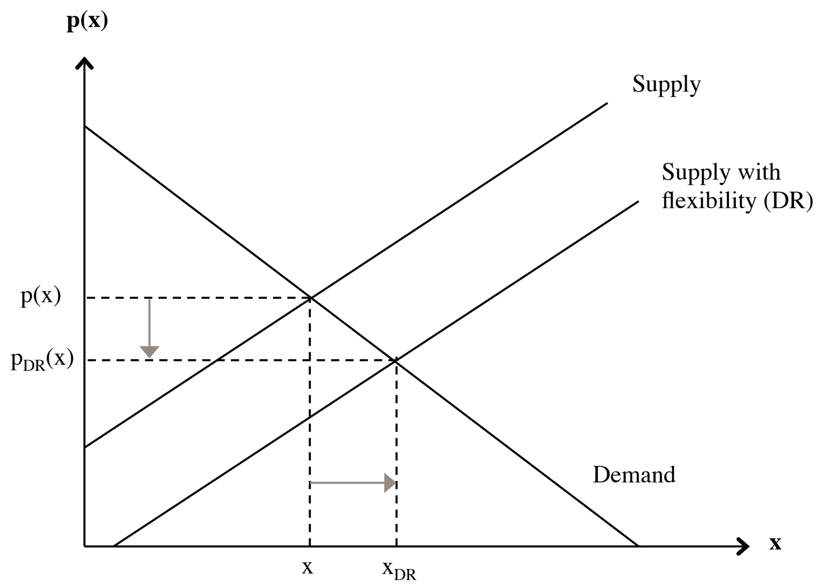


Figure 6.4: Bidding flexibility as supply in Elspot.

By aggregating multiple suppliers of flexibility, the aggregator can meet the volume requirements for participating in Elspot. It is also assumed that the aggregator has potential to be a balance responsible entiy in the power system. Hence, he can submit bids of flexibility as supply in Elspot and receive spot price for the accepted bids. It is reasonable to assume that the volume of flexibility traded by the aggregator does not impact the spot price since there are large turnover volumes in Elspot. The aggregator buys flexibility from a supplier through a bilateral contract as described in subsection 6.2.1, and when selling the flexibility in Elspot the aggregator's profit becomes

$$\pi_A^S(x) = v(p^S(x)\underline{x} - \underline{y}) + (1 - v)(p^S(x)\bar{x} - \bar{y}) - F_A - C^R(x) \tag{6.20}$$

where $p^S(x)$ is the hourly spot price and $C^R(x)$ is the regulating cost if imbalance occurs. The latter is neglected in the following calculation. Volumes for the efficient $\underline{x}$ and the inefficient supplier $\bar{x}$ are here given by

$$\underline{x} = \frac{p^S(x) - b(1 - \underline{\theta})}{2a} \tag{6.21}$$

$$\bar{x} = \frac{p^S(x) - b(1 - \bar{\theta})}{2a} - \frac{v}{1 - v}\left(\frac{b\Delta\theta}{2a}\right) \tag{6.22}$$

As can be seen from (6.21) and (6.22) the volume of flexibility required from the suppliers depends on the spot price for electricity. Low spot price leads to low volumes and additionally low profit for the aggregator. The incentive payments to the suppliers are the same as in (6.7) and (6.8). By bidding flexibility into Elspot the spot price and turnover volume will decrease, thus building and investing in new generators for peak load hours can be avoided. The price variations are relatively small and the present spot prices are low. In addition profits are uncertain as this is an day-ahead market and imbalances may occur. Consequently, it is assumed that an aggregator can gain more profit from participating in other markets or by exploiting other business models.

6.3.2 The Balancing Market

The Balancing Market is activated due to imbalance in the system. The market participants can submit bids for both upward and downward regulating power. The regulating prices for upward regulation are usually higher than in the spot market. Today, most of the market participants are large hydro power producers with low marginal production costs and therefore the regulating prices are relatively low. In other countries with expensive peak load power plants, the regulating prices are significantly higher. It is assumed that flexible consumption will have a lower marginal cost than most producers, and hence the regulating prices might decrease when bidding flexibility into the Balancing Market.

Like in Elspot, there are certain requirements for participating in the Balancing Market. First, the aggregator must be approved by the TSO to have balance responsibility. As discussed in the previous subsection this is a barrier that can be overcome. Second there are restrictions on combined delivery, and hence an aggregator cannot combine production and consumption devices in its portfolio. Additionally, there are requirements for minimum volume, duration and response time of 15 minutes [30]. The short response time demanded creates the need for advanced real-time communication equipment between the aggregator and the suppliers, and high annual and one-off costs might arise. Additionally both day-ahead and intra-day communication are required as operational schedules for every 5 minutes have to be sent the day before operation. The threshold of 10 MW requires a large number of suppliers to be managed by the aggregator and this will make it difficult to manage operational schedules as many consumers have stochastic behavior [5].

The Balancing Market is cleared by sorting the regulating bids in merit order and the hourly regulating price $p^{BM}(x)$ is determined by the highest bid activated in the respective hour. The aggregator is assumed to be a price taker in this market as well and the profit of the aggregator submitting bids of flexibility in the Balancing Market becomes

$$\pi_A^{BM}(x) = v(p^{BM}(x)\underline{x} - \underline{y}) + (1-v)(p(x)^{BM}\bar{x} - \bar{y}) - F_A \tag{6.23}$$

where $p^{BM}(x)$ is the upward regulating price since the aggregator is assumed to only submit bids for upward regulation. Here $\underline{x}$ and $\bar{x}$ are given by

$$\underline{x} = \frac{p^{BM}(x) - b(1-\underline{\theta})}{2a} \tag{6.24}$$

$$\bar{x} = \frac{p^{BM}(x) - b(1-\bar{\theta})}{2a} - \frac{v}{1-v}\left(\frac{b\Delta\theta}{2a}\right) \tag{6.25}$$

The incentive payments to the suppliers are still given by (6.7) and (6.8). The trade-off between trading in Elspot and the Balancing Market is given by the market price as well as the realized volume. By definition $p^{BM} \geq p^S$, but at the same time the turnover volumes are often smaller in the Balancing Market. Hence, it is difficult to argue in which of these markets the aggregator will obtain a larger profit, but if it is assumed that equal volumes of flexibility are activated in each of the markets this will result in $\pi_A^{BM} \geq \pi_A^S$. However, it is uncertain wether the bids submitted are activated or not.

6.3.3 The Reserve Option Market

In both Elspot and the Balancing Market the aggregator cannot be certain that his bids are activated and might face low or no income. Additionally, his profit in these markets are dependent on the market price and the bidding volume as can be seen from (6.20) and (6.23). Due to this challenge it is interesting to investigate the Reserve Option Market as a possible market for the aggregator to sell flexibility. Because of the high minimum volume requirements for trading in this market and the long duration of the options, small suppliers of flexibility, i.e. households and commercial businesses, will not be able to participate. This opens up a large potential for the aggregator to submit bids on behalf of these suppliers with an aggregated portfolio.

The price setting of the option premium exploits the principle of marginal pricing [31].

All accepted bids receives the same price in each price area given by the highest accepted price. If the supplier cannot activate flexible power in every hour during the week, he can restrict the bid with a specified number of *resting hours* between two activations. The maximum amount of resting time is 8 hours per week, and these hours reduce the option premium. The supplier can also restrict the *length* of an activation period. If the length of activation is 4 hours or less, the option premium will be reduced as well. Thus, these restrictions have to be taken into account when deciding the option premium paid to the aggregator. The option premium $O(x)$ for having x MW power available is calculated as

$$O(x) = \eta\sigma p^{\mathrm{ROM}}(x)x \tag{6.26}$$

where η and σ are the truncation rate for restricting the length of activation and resting time respectively. These rates are determined by Statnett as the TSO. If the seller of the option violate the obligation to supply flexibility, Statnett will reduce the option premium. The penalty $A(x)$ can be found as

$$A(x') = \psi m(x)x't \tag{6.27}$$

where ψ is a factor corresponding to the truncation rate of the option premium, x' is the volume of inaccessible power and t is the duration of the inaccessibility of the power. In practice, the penalty will not be larger than the option premium. The penalty is neglected in the numerical and analytical calculations. In some operational hours a need to obtain additional regulating power in certain areas arises. In these situations the TSO can accept bids with a higher price, without influencing the market price. Such options are called special options and they will receive a price equal to the bidding price, i.e.*"pay-as-bid"*.

If the aggregator manage to aggregate a large portfolio of flexibility he can participate in the Reserve Option Market in lieu of only the Balancing Market. By doing so, the aggregator receives an option premium for placing a certain volume of available flexibility. For simplicity, it is assumed that the aggregator only pays the suppliers for activated flexibility. The aggregator's maximization problem in this market becomes

$$\max_{\{x,y\})} \pi_A^{ROM} = v\left(p^{\mathrm{BM}}(x)\underline{x} - \underline{y}\right) + (1-v)\left(p^{\mathrm{BM}}(x)\bar{x} - \bar{y}\right) + O(x) \tag{6.28}$$

Note that this is a one-to-one relationship between the aggregator and a single supplier. Here $O(x)$ is a share of the total option premium for providing flexibility given in (6.26) and $p^{\mathrm{BM}}(x)$ is the regulating price that the aggregator receives by activating flexibility in the Balancing Market. By using the same solution procedure as in Subsection 6.2.1, the incentive compatibility contracts give the following volumes

$$\underline{x} = \frac{p^{\mathrm{BM}}(x) - b(1-\underline{\theta})}{2a} \tag{6.29}$$

$$\bar{x} = \frac{p^{\mathrm{BM}}(x) - b(1-\bar{\theta})}{2a} - \frac{v}{1-v}\left(\frac{b\Delta\theta}{2a}\right) \tag{6.30}$$

The incentive payments are still given by equation (6.7) and (6.8). Compared to the situation where the aggregator only sells flexibility in the Balancing Market, the aggregator now receives a fixed option premium regardless of how much flexibility is actually activated in the Balancing Market. This fixed premium can make the aggregator's profit less uncertain. However, the aggregator has to reserve volumes of flexibility over a longer time period when trading in this market, in which can decrease the opportunity for the aggregator to achieve profits through other business models.

6.3.4 Illustrative study of trading flexibility in existing markets

To illustrate the profit for the aggregator in the different markets and evaluate in which markets he can obtain the highest profits, some illustrative calculations have been performed. The calculations are based on hours with relatively high prices as flexibility often is needed in these hours. As shown in Table 6.1 both the hourly and yearly profits from selling flexibility bought from one supplier in Elspot are low due to the low electricity price compared to the estimated cost of supplying flexibility. On a yearly basis, when aggregating over 10 000 households, the aggregator obtain a significantly higher profit, but this profit is highly dependent on the market price hence the aggregator faces uncertain income. The supplier faces less financial risk since he receives the reservation profit regardless of the size of the market price. It should be emphasized that the supplier additionally will gain from lower electricity bills[4] by reducing load or shifting load to hours with a lower electricity price. This gain is substantially higher than the payment from the aggregator.

Table 6.1: Profits from bidding flexibility in Elspot in a high price scenario.

Profits [NOK]	Hourly benefit	Yearly profit	Yearly gain from reduced load
Efficient supplier	0,10	45,70	326,88
Inefficient supplier	0,05	21,90	331,09
Aggregator	0,29	126,39	
Aggregator (10K households)	2886	1 263 860	

In order to compare profits obtained in the various markets, it is assumed that the aggregator has an available volume of 5 000 kW flexibility in a given hour. The whole

[4]Here it is assumed that the supplier have a spot price contract with the retailer and is paying the actual spot price for each hour

volume of flexibility in the portfolio is activated in Elspot while only 1 000 kW is activated in the Balancing Market. In the Reserve Option Market the aggregator receives an option premium to make the entire portfolio available. As can be seen from Table 6.2 the aggregator obtains highest profit when trading in the Reserve Option Market due to the option premium. Nevertheless, it is uncertain how large volumes are accepted in this market and if the aggregator have a limited portfolio of flexibility he should optimize the utilization of this flexibility by considering the probability of when the peak-load hours, and thus the highest prices occur. In the future the regulating prices might increase which can result in higher profits from the Balancing Market and the Reserve Option Market. When trading flexibility in existing markets the aggregator will face high costs associated with advanced meters and controlling systems so the profits presented in these calculations will most likely be lower in reality.

Table 6.2: Comparing revenues [NOK] for the aggregator in various existing markets.

	Elspot	Balancing Market	Reserve Option Market
Weekly option premium			50 000
Option premium per activated kW in BM			10 000
Revenue aggregator	5 441	1763	11 763

The three existing market opportunities clearly represent trade-offs for the aggregator. By trading in Elspot the aggregator can activate large volumes, but face uncertainty with imbalance costs and low spot prices. Sacrificing activated volumes the aggregator obtains higher prices and no imbalance costs in the Balancing Market. The Reserve Option Market, on the other hand, require binding up large volumes over time in return for an option premium, thus sacrificing alternative use of the flexibility. The aggregator's load scheduling problem should include these trade-offs.

The existing electricity markets, and especially the Reserves Option Market, provide important business opportunities for an aggregator. Nevertheless, by trading flexibility in these markets the problems that many actors face in the present power market are not fully solved as the flexibility only adjusts prices and provides electricity reserves. Hence the full value of flexibility described previously is not realized. Therefore the aggregator should expand his business model by simultaneously trading flexibility bilaterally with buyers who are not able to participate in these market.

6.4 Combined Business Model for an Aggregator

A combined business model can expand the horizon of flexibility by both selling excess flexibility in specified markets as well as trade through bilateral contracts. As stated in previous chapters, some actors have limited access to markets or are excluded from various trading methods due to lack of profit. By engaging in different trading methods, the aggregator can reach out to more buyers. Additionally, in reality buyers of flexibility will not demand flexibility in the exact same hours, and thus the aggregator can optimize the value of his flexibility portfolio by exploiting this. The trade-off between different trading methods for an aggregator will be discussed in this section. It is assumed that the aggregator has a certain volume of flexibility available to a given price, and hence only the aggregator's revenue is studied here.

6.4.1 The trade-off between contracts and markets

The aggregator faces a trade-off between the volume of flexibility to be bound in contracts and the volume of submitted bids in a market, and it is difficult to calculate the optimal combination of these methods without using an advanced optimization model[5]. When determining the optimal combination, the aggregator must consider the alternative value of other opportunities. Market barriers, market access, bargaining power and other complicating factors should also be taken into account. The aggregator must ensure sufficient flexibility available to cover all his agreements at any time, as he will incur large penalty costs if he fails to do so. The aggregator's profit when operating with a combined business model can be described as

$$\max \pi_A^{CBM} = \pi_A^M \rho + \pi_A^C (1 - \rho) \tag{6.31}$$

where π_A^M is the profit obtained from trading in existing markets, pi_A^C is the profit from bilateral contracts with buyers and ρ indicates the allocation of flexibility. As the expression states, the flexibility should be allocated to where it is valued the most. In contracts, the aggregator has the opportunity to determine the rules by designing the contract and specifying the contract terms. It is believed that buyers requiring secure supply, as grid companies, would prefer to engage in contracts rather than markets to ensure a sufficient volume of flexibility available at all time. In contrast, retailers and wind power producers might be less interesting in committing on a long-term perspective as their problems are related to more unpredictable incidents. However, these actors might be willing to engage in contract on a seasonally basis, as the regulating prices are higher during the winter. Short-term contracts with certain actors could be combinable with long-term contracts, and can ensure that excess flexibility in given periods is sold.

In the existing electricity markets the aggregator can obtain profits by optimizing bids submitted in the different markets. To do so, the aggregator needs an advanced optimization model considering the frequency of events and timing of the peak load, where

[5]This topic has been investigated in several studies, for instance [32]

prices are highest. Trading flexibility in existing electricity markets does not solve the capacity problems of the grid companies, but retailers and wind power producers can indirectly gain from lower regulating prices. Bids of flexibility in Elspot is expected to decrease the average spot price, and hence retailers, as buyers in this market, will gain from this while wind power producers, as suppliers in this market, will face revenue losses. As discussed in Subsection 6.3.4 the Reserve Option Market provides the highest profit for an aggregator as he receives an option premium regardless of the volume of submitted bids.

Due to the fact that the aggregator must ensure sufficient flexibility available in all agreements he will not be able to bind up large volumes in the Reserves Option Market and at the same time engage in long-term contracts on large volumes with a grid company. Hence, the aggregator could specialize on one core business and find smart solutions to utilize excess flexibility in every hour. One opportunity is to engage in short-term contracts with retailers or wind power producers, or trade the excess flexibility in existing electricity markets or separate flexibility markets. Research has suggested that new separate flexibility markets will arise. It is, however, uncertain wether an aggregator will exist within such market but if the aggregator can act as a monopoly in a flexibility market this will be even more profitable than contracts.

6.4.2 Illustrative study of a combined business model

The profits from different business models are compared by performing simple estimates. The calculations are based on an available volume of 5 000 kW flexibility in a specific hour, like in the calculations in Subsection 6.3.4. Thus the costs related to the flexibility portfolio are equal in both trading methods, making the results comparable. The flexibility is aggregated from 5 000 households in which can reduce 1 kW each in the specified hour. The two-part linear contract applied in the calculations is presented in Subsection 6.2.2.

Table 6.3: Contracts between the aggregator and the buyers of flexibility.

	Grid company	Wind power producer	Retailer
Wholesale price	0,8	0,8	0,8
Lump sum	33 803	-63	867
Revenue aggregator	37 765	3 899	4 829

As seen from Table 6.3 the lump sum in the two-part linear contract between aggregator and wind power producer is negative due to profits lower than their reservation profits. Additionally, the profit obtained in a contract with a retailer or wind power producer is substantially lower than in the contract with the grid company. The profit from contracting with a grid company yields the overall highest profit from the all alternatives investigated, while trading in the Reserve Option Market yields the second highest profit. Based on the calculations the aggregator will prefer to engage in a long-term contract with a grid company when having a limited volume of flexibility available, and supplement with trading excess flexibility in the electricity markets as this has proved to be profitable.

6.5 Local Flexibility Markets

As stated, grid companies need flexibility from geographic specific suppliers in order to solve various capacity and reliability problems in the distribution grid, which brings along a need to granulate the demand and supply in local areas. The authors of [14] and [15] illustrates mathematically how customer groups can be defined to address the local need for flexibility. In order for grid companies to buy flexibility in a separate market the market operator can match flexibility demanded from a specific supplier group with supply from the same group. It would be possible to have one large flexibility market in Norway divided in fine-grained supplier groups corresponding to each buyer. However, the market clearing would probably be too complex and lead to inefficient outcomes. In lieu of one large market, multiple local markets could balance demand and supply in each supplier groups in a more efficient way. The market clearing model for local flexibility markets is based on the models derived in [14] and [15] but with some modifications. The models in these articles treats flexibility as a public good, whereas the flexibility in this thesis is looked upon as a private good. The customer groups are called supplier groups here since electricity customers are suppliers of flexibility. If grid companies are the buyers, a supplier group includes all suppliers connected to a common load point of a feeder at a distribution level. In case of a retailer, a group can consist of all suppliers within the same price area in Elspot, or of all the suppliers with the same electricity supply contract.

6.5.1 Market clearing of a local market

The market clearing of a local flexibility market should be *Pareto optimal*. Scheduling a resource, i.e. flexibility, for a number of agents is Pareto optimal if no change from this schedule can increase benefit for one agent without reducing benefits for other agents [14]. To reach Pareto optimality, the following maximization problem must be solved

$$max \left\{ \sum_{j=1}^{J} B_j - \sum_{s=1}^{S} C_s \right\} \tag{6.32}$$

Equation (6.32) states that a flexibility schedule is Pareto optimal if the total surplus derived from this schedule for all agents together is maximized. Here B_j is the total benefit for buyer j and C_s is the total cost of producing flexibility for supplier s. The individual benefits taking supplier groups into account is given by

$$B_j = \sum_{n=1}^{N_j} \left(-\alpha_{j,n} y_{j,n}^2 + \beta_{j,n} y_{j,n}\right) \qquad \forall j \in J \tag{6.33}$$

Each buyer involves a corresponding set of supplier groups. Equation (6.33) implies that the total benefit for each buyer is the sum of the benefits from each supplier group n. $\alpha_{j,n}$ and $\beta_{j,n}$ are the valuation coefficient and are individual for each buyer and for flexibility supplied by each supplier group. For a grid company it is reasonable to assume that flexibility from suppliers in a specific location is more valuable than flexibility from other locations as they solve different problems. $y_{j,n}$ is the total amount of flexibility demanded by buyer j from supplier group n. Buyers demand this aggregated amount of flexibility from a group of suppliers but do not need to know exactly which suppliers were the providers. The suppliers' individual costs of providing flexibility is defined by

$$C_s = \sum_{j=1}^{J} a_s x_{j,s}^2 + b_s(1-\theta_s)x_{j,s} \qquad \forall s \in S \tag{6.34}$$

Equation (6.34) illustrates that the cost for each supplier is defined as each single supplier's cost function with individual cost coefficients a_s and b_s as well as a willingness parameter θ_s like before. $x_{j,s}$ is the amount of flexibility that supplier s provides to buyer j. The benefit for the buyers depends on both the supplier group and the buyer. Consequently, the market clearing will result in different market prices dependent on j and n. This is a form of price discrimination, and it is not clear if such pricing will be accepted by the Competition Authorities in the future. However, this model will assume that prices can differ between and within supplier groups.

To ensure that demand of flexibility equals supply in each supplier group, a constraint for the demand-supply-balance must be included in the market clearing

$$y_{j,n} = \sum_{s=1}^{S} u_s^{j,n} x_{j,s} \qquad \forall j \in J, \forall n \in N_j \tag{6.35}$$

The left-hand side of (6.35) is the aggregated amount of flexibility demanded by buyer j from supplier group n. On the right-hand side all the individual volumes of flexibility $x_{j,s}$ from the suppliers included in each supplier group are summed up to find aggregated supply. $u_s^{j,n}$ is a binary coefficient that represent the relational status of each supplier s to group n, which is 1 if the supplier is included in group n, and 0 otherwise. Market price for buyer j and supplier group n is found from each buyer's demand curve at the given volume of flexibility $y_{j,n}$

$$p_{j,n}(y_{j,n}) = -2\alpha_{j,n} y_{j,n} + \beta_{j,n} \tag{6.36}$$

If several buyers demand flexibility from the same suppliers[6] in an hour the total cost of supplying the flexibility is calculated based on the total demanded flexibility from all buyers. Consequently, the costs will be higher than they are in reality as the same flexibility could be procured by several buyers without raising the costs if they are supplied by the same suppliers. As the market clearing maximizes overall benefit only the buyer with highest benefit in each supplier group will buy flexibility. The profit for buyer j becomes

$$\pi_j = \sum_{n=1}^{N_j} \left(-\alpha_{j,n} y_{j,n}^2 + \beta_{j,n} y_{j,n} - p_{j,n} y_{j,n}\right) \qquad \forall j \in J \tag{6.37}$$

The supplier profit on the other hand is given by

$$\pi_s = \sum_{j=1}^{J} \left(p_{j,s} x_{j,s} - a_s x_{j,s}^2 - b_s(1-\theta_s) x_{j,s}\right) \qquad \forall s \in S \tag{6.38}$$

From the perspective of each market participant this model proposes sub-optimal outcomes. If buyers could collectively pay for the flexibility that several buyers demand their cost would reduce and buyers with lower benefits could buy more of the flexibility needed to solve various problems. A local market clearing is illustrated with a small test system in the following subsection, followed by a proposed solution to a more efficient scheduling of this resource.

6.5.2 Illustrative study of a local flexibility market

A test system consisting of 20 suppliers of various types, one grid company with two different supplier groups and one retailer with one supplier group including all the suppliers is used to illustrate a local flexibility market as shown in Figure 6.5. It is assumed that all suppliers and buyers in the test system have access to the market. The grid company value the flexibility from both supplier groups equally, hence the valuation coefficients are the same in both groups. However, the groups consist of different supplier types who have different costs of providing flexibility. The retailer's benefit is given by the benefit function described in Section 3.4 for a *future* scenario with high imbalance costs. The model is solved by using a nonlinear solver in Excel. The valuation coefficients estimated in Section 3.4 are scaled down for both the retailer and the grid company in order to represent benefit of a local problem matching the low supply in the test system. Note that the results for this reason are not directly comparable with the numerical results in Chapter 4 and 5.

Table 6.4 shows the results of the optimization. Given the grid company's high estimated benefit of procuring flexibility he want to buy a large volume of flexibility to a higher price than the retailer with lower benefit. Thus, only the grid company buys flexibility

[6] Supplier groups may overlap so that one supplier is represented in several supplier groups.

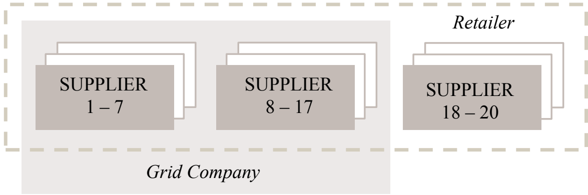


Figure 6.5: Test system for a local flexibility market.

from the suppliers in overlapping supplier groups. Consequently, the retailer only buys flexibility from the three suppliers not included in any of the two supplier groups related to the grid company. Since it is assumed in this test system that both buyers need flexibility in the same hour, the retailer would procure less than if the grid company did not procure any flexibility in the given hour, thus increasing the supply that the retailer could buy. In reality, buyers may not necessarily demand flexibility from the same locations in the exact same hours as they have different problems to solve. Nevertheless, as some challenges might be related to each other the same flexibility will sometimes be demanded at the same time period, and a flexibility market should address this in the market clearing in order to reach efficiency.

Table 6.4: Results from the simulation of a local flexibility market with supplier groups.

	Grid company		**Retailer**
	Group 1	Group 2	Group 1
Volume [kW]	102	184	9
Price [NOK/kW]	6,60	6,51	4,72
Profit [NOK]	1 895		45

6.5.3 Flexibility as a public good

So far in this thesis flexibility has been treated as a private good benefiting only the actor buying flexibility. However, flexibility is a special type of commodity that is closely linked to the electricity market and can influence other actors in the electricity system regardless if they are participants in the flexibility market. Often the buyers will demand flexibility in different hours depending on their problems. Sometimes, however, they might demand flexibility from the same geographic area and in the same hour. For instance, if a grid company and a retailer demand 5 MW reduced electricity in the same hour and from the same suppliers, the suppliers only need to reduce 5 MW in total to meet the demand from both buyers. When the flexibility is treated as a private good both buyers would pay for the same commodity. From a socio-economic point of view this is inefficient. A possible way of addressing this efficiency problem is to treat flexibility as a *public* good that is jointly used by several independent buyers in given hours. In contrast bilateral contracts fail to address the problem as the various contractual relationships are not coordinated, and each bilateral contract optimizes individual profits.

The authors in [14] and [15] propose two different market clearing methods in a separated flexibility market where they treat flexibility as a public good. [14] defines a pool-based market clearing scheme including a constraint related to the contribution percentage each buyer has to pay when the flexibility is jointly used. These contributions must be specified in an assurance contract which is a financial mechanism for guaranteeing an efficient provision of the public good [14]. How much each buyer should contribute to the payment of flexibility depends on the benefit this buyer receives from the flexibility bought.

In [15], the same authors develop an alternative decentralized market clearing scheme called agent-based. In this scheme, each market participant is assumed to be an "economic agent" that only maximizes own benefit based on information about actions taken by others agents. The strength of this model compared to the pool-based model is that it does not include contribution rates and the agents are not required to submit demand and supply curves which can be difficult to predict. The market clearing scheme employ *Walrasian auctions*, in which multi-round demand-supply balancing price adjustments takes place [6]. The market operator adjusts the prices of flexibility in each round to converge supply and demand to the market equilibrium point. The iterative auction can be modeled with a tâtonnement process, which is a form of hill-climbing algorithm proposed by Walras [6].

In order for local flexibility markets to function well and be efficient in an economic perspective, it might be necessary to consider flexibility as a public resource. Further analysis and modeling must examine which players should contribute with payments for flexibility when more than one buyer demand the same resource[7]. The proposed model in [15] is a suitable basis for further investigations related to local flexibility markets. However, the model could also consider how payments could be divided when some participants procuring flexibility influence other agents in a negative way.

6.5.4 Aggregator participating in local markets

Sophisticated systems automating the supply of flexibility into these local markets can obviously diminish aggregators importance. If these systems manage to provide flexibility at a lower cost and more efficiently than intermediary actors, and at the same time release the full potential of flexibility, aggregators will be redundant in the long run in an economic perspective. However, other factors must be considered as well. First, various market barriers can hinder small suppliers to participate in the flexibility markets like high transaction costs and participation fees. As the activation of flexibility affect

[7]Flexibility demanded from the same suppliers in a time period

other than the participant buying or selling the resource, balance responsibility is crucial to secure reliability in the energy system. Thus, each supplier of flexibility in the local market should be a balance responsible party or having an agreement with another actor possessing this role. As it is not realistic that small suppliers are balance responsible parties, they are dependent upon other actors in order to supply flexibility in the market which might prevent participation. Additionally, costly investments are required to install the sophisticated systems needed to automate the supply into the market. Small suppliers are less willing to incur these costs than larger actors. An aggregator may have larger opportunities for extracting profits from flexibility, and for that reason he could be willing to invest in systems needed. Aggregators specializing in innovative flexibility products as their core businesses are capable of providing flexibility services to a lower marginal cost than other actors.

From a broader perspective, several options for aggregators to participate in local flexibility markets exist. The development of new technology, suppliers' behavior and the division of roles in the future energy markets are key factors to determine design of new flexibility markets. Competition among aggregators is especially important in local markets in order to prevent inefficient trading of flexibility, as it may be easier to exercise market power in a local market.

6.6 Future Solutions for Flexibility

Various solutions for activating flexibility and allocating the value of this resource have been presented. Major changes in the electricity system are required in order to exploit the proposed business models. [8] indicates that these changes will be a gradually process. A number of factors will influence the way trading of flexibility is introduced to the energy markets and the division of new and existing roles, both for short-term and long-term adaptions. Based on the analyses throughout the thesis this section briefly propose solutions to utilize various business models and discuss long-term adaptions in the electricity system.

6.6.1 Gradually introducing flexibility as a resource

The transition to a market dealing with present and future challenges is a comprehensive process which require several adaptions. The first phase of this transition should focus on making flexible consumption of electricity interesting for individual suppliers. In this phase only a small subset of buyers and suppliers will realize the value of flexibility [8], hence small volumes of flexibility will be traded. Contractual relationships will be a natural way of trading flexibility in an early transition phase. As mentioned, aggregators might be the necessary driving force to attract suppliers to participate. Flexibility markets will most likely not be formed at this stage. Moreover, few suppliers have installed advanced control systems necessary to bid directly into a market in this phase. For these reasons the authors believe that aggregators will be key roles in the early transition phase. Large industry and commercial suppliers can contract directly with buyers whereas households are more dependent on aggregators. Based on the analyses of various contract types, a nonlinear incentive compatible contract is proposed for the aggregator to activate flexibility from suppliers. Suppliers select a suitable volume of flexibility they are willing to provide to the aggregator for a given payment from a large menu. In return, the aggregator controls and manage their loads. The suppliers can restrict the loads to be controlled. In addition, the aggregators should offer innovative services to make the flexibility resource more attractive to suppliers. The contracts should distinguish between available flexibility and actual activated flexibility with an attached payment schedule. For instance, aggregators can offer a service in return for available flexibility and pay the contracted price for activated flexibility.

Aggregators have to engage in bilateral contracts with the buyers as well, and as indicated by the analyses a two-part linear contract is a suitable alternative for the aggregator to extract profit, and simultaneously the optimal value chain profit is obtained. The buyers must pay a wholesale price for each volume of flexibility they demand from the aggregator as well as a fixed payment, and it should be agreed in this contract as well whether the buyers must pay for all available flexibility or the activated flexibility. The latter reduces the risk for buyers, making it easier for them to participate. The lump sum payment could be used to pay for having a certain amount of flexibility available at given times while the wholesale price pays for activated flexibility. Bargaining power will decide the allocation of profits among the participants. As buyers may not be aware of the value of flexibility in the beginning, it is reasonable to assume that the aggregator cannot extract the whole value chain profit and must give the buyers attractive offers. For instance a grid company may demand a risk premium for postponing investments as there is uncertainty and thus higher risks involved. The contracts can typically be individually tailored rather than being standard contracts in this phase [8].

When more flexibility is mobilized and multiple buyers become aware of the value of flexibility a market place can evolve. In a market place the opportunities of flexibility becomes apparent and makes it easier for buyers and suppliers to trade flexibility. This will also increase the transparency and the competition among flexibility traders, making the trading more efficient. For a relatively new traded resource it is important that participants have easy access to the resource. Thus, a market place is an important step for making flexibility available. Existing electricity markets can be an additional market place for trading flexibility. The existing market barriers should be removed for this to happen, making it possible for new entrants to submit bids of flexibility into these markets. As discussed in Section 6.3, an aggregator might extract profits from trading in the Reserve Option market. If the aggregator possesses a large flexibility portfolio he can exploit a combined business model where contractual relationships are the primary source of income and trading in existing markets serve as a supplementary income source.

The transition phase can eventually lead to creation of new markets for trading well defined flexibility products with large market volumes. Local markets defined in Section 6.5 will provide flexibility to all potential buyers. The local dependency of grid companies' challenges are addressed by these markets and the market operator can serve as the coordinating role instead of the aggregator. Unlike an aggregator, a market operator tries to maximize total market benefit. Thus, trading flexibility through markets will in most cases lead to more efficient outcomes than bilateral contracts coordinated by aggregators.

6.6.2 Long term market adaptions

Existing electricity markets and separate flexibility markets are designed for different purposes. Whereas the existing markets intend to trade electricity and secure electricity reserves, flexibility markets aim to provide flexibility to the system by letting all potential buyers and suppliers participate. Flexibility is a virtual resource physically linked to electricity, hence the markets affect each other. Nevertheless, they are not necessary capable to combine in one market which brings along an interesting aspect: how can both markets exist in the long run?

Three key factors affect the long-term existence of parallel markets in the electricity system. First, the prices in the existing electricity markets and the local flexibility markets are of importance. A large gap in the prices may exclude one of the markets. For instance, if the flexibility markets operate with significantly higher prices than the electricity prices few buyers are interesting in procuring flexibility. Some buyers, however, value the flexibility high enough to trade in the flexibility market if they do not have access to flexibility from other trading methods which leads to the second key factor. Barriers of market access prevent certain actors to freely participate in all markets. If some buyers and suppliers do not have access to provide flexibility in electricity markets this indicates a need for a separate market. Without an intermediary party like an aggregator or a retailer, small suppliers can realistically be excluded from electricity markets due to certain barriers. Finally, balancing of the electricity system is crucial and the parallel markets must secure balance in order for both of them to exist as electricity and flexibility is physically linked. If flexibility is activated in a flexibility market, this affects the electricity balance of the system. Hence the markets must be coupled and should be operated synchronously. Coupling the markets ensures that the flexibility is employed where it offers the most value, and the same resource can be activated for different purposes in the power system while inducing both private earnings and the economy at large.

Chapter 7

Conclusion

The main scope of this thesis has been to present and analyze methods for trading demand side flexibility, including all participants willing to supply or buy flexibility. In order to do so, factors affecting the overall efficiency of various business models, like benefits, costs and divisions of power between actors, have been analyzed. The quantification of costs and benefits associated with flexibility served as a basis in the design of business models. Although the costs and benefits are only estimates, they illustrate important trends consistent with other research. The results clearly indicated that grid companies possess largest potential of exploiting flexibility as this resource can solve the majority of future problems in the distribution grids. This allocation of benefits have great influence on contractual and market-based approaches of trading as the gap can prevent other actors from trading flexibility and restrict the potential of value creation. For a retailer, the flexibility can be more profitable than illustrated in this thesis by undertaking the role of an aggregator. Doing so, the retailer can optimize his existing customer portfolio. The analyses performed implied insufficient gains for the wind power producer from procuring flexibility in both a present and future scenario. Additionally, as a producer he will incur lower income following from decreasing average electricity prices when flexibility is introduced to the system. Consequently, the producer should rather focus on optimizing bids in the electricity market.

The analyses of contractual trading of flexibility confirmed the importance of contracts in the power market. Contracts can serve as tools for extracting flexibility from suppliers and provide tailored solutions to overcome challenges in the electricity system. As the grid companies postpone long-term investments when exploiting flexibility they need reliable supply of the resource throughout the period, in which a tailored contract can facilitate. However, tailored contracts are harder to achieve with small suppliers, bringing along a need for an intermediary party. Contracts with small suppliers, typically households, can be standardized to reduce transaction costs as long as they are incentive compatible. On the other hand, additional services are required to make flexibility interesting for suppliers. In light of the analyzed contracts, uncertainty and uneven distribution of information affect both the overall efficiency of the trading as well as the distribution of profits. Risk preferences are decisive for the design of contracts and the participating actors. With uncertainty present a risk averse retailer or wind power producer may prefer to trade in a market in lieu of binding volumes of flexibility in a contract with long duration. For grid companies on the other hand, uncertainty can prevent them from trading in markets as both the available volume of flexibility and the market price are uncertain, involving higher risks compared to a specified long-term contract.

In contrast to bilateral contracts, the analysis of flexibility markets suggested that flexibility can be traded more efficiently in a market. A flexibility market opens up for trading by a larger number of participants and by doing so utilizing the potential of flexibility in a better way. However, trading in a separate flexibility market requires significant adaptions to overcome challenges as geographical locations, price discrimination and connection to the electricity market since the two resources are physically linked. Both benefits of procuring flexibility and the division of market power clearly affect efficiency of the market and participating actors. The calculations illustrated that actors with significantly higher profits than others force the market price up and prevent potential buyers to participate. This effect is enhanced if few buyers dominate the market like grid companies possibly are capable of. A large aggregator can modify the division of power in the value chain by reducing the dominating role of grid companies. Simultaneously, the aggregator serves as a driving force to attract small suppliers, increasing the competition in the trade of flexibility.

The analyses also emphasized the implication of flexibility as a jointly consumed commodity. As the same flexibility can be procured by multiple buyers the design of business models must account for this in order to reach efficiency. The market-based approach of trading can handle this by coordinating payments for the same resources, thus increasing the demand. The local flexibility market modeled in this thesis does not address this problem, but as suggested in other research treating flexibility as a public good is a way to facilitate efficient trading in a local market. Bilateral contracts tend to fail coordinating jointly consumed flexibility. An aggregator can take advantage of this by selling the same resource to multiple buyers through contracts. This will harm the competition and decrease social surplus.

As the analyses throughout the thesis suggest, both flexibility markets and bilateral contracts are important for future trading of demand side flexibility and should be thoroughly investigated in further research. Greater attention on the change of new and existing actors as well as the interactions between them will be necessary to release the full potential of flexibility. The proposed business models in this thesis add knowledge about how demand side flexibility, as a new resource, can be integrated in the electricity system and simultaneously create value for multiple participants. This thesis forms a basis for further research of contract and market design in the power market. Comprehensive load scheduling models for buyers or intermediary parties ought to be studied in more detail. Previous load scheduling models have focused on trading in existing markets, thus future research is recommended to incorporate contract design with suppliers and additionally investigate the possibility of trading in flexibility markets. The design and functionality of separate flexibility markets need to be examined in more detail. Furthermore, innovative solutions and services for intermediary parties should be studied. In parallel with further research Authorities are strongly advised to facilitate use of demand side flexibility in the electricity system and should also help enlighten actors about the value of flexibility.

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Appendices

A.1 Data files with calculations

Excel-files containing all calculations are submitted together with the Master's Thesis to the DAIM database used by NTNU for submission of Master's theses. The following files are attached:

- *3 Cost Functions.xlsx*
- *3 Benefit Functions.xlsx*
- *4 Contract Design.xlsx*
- *5 Separate Flexibility Market.xlsx*
- *6 Novel Business Models.xlsx*

A.2 Input data for regression analyses

This Appendix presents tables with input data for the regression analyses performed in Chapter 3. The analyses are performed by using the *Curve fitting tool* in MATLAB.

Table A.1: Inputdata for the regression analysis for an industry supplier.

Curtailed load [kW]	Cost [NOK]
0	0
46	92
92	369
138	830
184	1 476
230	2 306
278	3 279

Table A.2: Inputdata for the regression analysis for a commercial business supplier.

Curtailed load [kW]	Cost [NOK]
0,0	0,0
3,8	13
7,6	50
11,4	113
15,2	202
19,0	315
23,0	449

Table A.3: Inputdata for the regression analysis for a household supplier.

Curtailed load [kW]	Cost [NOK]
0,0	0,0
0,67	0,3
1,34	1,4
2,01	3,1
2,68	5,5
3,35	8,6
4	12,0

Table A.4: Inputdata for the regression analysis for a grid company.

Available flexibility [kW]	Share of postponed investment [%]	Years postponed	Value gain [NOK]
0	0	0	0
1 000	20	5	12 336
2 000	35	6	25 309
6 000	70	9	70 883
11 000	90	10	99 007
20 000	100	11	118 338

Table A.5: Inputdata for the regression analysis for a wind power producer in a present scenario.

Available flexibility [kW]	Share of reduced imbalance cost [%]	Benefit [NOK]
0	0	0
750	30	414
1 500	50	690
3 075	80	1 104
5 025	95	1 311
7 500	100	1 380

Table A.6: Inputdata for the regression analysis for a wind power producer in a future scenario.

Available flexibility [kW]	Share of reduced imbalance cost [%]	Benefit [NOK]
0	0	0
750	30	783
1 500	50	1 305
3 075	80	2 087
5 025	95	2 479
7 500	100	2 609

Table A.7: Inputdata for the regression analysis for a retailer in a present scenario.

Available flexibility [kW]	Share of reduced imbalance cost [%]	Benefit [NOK]
0	0	0
300	30	685
600	55	1 256
1 050	80	1 827
1 650	95	2 169
2 250	100	2 283

Table A.8: Inputdata for the regression analysis for a retailer in a future scenario.

Available flexibility [kW]	Share of reduced imbalance cost [%]	Benefit [NOK]
0	0	0
300	30	1 370
600	55	2 511
1 050	80	3 653
1 650	95	4 338
2 250	100	4 566

A.3 Additional calculations and derived expressions

This Appendix contains additional calculations and derived expressions for Chapter 4.

A.3.1 One-part linear contract under uncertainty

The expected profit of the buyer:

$$E_{\alpha,\beta}[\pi_{B,U2}] = \frac{(E[\beta] - b(1-\theta))^2}{4(E[\alpha] + 2a)} \tag{7.1}$$

Actual profit obtained by the buyer:

$$\pi_{B,U2} = \frac{(b(1-\theta)(\frac{1}{2}\alpha - a - E[\alpha]) + a(2\beta - E[\beta]) - \frac{1}{2}\alpha E[\beta] + \beta E[\alpha])(E[\beta] - b(1-\theta))}{2(E[\alpha] + 2a)^2} \tag{7.2}$$

The profit of the supplier:

$$\pi_{S,U2} = \frac{a(E[\beta] - b(1-\theta))^2}{4(E[\alpha] + 2a)^2} \tag{7.3}$$

A.3.2 Two-part linear contract under uncertainty

The expected profit of the buyer:

$$E_{\alpha,\beta}[\pi_{B,U3}] = \frac{(b(1-\theta) - E[\beta])^2}{4(E[\alpha] + a)} - \pi_S^- \tag{7.4}$$

Actual profit obtained by the buyer:

$$\pi_{B,U3} = \frac{(\beta - b(1-\theta))(E[\beta] - b(1-\theta))}{2(a + E[\alpha]} - \frac{(\alpha + a)(E[\beta] - b(1-\theta))^2}{4(a + E[\alpha])^2} - \pi_S^- \tag{7.5}$$

The profit of the supplier:

$$\pi_S = \pi_S^- \tag{7.6}$$

A.3.3 Profit-sharing contract under asymmetric information

The buyer's maximization problem:

$$\begin{aligned} \max_x E_\theta[\pi_{B,A1}(x)] &= E_\theta[(-\alpha x^2 + \beta x - a x^2 - b(1-\theta)x)\rho] \\ &= \rho \int_{\bar{\theta}}^{\theta} -\alpha x^2 + \beta x - a x^2 - b(1-\theta)x \,\mathrm{dF}(\theta) \end{aligned} \tag{7.7}$$

The supplier's maximization problem:

$$\begin{aligned} \max_x E_\theta[\pi_{S,A1}(x)] &= E_\theta[(-\alpha x^2 + \beta x - a x^2 - b(1-\theta)x)(1-\rho)] \\ &= (1-\rho) \int_{\bar{\theta}}^{\theta} -\alpha x^2 + \beta x - a x^2 - b(1-\theta)x \,\mathrm{dF}(\theta) \end{aligned} \tag{7.8}$$

Optimal volume of flexibility:

$$x^*_{A1} = \frac{\beta - b(1-E|\theta])}{2(a+\alpha)} \tag{7.9}$$

Expected value chain profit:

$$E_\theta[\pi_{VC,A1}] = \frac{(b(1-E[\theta]) - \beta)^2}{4(a+\alpha)} \tag{7.10}$$

The profit of the buyer:

$$\pi_{B,A1} = E_\theta[\pi_{VC,A1}]\rho \tag{7.11}$$

A.3.4 Two-part linear contract under asymmetric information

Expected buyer profit is given by:

$$E_\theta[\pi_{B,A3}] = E_\theta[-\alpha x_{A2}^2 + \beta x_{A2} - w^*_{A2}x - L^*_{A3}] \tag{7.12}$$

The actual buyer profit:

$$\pi_{B,A3} = -\alpha x_{A2}^2 + \beta x_{A2} - w^*_{A2}x - L^*_{A3} \tag{7.13}$$

The supplier's profit:

$$\begin{aligned} \pi_{S,A3} = &\frac{(b(1-\theta) - b(1-\bar{\theta}))(b(1-\theta) + 3b(1-\bar{\theta}) - 2\beta - 2b(1-E[\theta]))a}{4a(a+\alpha)} \\ &+ \frac{\alpha(b(1-\theta) - b(1-\bar{\theta})(b(1-\theta) - 2b(1-E[\theta]) + b(1-\bar{\theta}))}{4a(a+\alpha)} \end{aligned} \tag{7.14}$$

A.3.5 Nonlinear contract under asymmetric information

The first-best best outputs are given by the following first-order conditions:

$$\frac{\mathrm{d}B(\underline{x}^*)}{\mathrm{d}\underline{x}^*} = 2a\underline{x}^* + b(1-\underline{\theta}) \tag{7.15}$$

and

$$\frac{\mathrm{d}B(\bar{x}^*)}{\mathrm{d}\bar{x}^*} = 2a\bar{x}^* + b(1-\bar{\theta}) \tag{7.16}$$

The efficient output of flexibility:

$$\underline{x}^* = \frac{\beta - b(1-\underline{\theta})}{2(\alpha + a)} \tag{7.17}$$

$$\bar{x}^* = \frac{\beta - b(1-\bar{\theta})}{2(\alpha + a)} \tag{7.18}$$

The supplier's participation constraints:

$$\underline{y} - a\underline{x}^2 - b(1-\underline{\theta})\underline{x} \ \geq \bar{\pi}_S^- \tag{7.19}$$

$$\bar{y} - a\bar{x}^2 - b(1-\bar{\theta})\bar{x} \ \geq \bar{\pi}_S^- \tag{7.20}$$

Here y is the incentive payment to the supplier for a given volume of x delivered. This payment schedule vary with the supplier type θ. The optimal payments are given by $\underline{y}* = a\underline{x}^2 + b(1-\underline{\theta})\underline{x}$ and $\bar{y}* = a\bar{x}^2 + b(1-\bar{\theta})\bar{x}$ for the efficient and inefficient supplier respectively. This solution provides a benchmark for the solution under asymmetric information.