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Participation of consumers in the Finnish electricity sector- an analysis of profit potentials and subsequent market impacts

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Tiivistelmä

Sähkön toimitusvarmuus on riippuvainen tuotannon ja kulutuksen välisestä lähes täydellisestä tasapainosta. Tämän tasapainon ylläpito on kallis ja haastava vastuu, jonka kantaminen on perinteisesti kuulunut pitkälti sähköntuottajille. Verkon toimivuuden varmistaminen on edellyttänyt kulutuksen ja tuotannon ennustamisen riittävällä tarkkudella sekä tuotantolaitoksien kyvykkyyttä jatkuvasti säätää tuotantoaan vastaamaan kysyntää. Vaihtelevan tuotannon osuus sähköntuotannossa kasvaa jatkuvasti, mikä edellyttää säätökykyisen kapasiteetin lisäämistä. Tuotantokapasiteetin lisääminen säätötarpeiden kattamiseksi on taloudellisesti ja teknisesti epätehokasta, mikä on kannustanut vaihtoehtoisten säätökykyisten komponenttien kehittämiseen.

Kun tavoitteena on kulutuksen ja tuotannon välinen taspaino, on samantekevää suoritetaanko säätö kulutuksen vai tuotannon puolella. Teolliset kuluttajat ovatkin jo vuosikymmeniä osallistuneet säätötoimenpiteisiin säätämällä kulutustaan. Kytkemällä pois kulutuskuormia voidaan pienentää tehopiikkejä tai jopa välttää kantaverkon kaatuminen. Näiden toimenpiteiden suorittaminen on taloudellisesti erittäin arvokasta, mikä houkuttelee säätökykyisiä kuluttajia tarjoamaan omaa kuormaa sille sopiville markkinoille.

Suomessa ylläpidetään useita markkinoita joissa niin sähkön tuottajat kuin kuluttajatkin voivat kapitalisoida säätökykyistä kapasiteettiaan verkon tasapainoon ja sähkön riittävyyteen edistäviin toimenpiteisiin. Lisääntyvä tarve joustavuudelle sekä automaation kehittymisen myötä parantunut kyky valjastaa kuormien joustavuutta on herättänyt huomattavan määrän kiinostusta yhä pienempien kuormien hyväksikäyttämiseen näillä markkinoilla. Tämä työ pyrkii selvittämään minkä suuruiset tuottopotentiaalit eri markkainapaikat pystyvät tarjoamaan. Lisäksi työssä tutkitaan millaisia sivuavaikutuksia saattaa syntyä siitä, että kuluttajat säätävät kulutustaan markkinaehtoisesti, ja pohditaan miten nämä vaikutukset heijastuvat markkinoiden tilaan.

Avainsanat Kysyntäjousto, taajuusohjatut reservit, säätösähkömarkkina

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Abstract

The security of electricity supply relies on maintaining a near perfect balance between the generation and consumption of electricity. Carrying out the procedures required to maintain this balance has largely been the responsibility of electricity producers, and can often prove to be technically and economically challenging. Ensuring the functionality of the grid requires sufficient forecasting of both generation and consumption, as well as the capability of electricity producers to alter their generation to meet demand. As the share of intermittent and variable sources of electricity continues to grow, the demand for flexibility is exceeding the capacity provided by electricity generators capable of economically carrying out these tasks. Increasing production capacity explicitly for the purpose of providing balancing power is highly inefficient, which has sparked interest in developing alternative sources of flexibility.

In the pursuit of maintaining the balance between generation and consumption, it is irrelevant whether the balancing procedures are carried out on the generation or consumption side. Industrial consumers have successfully participated in tasks related to security of supply and grid balance. By cutting off consumption loads, consumers can reduce power spikes, or even avoid a power outage. These are highly valuable procedures, which has led to an increasing interest among consumers to provide the flexibility of their loads to the relevant marketplaces.

There are currently various markets in place which provide consumers and producers of electricity alike the possibility to capitalize on their ability to provide balancing tasks. The increasing demand for flexibility as well as technological developments which allow ever smaller consumption loads to be harnessed has encouraged previously unused resources of flexibility to participate in these markets. This paper aims to determine the profitability of various methods of demand side management, as well as determine the collateral impact the participation of consumers in markets may entail on both the electricity infrastructure as well as the markets themselves.

Keywords demand-side management, frequency containment reserve, balancing power market

Contents

Abbreviations

aFRR	Automatic frequency restoration reserve
BRP	Balance responsible party
FCR-D	Frequency controlled disturbance reserve
FCR-N	Frequency controlled normal operation reserve
MWh	Megawatt hour

1 Introduction

The European commission has highlighted the pursuit of incorporating demand-based flexibility in various tasks related to the operation of a well-functioning electricity sector as a primary point of interest (European Commission 2013). The behaviour of consumers directly dictates the requirements set for the generation of electricity, and developing consumption behaviour in a way that enhances the production of electricity is a valuable asset to the entire electricity sector. This paper aims to assess the services consumers are capable of providing under current market structures in Finland. The markets considered are the frequency containment reserves for normal operation, the frequency containment reserves for disturbances, the balancing power market and Elspot-based load shifting.

Consumers' aptitude to provide valuable services to the electricity sector are dictated by their ability to meet the technical requirements of each market. These requirements are reviewed in the first section of this paper. The potential willingness of consumers to participate in these markets depends on the financial potential of the participation as well as the impact the management of consumption has on the consumer environment and consumption component. The economic potential as well as the relevant factors in the formation of prices in the markets are reviewed in the second section of this paper. Although the nature of the consumption component is not extensively considered under the framework of this paper, the expected impact control cycles have on the consumers are considered assuming that certain universal factors are inherent to consumption loads.

Finally, the impact of the provided control is considered for the probable forms of participation. Consumers are inclined to utilize their consumption flexibility in a way that maximizes the financial profit received through the provided service. Consumption behaviour which provides the greatest financial profit does not axiomatically entail that this behaviour has provided maximal benefit to the electricity system as a whole. The impact analysis aims to provide insight to market inconsistencies which may contradict the pursuit of achieving the desired benefit of consumer participation in the relevant markets.

2 Basics of Electricity Generation

In the pursuit of mitigating carbon emissions caused by the electricity sector, traditional thermal power plants will continue to be phased out, while intermittent power sources such as wind and solar power are increased. Concerns have been raised over whether this transformation challenges the foremost requirements of electricity generation of providing affordable power with maximum security. The functionality of the grid requires generation and consumption of electricity to be equal at all times. In order for this balance to be properly maintained, adequate control capability must be continuously available. Conventionally, the electricity sector has relied on power generators' ability to adequately manage their power output to ensure the availability of power and maintain the required balance within the grid. Increased integration of power sources incapable of sufficiently controlling their power output has required consideration over whether conventional methods will be competent in economically ensuring a secure supply of electricity. (Lund 2015, Huber 2014)

The functionality of an electricity grid requires nearly perfect correlation of demand and supply. In conventional terms, this means that electricity generators alter their output to match the consumer load. This requires large quantities of so called load matching power sources, which are able to manage their power production with minimal delay. Thanks to the abundance of hydropower in the Nordic grid, this task can be carried out fairly comfortably, as the technical properties of hydro power allow for explicit control without being economically inconvenient. Other power sources are considerably less fortunate. A rough representation of the properties significant in terms of power control are shown in table 1.

	Thermal power plant	**Combined cycle power plant**	**Gas turbine**	**Engine**	**Nuclear power plant**
Typical nominal power					
Mwe	600-900	60-400	10-300	1-20	1000-1600
Efficiency					
old	40 %	50 %	32 %	45 %	33 %
new	47 %	60 %	38 %	48 %	37 %
Activation times					
cold start	5-10 h	2-3 h	10 min	15 min	2 days
warm start	3-5 h	1-1.5 h	10 min	15 min	1 day
hot start	1.3-2.5 h	0.5-1 h	10 min	5 min	8-16 h
Minimum power	40 %	40-50 %	50 %	30 %	(15-)30 %
Power change rate	3-6 %/min	4-6 %/min	5-10 %/min	25 %/min	

Table 1
Flexibility properties of power plants (ÅF-Consult 2012)

Thermal power generators are poorly equipped to deal with rapid changes in demand, particularly unexpected peaks that have not been sufficiently prepared for. Although gas turbines and engines are technically more apt to fulfilling the required control, they are significantly more expensive, and due to their high cost, are investments that are likely to be avoided unless absolutely necessary. Nuclear power plants, especially traditional generator types, have very limited capability when it comes to managing their power output, and typically produce their nominal power output throughout the year, excluding maintenance breaks. Traditional coal- and bio-fuelled power plants have a limited potential to control their output, and their applicability varies considerably, as there is a wide variety of existing power plant types. Under optimal conditions, thermal power can react within an hour's notice. (ÅF-Consult 2012)

Hydropower has significantly superior properties when considering the potential to manage power output, as shown in table 2.

	Hydropower	**Pump as turbine**
Efficiency		
old	87 %	66 %
new	92 %	70 %
Activation times		
cold start	n/a	5-10 min
warm start	1-2 min	30 sec
hot start	1-2 sec	1-2 sec
Minimum power	15-20 %	5-20 %
Power change rate	large	large

Table 2
Flexibility properties of hydropower plants (ÅF-Consult 2012)

Although the technical properties of hydro turbines allows excellent control potential, the availability of control is not trivial. In order for hydropower plants to be able to provide flexibility, they must have adequate water reserves available. This requires not only the physical capacity of the water reserve, but also the sufficient availability of water. Although considerably more reliable than solar and wind, hydropower is also dependant on weather patterns, and its ability to provide power may be restricted due to unfavourable weather. Just as any other market participator, owners of hydro capacity aim to maximize the profitability of their power production. Storing large reserves of water for the sake of maximizing control capability is not in the best interest of the hydropower plant owner, as the payoff of retaining reserves is not a financially reliable practice. In addition to its reliance on the available water reserves, hydropower influences the water system that it operates in. The power output of a hydropower plant depends on the amount of water passing through its turbines, and rapid changes in power output cause corresponding fluctuation in the water flow, which can be harmful to the surrounding environment. Mitigating the hydropower plants effect on the water system may inflict restrictions on its allowance to rapidly alter its power output.

As developments in the electricity sector call for increased flexibility, it is important to extend flexible resources beyond those currently available, and provide supplemental methods of providing ancillary services and ensuring energy security. In light of this challenge, consumers' potential to take part in tasks related to security of supply has been a key point of interest in the designing of future energy systems.

3 Basics of the Electricity Market Participation

All parties operating in the electricity market are responsible for operating in a way that ensures the proper functionality of the system as a whole. The electricity market is currently divided into hourly segments, which are prepared for individually. In principal, each party operating in the electricity market is responsible for maintaining its balance of production/procurement and consumption/sales. This is not achievable in practice, which is why market parties must have an open supplier, who is capable of ensuring the power balance for each market hour is achieved. Market parties whose open supplier is the transmission system operator, in Finland's case Fingrid, are referred to as balance responsible parties. They are required to provide Fingrid with a production and consumption balance for each hour. The balance responsible parties' capability to provide reliable production and balance settlements is a key underlying factor in maintain the overall system balance.

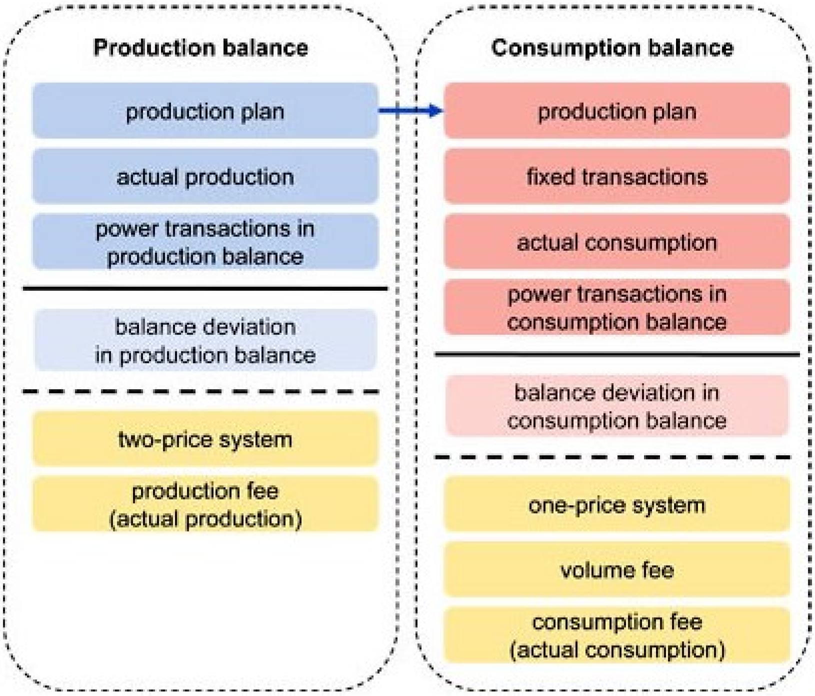


Figure 1
Balance settlement structure (Fingid a)

The primary marketplace in which market parties acquire electricity for their consumers is the Elspot market, which operates on a day-ahead basis. Bids are made to the Elspot market based on the prevailing forecasts for the following day, and the market is closed at 12:00 CET each day, after which trades are finalized. Forecasts of consumption and production are never perfect, and can change as the delivery hour approaches. In order to allow market parties to react to developments in forecasts, the Elbas market allows market operators to sell and procure electricity after the Elspot trading has been finalized, allowing for previous errors made in forecasts to be compensated for. The Elbas market operates on a "pay-as-bid" basis, which means that trades are made directly between market operators once a mutual price is agreed upon. This means that there is no universal price for the Elbas market, but instead the price is independent for each trade made. For this reason the Elbas market is not covered extensively in this paper, as it is difficult to make assumptions on the compensation received. The Elbas market hour is active from the closing of the Elspot market to within 1 hour of the delivery hour. Balance responsible parties are required to inform the transmission system operator of their final balances 45 minutes before the operation hour. All market parties are inclined to follow the plans set in the production and consumption balances, as they are responsible for accounting for deviations from their balances by buying or selling imbalance power, which is likely to be financially unfavourable. A relative timeline of the main stage of electricity trading in Finland is visualized in figure 2.

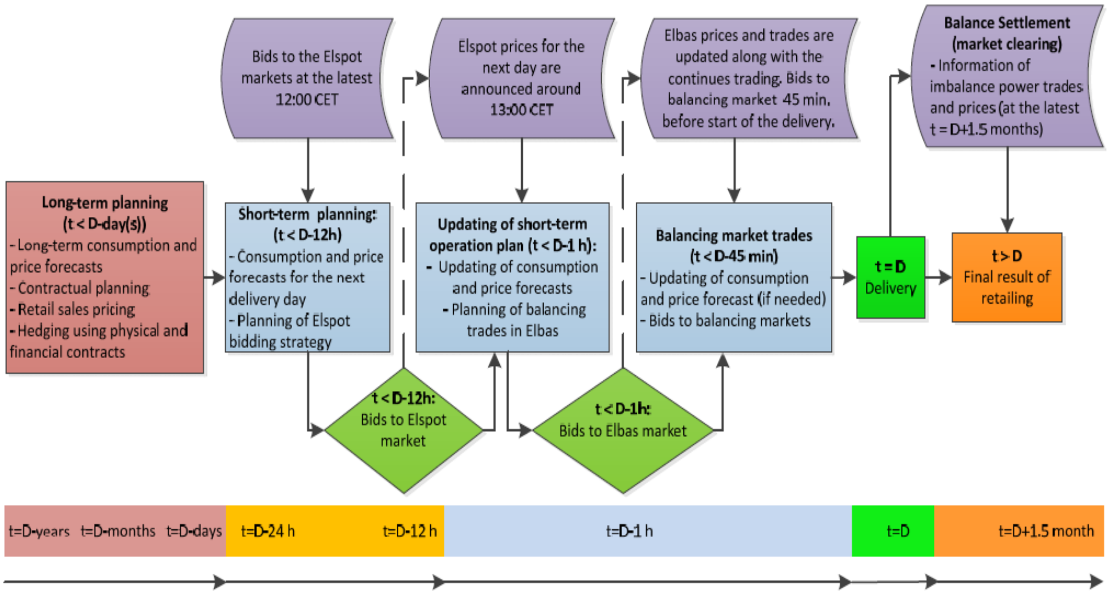


Figure 2
Timeline of market participation in Nordic countries (Valtonen 2015)

Despite the possibility to procure electricity up to one hour from delivery, unexpected events can often lead to circumstances which market parties are not capable of preparing for. In order to be able to adequately react to deviations from initial procurements of electricity, Fingrid manages the balancing power market, which allows balance responsible parties to sell and procure electricity within the operation hour. Market operators capable of providing balancing power can bid capacity to the balancing power market.

The Elspot, Elbas, and balancing power market operate based on hourly total energies. In order to account for volatility within the operation hour, reserve markets provide a marketplace in which market operators can provide sources of frequency containment and frequency restoration. These reserves are responsible for accounting for the constant fluctuation of consumption (and to some extent production) as well as rapid unexpected changes caused by technical disturbances in electricity generation or transmission components.

The quality of power is dictated by its ability to maintain a constant frequency. In the Nordic grid, the nominal frequency of the grid is 50 Hz, and maintaining this frequency is vital to the functionality of the grid as well as the proper operation of components receiving power from the grid. Various reserves are allocated to ensure that the grid frequency is not jeopardized.

The primary reserve resources follow guidelines that aim to contain the grid frequency within a certain threshold. These are referred to as frequency containment reserves, and in Nordic countries frequency containment reserves are further divided into two separate reserves. The normal operation reserves (FCR-N) are responsible for accounting for the continuous minor fluctuation of the frequency, with the purpose of containing this fluctuation to a maximum of 0.1 Hz. Disturbance reserves (FCR-D) are reserved for abrupt shortages in power, providing rapid reserves for periods in which the frequency drops below 49.9 Hz, with the intention of keeping the frequency above 49.5 Hz.

Frequency restoration reserves serve the purpose of replacing the containment reserves, thereby ensuring the containment reserves are available for future use while concurrently recovering the frequency to its nominal value. Frequency restoration reserves are provided manually through the balancing power market. Additional automated frequency restoration reserves are procured through a recently implemented market, which began operation in August of 2016. Due to the lack of data for the aFRR market and the immaturity of the market, this market is not included in the framework of this paper. The frequency containment and restoration reserves are pictured in figure 3.

A summary of the markets considered in this study are shown in table 3.

Market place	**Type of contract**	**Minimum size**	**Activation time**	**How often activated**
Frequency controlled normal operation reserve	Yearly and hourly markets	0,1 MW	3 minutes	Constantly
Frequency controlled disturbance reserve	Yearly and hourly markets	1 MW	5 s / 50% or 30 s / 100%	Several times a day
Balancing power market	Hourly market	10 MW	15 minutes	Several times a day
Elspot market	Hourly market	0,1 MW	12 h	-

Table 3
Summary of market commodities included in the framework of this paper (Fingrid c)

4 Purpose of Flexibility

Electricity consumption is often viewed from an energy standpoint, in which the underlying factor is the amount of watt hours consumed. What consumers often fail to take into account is that the requirements for producing electricity vary considerably based on the prevailing conditions. Electricity is procured based on the merit order effect, with prioritizes power sources based on their running costs. Renewables have near-zero running costs, as they utilize primary energy sources which are essentially free. Nuclear power plants are economically highly efficient in terms of fuel costs, and are therefore used essentially at all times. Other thermal power plants vary substantially in their economic efficiency, with CHP plants providing base-load power throughout the winter period and condensing and gas turbines providing supplemental generation based on the amount of demand exceeding the baseload production. When the overall demand for electricity is moderately low, this demand can be satisfied by the technically and economically most efficient power sources. However, a characteristic of the electricity market is that as demand increases, the price tends to increase exponentially. An idealized merit order curve is shown in figure 3.

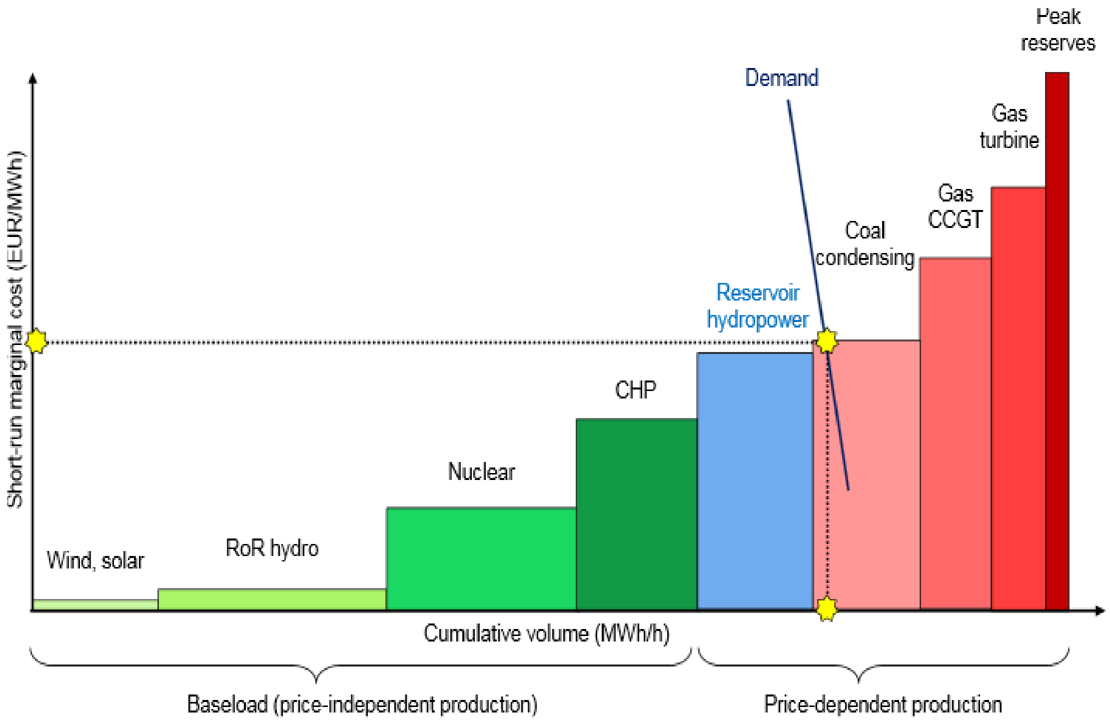


Figure 3
Idealised representation of the merit order

When electricity demand considerably exceeds the baseload production, the overall market price tends to rise drastically, as increasingly expensive forms of generation must be deployed in order to meet the requirements of demand. In addition to their higher running costs, many of these peak power plants are utilized for only a minor portion of the year, weakening the profitability of the initial investment and upkeep costs.

The majority of consumers pay for electricity based on the total energy consumed. This means that consumers pay the same price for their electricity regardless of the effective price dictated by the Elspot market. This leads to a misrepresented view in which electricity is a generic resource that is equally valuable unconcerned of when it is consumed.

Incorporating more accurate methods of electricity pricing for consumers would allow consumers to shift flexible consumption loads from periods in which expensive and unfavourable forms of generation are required to periods during which ample amounts of economically efficient capacity is available, thereby enhancing both the technical and financial operation of the electricity sector. This method is covered in Elspot-based load shifting, in which consumers are assumed to pay for their consumption based on the hourly consumption and corresponding market rates of the Elspot market.

In addition to peak consumption periods, there are various other circumstances in which the generation of electricity can bare a particularly large burden. As mentioned previously, the majority of power plants are limited in their ability to compensate for rapid changes in demand, requiring ample notice and time to adjust their power output. In order to ensure power security as well as grid functionality during unexpected conditions, rapid sources of flexibility are required, providing the ability to promptly offset the deviation in the production-consumption equilibrium. This task is covered in this paper through the participation in the balancing power market, which provides consumers the possibility to provide balancing capacity, capable of compensating for unexpected deviations that occur during the operation hour.

The infrastructure required to perform tasks related to the transmission and distribution of electricity is extremely valuable, and is at risk of being damaged if the state of the grid is compromised. The economic consequences of grid failures and the resulting power outages are potentially enormous, and ensuring that the risk of these failures is minimized is of high priority to the transmission system operator. The transmission system operators of Nordic countries maintain frequency containment and frequency restoration reserves for the purpose of securing the quality of power is maintained at a satisfactory standard. Such reserves must be capable of reacting virtually instantaneously to frequency deviations. These tasks present a demand for technically highly proficient flexibility, which most electricity generators are incapable of providing. Forms of flexibility suited for carrying out tasks related to frequency containment are vital to the functionality of the grid, and are a highly valuable asset.

As increasing amounts intermittent sources of wind and solar power are implemented, the demand for flexibility is expected to increase. Wind power generation causes fluctuations in the merit order curve, and is likely to cause larger variability in price differences. As the power output of wind power depends entirely on weather conditions, it is inherently susceptible to forecasting inaccuracies, and these errors require flexible components in order to offset the deviations from forecasted production plans. Concurrent phasing out of thermal power plants substituted by nuclear power decreases the flexible capability of the base load, transferring the burden of flexibility to be even more dependent on non-generation based components.

5 Properties of flexible loads

In terms of their consumption-related properties, components capable of demand-side management cover a virtually endless spectrum. A thorough review of the various consumption loads is not within the framework of this paper, and only the necessary properties will be discussed. The consumption components simulated in the calculations are assumed to be ideal, therefore representing the theoretical maximum of the profit potential.

The loads simulated in this paper are considered to be continually in use under normal operation, functioning at a nominal power consumption throughout the day. The loads are capable of cutting off their power consumption entirely for the duration of 1 hour. This would lead to an energy deficit in the consumption environment. In order to ensure that the system that the consumption component is operating in receives the amount of energy it requires to function properly, this deficit must be compensated for by increasing the consumption of the component by the corresponding electricity amount at a later time. The process of increasing consumption in order to compensate for previously carried out load cut-off is referred to as the payback process. This process can also be done in reverse, wherein the initial control would be to increase consumption, resulting in an energy surplus within the consumption system, requiring a subsequent decrease in consumption as the payback.

When considering the operation of a consumer, it is adamant to keep in mind that the participation in markets should have as little of an impact on the consumption environment and consumption component as possible. Carrying out control cycles requires consumption to deviate from its normal operation, which is likely to decrease the overall efficiency at which the component functions. These control actions may also have an impact on the consumption component itself, requiring additional maintenance and or decreasing its lifetime. The energy imbalance caused by the control impacts the consumption environment, as the consumption system is no longer in its nominal state, which may have a variety of drawbacks, and in some cases entails risks to the consumer.
Management of the energy balance of the consumption environment is one of the most critical constraints to the operation of a consumption component used for demand-side management. When considering optimal market strategies for the markets in which energy is traded, the Elspot and balancing power market, it is often beneficial to delay the payback period for extended periods. The delay of payback causes the load environment to maintain an energy imbalance for extended periods of time. Thermal loads providing either heat or cooling to the consumption environment are likely candidates for the perceived control, and the impact control cycles have on these systems is considered when assessing the impact of control cycles on the consumer. When considering a load such as heating, an energy deficit may cause discomfort, as the initial load cut-off would cause the temperature of the environment to drop, with the temperature returning to its desired level once the payback has been carried out. Correspondingly, if a freezer were to provide flexibility services by decreasing its consumption, this would increase the temperature within the freezer, possibly putting the contents at risk of decreasing in quality.

For Elspot based load shifting, the drawback of imbalances can be partially resolved by planning load shifts to entail an energy surplus or energy deficit based on which imbalance is considered less of a hindrance. The profitability of load shifting is based on the ability to reduce consumption during high prices and acquire payback energy during low prices. It is irrelevant whether the increase or decrease of consumption is carried out initially, providing the consumer with the option to experience an energy deficit (upregulation first) or surplus (downregulation first) as its buffer based on which one it sees as less of an encumbrance.

An energy deficit in a thermal system will often be considered a greater inconvenience, as it directly constricts the operation of the heating or cooling unit. Although an energy surplus would not cause this limitation, it does have drawbacks which must be considered. A thermal load consumes electricity primarily for the purpose of compensating for the amount of heat transfer occurring between the heater/cooler and its surrounding environment. This heat transfer is relative to the temperature difference between the cooler/heater and its surroundings. An energy surplus would mean that this temperature difference would be greater than under normal operation, thereby leading to higher losses through heat transfer. If the delay of payback is held off for long periods, these losses may lead to the load shifting becoming redundant. For consumers planning to participate in demand-side management, it is crucial to be able to adequately manage the consequences of the various control operations, and develop market strategies which incorporate constraints aimed to ensure control cycles are profitable and do not prove harmful to the consumption system.

6 Review of literature

Energiateollisuus Ry has coordinated a research project in which researchers from the Tampere University of Technology, Lappeenranta University of Technology and the Tampere University of Applied Sciences have collaborated in the pursuit of determining the potential of demand-side management in Finland (Järventausta 2015). Petri Valtonen of the Lappeenranta University of Technology has provided additional research on the utilization of consumption in the markets available in Finland (Valtonen 2015). These efforts provide the foundation for the research carried out in this paper. The intended purpose of the research carried out in this paper is to initially approach the concept of demand-side management from the consumer point of view. This allows the possibility to supplement the analysis of markets with constraints and relative factors determined by the consumer, and thereby provide additional insight to the expected participation of consumers in the respective markets.

This approach is fundamentally different to the literature reviewed, as rather than aiming to provided definitive evaluations of the financial potential of demand-side management, the intention of the analysis is to distinguish the factors which most significantly dictate the eventual profit. The motivation for this approach is that consumers are likely to vary in their technical capability as well as financial premise, which leads to a high uncertainty of the applicability of results if they have been achieved through generalization and extensive assumptions. By limiting the assumptions made of the nature of consumers and assessing the parameters which universally dictate their operation, this paper aims to provide the essential guidelines consumers require when assessing how they are able to utilize their potential for demand-side management.

7 Technical requirements

This section covers the technical requirements prescribed by the various markets. Consumers are likely to be capable of carrying out various actions related to the management of their consumption. The consumer's ability to capitalize on the potential of these actions is dictated by the suitability of the available flexibility to the technical requirements set by the marketplaces. These technical requirements are covered for each market separately with particular attention given to the assumption that the control is provided by a consumption load.

7.1 Frequency Containment Reserves for Normal Operation

The most frequently utilized reserves are the frequency containment reserves for normal operation, referred to as the FCR-N. These reserves are utilized essentially continuously, and aim to keep the frequency deviation within 0.1 Hz. Each region in the Nordic power network is assigned an FCR-N capacity requirement, which the transmission system operator is obligated to procure for each hour of the year. For the year 2016, the required FCR-N capacity for Finland was 140 MW.

FCR-N operators are required provide symmetrical control, meaning that the bid capacity must be available for both up- and downregulation. This can prove to be a hindrance to many willing market participators, as the symmetrical control requirement would allow for a maximum of 50 % of the total load capacity to be bid. For example, a 10 MW load participating in the FCR-N market would initially be set to consume 50 % of its nominal power, thereby providing the potential to provide 5 MW of upregulating power an 5 MW of downregulating power, which would account for a 5 MW capacity bid.

Thermal loads such as heaters and coolers operate at a fractional power rating by default, which allows them to avoid constraining the initial consumption, as the potential for downregulation (increase of consumption) is inherently available under normal operation. In fact, the symmetrical control serves as a benefit to thermal loads, which can be stringently restricted in their capability to deviate from their energy balance, as the symmetrical control scenarios do not typically result in substantial deficits (or surpluses) in hourly energy consumption.

Consumers have only recently begun participating in the FCR-N markets. SEAM, in collaboration with KWH Freeze and Fingrid, have utilized a freezer storage in the FCR-N hourly market, providing a 0.3 MW capacity for 8 hours each day since January 2015. (SEAM OY). Fortum has participated in the FCR-N market by aggregating the water heaters from 100 households. The pilot projects have demonstrated that consumers, specifically non-industrial consumers, are capable of meeting the technical requirements of the control required in the frequency containment reserves for normal operation. (Fortum OY)

The entire capacity must be capable of activating with a maximum latency of 3 minutes once the deviation from the nominal frequency reaches 0.1 Hz. The control must be carried out as linearly as possible with a maximum dead band of 50 ± 0.5 Hz. sufficient linearity is shown in figure 4, with the blue area showing the area within which the power output must be at grid frequencies between 49.9 and 50.1 Hz.

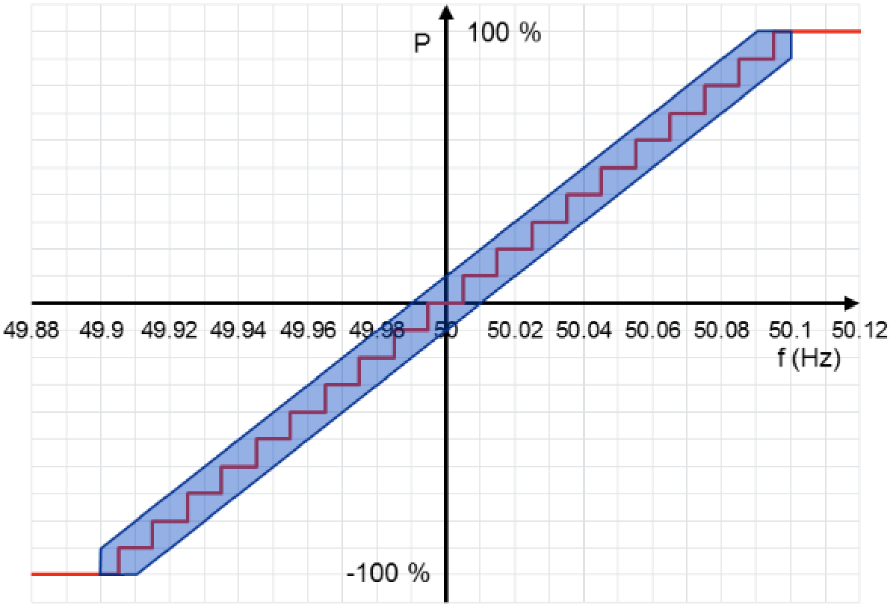


Figure 4
Guidelines for FCR-N control (Fingrid d)

The adequate functionality of an FCR-N component is verified by Fingrid through control tests, which determine the amount of FCR-N capable capacity. Once the capacity has been approved, it can be bid to the annual and hourly markets. All bids made to the FCR-N market must be made for a capacity of at least 0.1 MW. The capacity bid to the market may consist of separate components which have been aggregated to meet the requirement. Allowing market operators to participate in the market with relatively small capacities is propitious for consumers, as consumption components are often small, and would thereby require aggregation of large quantities in order to meet higher capacity requirements.

One of the main challenges consumers face in participating in FCR markets is in meeting the communication requirements set by Fingrid. In order to ensure adequate operation of reserves, Fingrid demands real-time data throughout the operation hour for which the reserve has been acquired. Operators responsible for FCR-N capacity are required to supply Fingrid with information on the amount of reserve capacity available at an interval of three minutes. In addition to the 3-minute data cycles which are delivered immediately, the market operator is required to measure and store per second data of the available active power, which can be used to verify the proper operation of the reserve in case there is reason to believe otherwise. The per second data must be kept available for 4 days. The requirements of data managements may prove to be a major obstacle to consumption loads consisting of many separate components, as this would entail extensive censoring and data aggregation in order to meet the data management requirements.

7.1.1 Impact of Participation in FCR-N on Consumption

Based on the guidelines set by Fingrid, a unit acting as part of the frequency containment reserves for normal operation could maintain its nominal consumption when the frequency deviation is less than 0.01 Hz, and adjust its consumption linearly when the frequency deviation is between 0.01 and 0.1. This would effectively minimize the consumption deviation required from the component while remaining within the mandated guidelines. The relation between relative consumption to the bid capacity and the grid frequency is shown in figure 5.

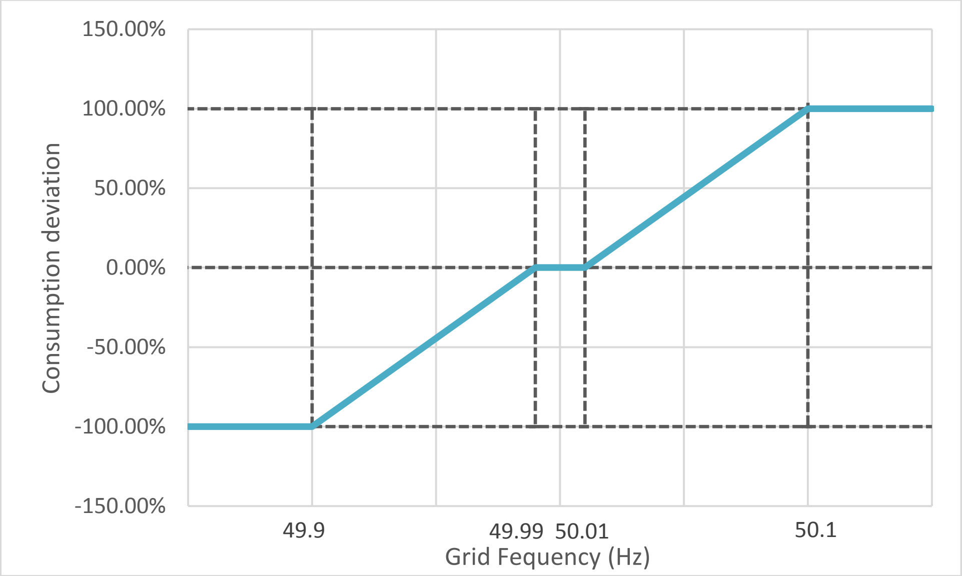


Figure 5
Consumption deviation for FCR-N control

When frequency in the grid is greater than 50.01, the consumption of the reserve unit is increased, leading to an energy surplus within the consumption system. Likewise, when frequency is below 49.99, the component would consume less than its nominal consumption, causing an energy deficit within the consumption system. The total energy imbalance caused by participation in FCR-N control can be calculated through the following formula.

$$\Delta Energy = Capacity \int_0^N Deviation(frequency_t)dt \tag{1}$$

$$C_{time} = \int_0^N Deviation(frequency_t)dt \tag{2}$$

Where Capacity is the bid capacity, Deviation(frequency) is determined by figure 6, frequency is the grid frequency at time t, and N is the number of time intervals. The energy Imbalance can be alternatively represented by a time coefficient C_{time}, in which

$$C_{time} = \frac{\Delta Energy}{Capacity} \tag{3}$$

A time coefficient of 1 thereby represents an energy surplus equivalent to 1 hour of additional consumption at bid capacity, a time coefficient of 2 represents an energy surplus equivalent to 2 hours of additional consumption at bid capacity, and so on. A positive time coefficient denotes an energy surplus, and negative time coefficient denotes an energy deficit.

Using frequency data for the 1st of January 2016, the minimum energy deviation caused by participation in FCR-N was calculated. For these calculations, a time interval of 1 minute was used ($t_n - t_{n-1} = 1$ minute), and the unit was assumed to be in use for the entire day ($N = 1440$). The frequency data is shown in figure 5, and respective energy deficit in figure 6.

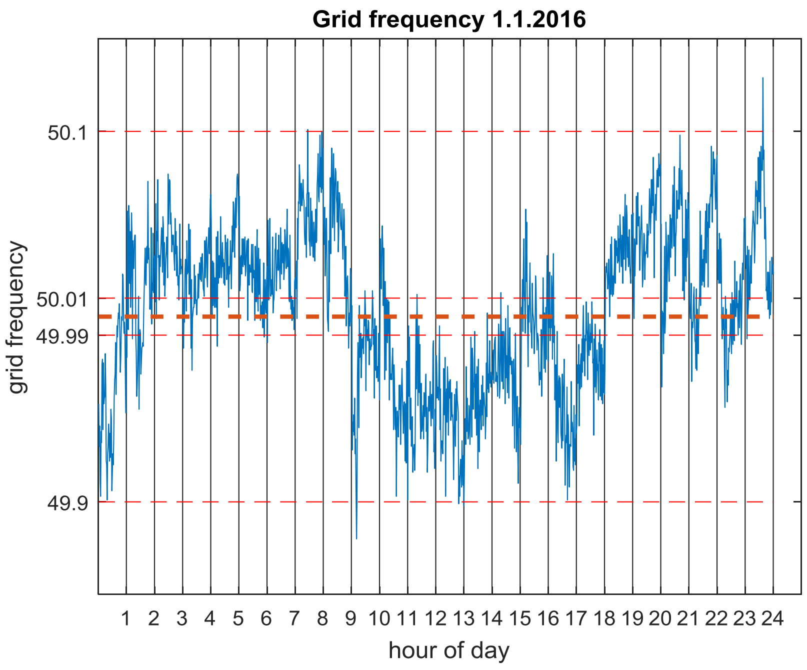


Figure 6
Minute-based grid frequency data

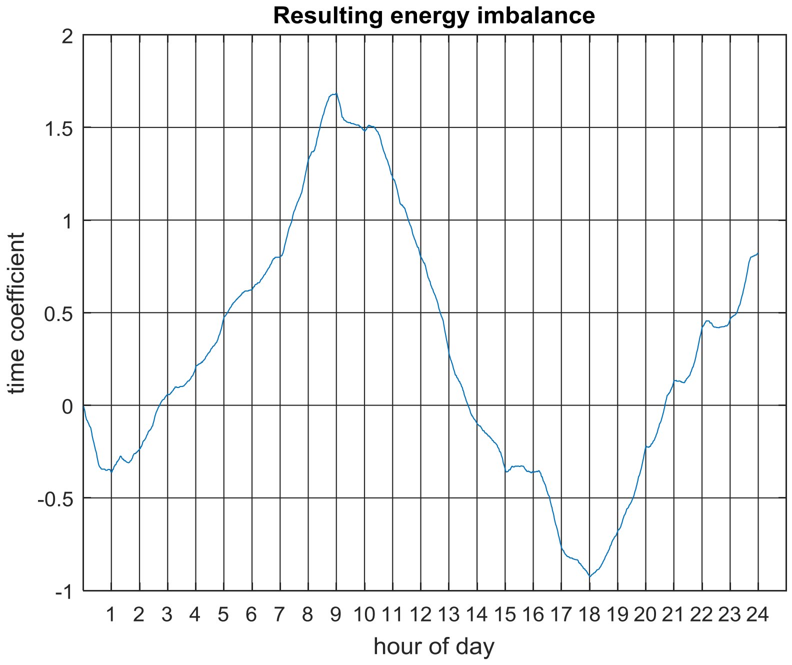


Figure 7
Energy imbalance within consumption system caused by participation in FCR-N control for the duration of 1.1.2016

Although the aggregate energy imbalance over the course of the day is relatively small, leading to an energy surplus equivalent to less than 1 hour of additional consumption of the bid capacity, the energy deviation can periodically be quite substantial, as extended periods of high or low frequencies are experienced. Consumers are likely to be restrained in their capability to deviate from their energy balance, which makes the energy deviation a critical element in determining a components ability to participate in FCR-N for consecutive hours. Long periods of high or low frequencies may lead to the consumption system buffer to exhausted, rendering systems incapable of offering the required control.

In order to provide further insight to the possible energy deviations, the daily energy imbalances for the period of 1.1.2016-7.1.2016 are shown in figure 8, assuming that at the beginning of each day the unit was in its nominal state ($C_0 = 0$).

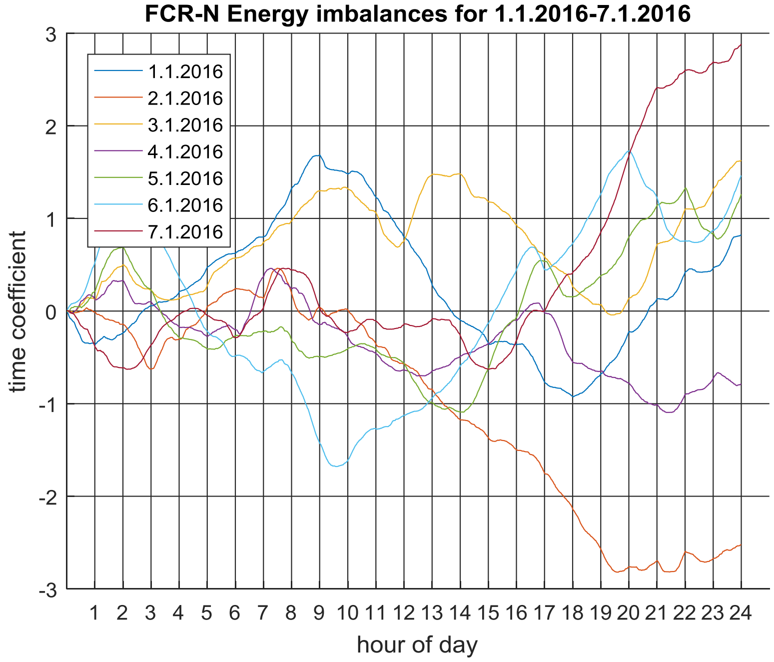


Figure 8
Energy imbalances within consumption system caused by participation in FC-N control for the days 1.1.2016-7.1.2016

Based on the period examined, participating in FCR-N control for several consecutive hours may lead to considerable energy imbalances. Acting as part of the FCR-N for the course 2.1.2016 would have led to a significant energy deficit, corresponding the cutting off of the entire bid capacity for nearly three hours. Over the course of 7.1.2016, the energy surplus caused by control participation corresponds to consuming additional energy at bid capacity for almost three hours. In order to ensure the capability of providing the required control, it may be appropriate to incorporate a constraint as to the maximum period a component is able to act in FCR-N control, after which the system would be returned to its nominal state.

7.2 Frequency Containment Reserves for Disturbances

Frequency containment reserves for disturbances are responsible for providing immediate upregulation in case the grid frequency drops below 49.9 Hz, ensuring that abrupt electricity deficits do not lead to power outages. Technical failures in power plants or grid components pose the risk of near-instantaneous drops in frequency, as power supply is unexpectedly lost. FCR-D must be capable of providing timely reaction to these events, requiring very rapid activation times. The required capacity for FCR-D for Finland varied between 220 and 265 MW in 2016.

Frequency containment reserves for disturbances have the strictest requirement in terms of latency. The reserve is required to be able to fully activate within 30 seconds, with a maximum dead band of 50 ± 0.5 Hz. FCR-D reserves can provide control by aiming to provide linear control throughout the frequency range of 49.9 and 49.5 Hz. Unlike FCR-

N, FCR-D is not required to provide downregulating capacity. The guidelines set by Fingrid for linear FCR-D are illustrated in figure 9.

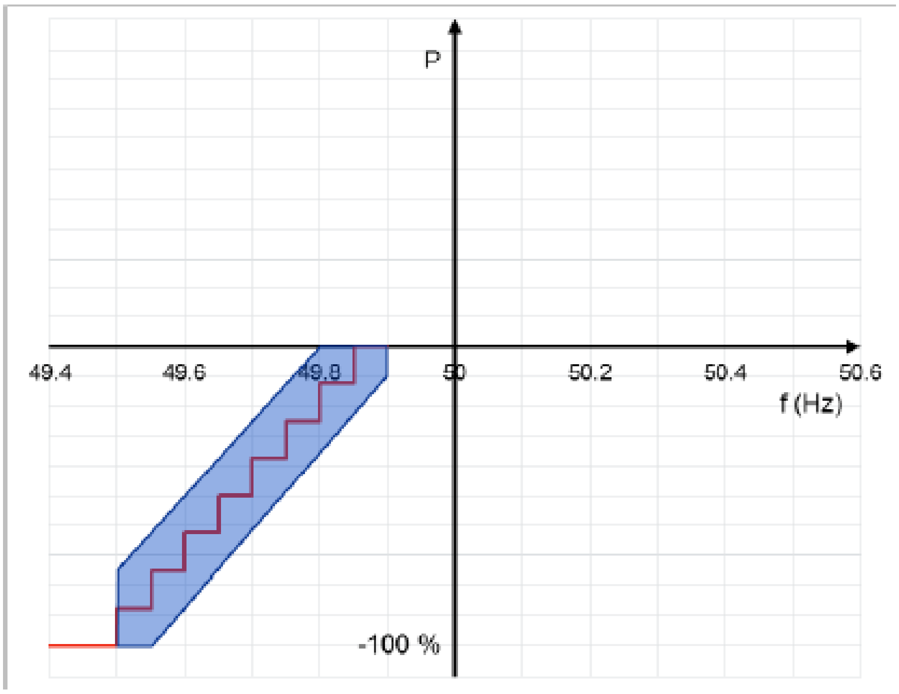


Figure 9
Guidelines for linear FCR-D control (Fingrid d)

As an alternative to linear control, FCR-D can be executed by instantaneously providing the entire reserve capacity. In this case the reserve is activated based on the achievable latency. The latency requirements for instantaneous FCR-D are summarized in table 4.

Frequency (Hz)	**Latency (s)**
< 49.7	< 5
< 49.6	< 3
< 49.5	< 1

Table 4
Latency requirements for non-linear FCR-D control (Fingrid d)

Although the technical requirements of FCR-D may give the initial impression that they are more demanding than FCR-N, for consumption loads this is in fact more often not the case. Despite requiring very fast activation times, the majority of loads are more suitable to the requirements of FCR-D compared to FCR-N, as they have they are inherently capable of nearly instantaneous power control. FCR-D does not require symmetrical control, which means that the ability to rapidly cut off power from the load is sufficient to meet the requirements. FCR-D is activated sparingly, as it is reserved for particularly problematic circumstances. Because of its high importance, FCR-D capacity is substituted by secondary reserves within 15 minutes of activation ensuring its availability for future use. This entails that the usage of FCR-D components is infrequent, and upon use the length of control is restricted to just 15 minutes. For these reasons, it can be assumed that the resulting energy deviation of participation in FCR-D are negligible. Consumers unwilling to significantly alter their consumption are likely to favour FCR-D, as the utilization of the capacity is far less than FCR-N.

The minimum capacity for the FCR-D markets is 1 MW. Although this is considerably higher than the minimum requirement for FCR-N, the technical requirements of FCR-D allow for a wider variety of components to be used, as it is not required to provide symmetrical control, and the linearity of control is not mandatory. Although most consumption loads are likely capable of acting as part of the FCR-D, the same data management is required for FCR-D as FCR-N, obligating market operators to provide continuous data at three-minute intervals, as well as storing per second data. This may discourage the incorporation of a large number of separate components.

7.3 Balancing Power Market

The balancing power market is delegated to supplementing the frequency containment reserves in reacting to unexpected developments in the energy balance within the operation hour. Its main task is relieving the frequency containment reserves for disturbances, as it is vital to have these reserves available at all times. In the case of significant drop in frequency, FCR-D are the first to react, providing the primary control. Capacity bid to the balancing power market is procured based on the capacity required to restore the frequency within the grid to its nominal value and allow the FCR-D capacity to be relieved. BPM participators are obligated to provide full capacity within 15 minutes of notice, thereby ensuring the maximum length of inadequate FCR-D capacity is constrained to 15 minutes. Balancing power capacities can also be activated to provide a source of downregulation under circumstances in which there is a substantial surplus of electricity (production > consumption).

Bids are made to the balancing power market for upregulating and downregulating power separately. From the consumer point of view, upregulation (providing electricity to the grid) would be carried out by decreasing consumption, and likewise downregulation (receiving electricity from the grid) would entail the increase of consumption. Upon activation, the entire bid capacity would be provided within 15 minutes of receiving notice. The capacity would remain activated for the duration of the market hour unless separate notice of relieving the capacity is received. The uncertainty of the length of control is somewhat problematic for consumers, as the amount of capacity bid to the market must be assessed based on the magnitude of capacity available for the entire hour, although the realized length of control is likely to be less than this. In calculations made for the balancing power market, it is assumed that the length of control is 30 minutes. Despite the assumed control length, the capacity provided in bids made must naturally be calculated under the assumption that the activation period may last the entire hour, and the consumer would be capable of providing the bid capacity for the entire hour.

Currently, the balancing power market is operated manually, and participators receive notice of bid activation via phone call. Bids made to the BPM must be at least 10 MW, which is a challenge to demand-side management solutions, as meeting this requirement likely requires the aggregation of a large number of individual components. As the development of markets to become more accommodating to consumer participation, it has been considered that the minimum bid capacity of the balancing power market would be decreased to 5 MW, which may lead to a greater amount of consumers capable of meeting the requirements of the market.

7.4 Elspot Market

Under the framework of this paper, Elspot market based demand-side management is not approached from the electricity retailers perspective, in which case retailers would manage demand-side management capacity as a component in their Elspot trading. Instead, it is assumed that consumers are capable of procuring electricity at spot-market rates, and utilize this method of invoicing to achieve profits through load shifting. In this sense, there are no specific technical requirements of the control, other than the capability to decrease the consumption for a given hour and correspondingly increase consumption for the payback hour. In order to enhance the effectiveness of load shifting based on the Elspot-market, it may be desirable to develop more sophisticated methods of carrying out the control of consumption. If such methods are incorporated, they may involve technical requirements, although it can be assumed that the participation of consumption in the Elspot market does not entail particular technical challenges.

8 Market overview

In this section the markets are reviewed without taking into account the participation of the consumer. This section aims to introduce the nature of the markets and provide insight into the factors that influence the formulation of prices. The development of the markets is considered, as these developments may potentially significantly change the state of the market in the coming years.

It is important to distinguish between markets in which energy is traded to markets in which the compensation is based on offered capacity. FCR-N and FCR-D markets are capacity-based markets, in which compensation is received based on the available power, whereas the Elspot and balancing power market are energy-based markets, in which the compensation is based on the provided energy. Understanding the requirements of each market as well as the nature of the commodities traded in these markets is critical in gauging capacity potential and determining optimal markets and respective strategies.

When considering the responsibility of FCR-N and FCR-D operators, it is not necessary to provide the grid with up- and downregulation, but rather to provide the potential to supplying up- and downregulation. FCR-D and FCR-N are put in place to ensure the availability of flexibility whenever this flexibility may be required. Whether this potential is actually utilized is not entirely relevant, as the value of the reserves is in the insurance of the frequency maintenance. Essentially this means that the market participator receives the same compensation regardless of the extent of effective utilization of the provided capacity. This is not entirely true, as in addition to the capacity payment received through the market, an energy compensation is received. However, the concept of the market remains the same, in that the desired product is capacity rather than energy. The demand is therefore determined by the power capacity requirement, with the energy compensation serving the purpose of reimbursing the resulting deviation in energy consumed/produced. Consumption-based resources of FCR are at somewhat of an advantage compared to production-based components, because whereas production units require running costs allocated to keeping capacity on line, consumption-based reserves can maintain their available capacity within the framework of their normal operation, and ultimately retain up- and downregulating capacity without any designated effort, as the capacity is inherently available. The FCR-D is especially advantageous in this regard, as consumers are able to receive compensation for their willingness to cut off the power supply, despite the likeliness of control being required being relatively low.

8.1 Frequency Containment Reserves for Normal Operation

Market participators in Finland can choose to either offer their FCR-N capacity to the annual market or the hourly market. In the annual market, a fixed price is set for all bids activated, which determines the price for all market hours throughout that market year. Yearly markets are carried out during the fall, and are not accessible once the initial contracts have been made. The price of FCR-N in the yearly market is determined by the highest approved bid. Operators participating in the yearly market are obligated to maintain the capacity sold to the yearly market throughout the year within the framework of their normal operation. For 2016, 89 MW of capacity took part in the yearly market. The compensation for this capacity was 17.42 €/MW. Capacity owners taking part in the yearly market receive the fixed price whenever they offer capacity to the reserves. When procuring the hourly obligated FCR-N capacity, the yearly market capacity is prioritized first, with all available capacity being ensured participation. Once capacity has been acquired through the yearly market, supplemental reserves are procured through a national hourly market. Additional capacity is acquired from Sweden, Russia, Estonia and Norway. Market data for the hourly market for 2016 is shown in figure 10.

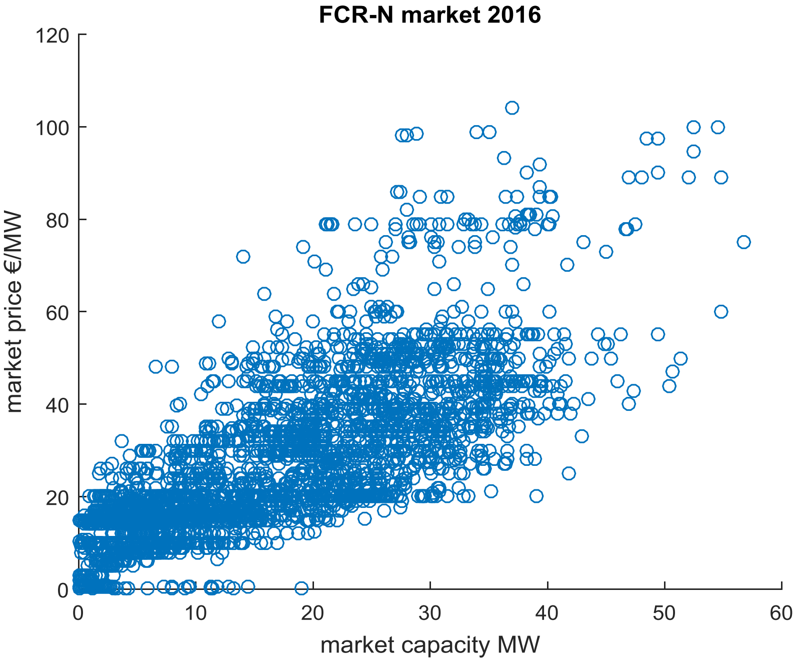


Figure 10
Market data for capacity acquired and respective price in the FCR-N hourly market during 2016

Over the course of 2016, the hourly market was utilized 5658 hours of the year, corresponding to a 64 % utilization factor. The average compensation through the hourly market was 26.1 €/MW, and on average 15.6 MW of capacity was procured. The maximum price for the year was 104.2 €/MW and the maximum capacity acquired was 56.7 MW. In addition to the compensation of reserve capacity provided, an energy compensation is also received. The energy compensation cannot be accurately evaluated based on the data available for this paper, although it has been stated that the effect it has on the overall annual profit is relatively insignificant, and it is therefore left out of results displayed in this paper entirely.

The FCR-N market was deployed in 2011. The market has experienced considerable fluctuation during its short history, as demand and supply seek a sustainable balance. A summary of hourly market values for the years 2012-2016 is summarized in table 5 and respective values in the yearly market are shown in table 6.

FCR-N Hourly	2016	2015	2014	2013	2012
Annual expense M€	3,1	4,1	8,0	6,7	4,3
Mean price €/MW	26	29	46	51	45
Max price €/MW	104	500	520	514	560
Mean overall capacity MW	16	18	21	14	11
Max overall capacity MW	57	75	86	64	51
Hours used N	5658	6780	6097	6135	5952
Utilization rate	64 %	77 %	70 %	70 %	68 %

Table 5
Annual values for FCR-N hourly market

FCR-N Yearly	2017	2016	2015	2014	2013	2012
Price €/MW	13	17.42	16.21	15.8	14.36	11.97
Total capacity MW	55	89	73.6	75.4	73.5	72.7

Table 6
Values for FCR-N Yearly market

The price level of the hourly market increased considerably for the first four years, likely due to a limited amount of market participators. Prices have recently dropped, and the mean hourly price was roughly half of 2013 values during 2016. It is important to remember that the hourly market serves the purpose of providing sources of supplemental capacity when the required capacity is not met through the annual market. 2013 experienced prices over 300 % that of the yearly market price. This is naturally not desirable, and the proper saturation of the market would lead to prices in the hourly market close to those of the annual market, avoiding the unequal compensation of effectively the same provided task.

2016 showed signs of increased competition in the hourly market, as the mean price was relatively close to the price in the annual market. Unlike previous years, the market did not experience high price spikes, with the price remaining below 105 €/MW throughout the year, whereas previous years had hours in which prices exceeded 500 €/MW, indicating an increase of economically efficient supply of reserves.

As the demand for the hourly market is largely effected by the amount of capacity available through the yearly market, increased participation in the yearly market naturally decreases the price level of the hourly market, as less supplemental capacity is required. As additional sources of FCR-N are deployed, the price level of the annual market can be expected to decrease even further, and assuming the saturation of both markets the hourly market prices will continue converging with the price level set in the yearly market.

Developments in the electricity sector are expected to entail a loss in inertia, requiring even more rapid reaction to frequency fluctuation. Fingrid, along with associated transmission system operators, are likely to react to these developments by increasing the latency requirements of FCR-N reserves. The increasingly stringent technical requirements for FCR-N components may restrict a large portion of currently used reserve units from providing the required control. This especially effects hydropower operators, as Kaplan-turbines have been highlighted as one of the production types most likely unable to meet the future requirements. The majority of hydropower plants in Finland are Kaplan-turbines, and if future reserves are implemented in which Kaplan-turbines are not a viable option, consumption-based sources of flexibility may become increasingly valuable (Fingrid e). Presumably the control provided through conventional FCR-N providers unable to meet future requirements will not be neglected, but rather considered as a separate resource, which would allow consumers to compete with comparably rapid forms of control in a market designated for highly capable sources of flexibility.

8.2 Frequency Containment Reserves for Disturbances

FCR-D procurements are made under the same premise as FCR-N, in which the obligated capacity is initially pursued through capacity participating in the yearly market, with supplemental capacity available through the hourly market as well as external links to Sweden and Norway. The price determined in the yearly market for 2016 was 4.5 €/MW, and a total of 367 MW participated in the yearly market. Hourly market data for 2016 is shown in figure 11.

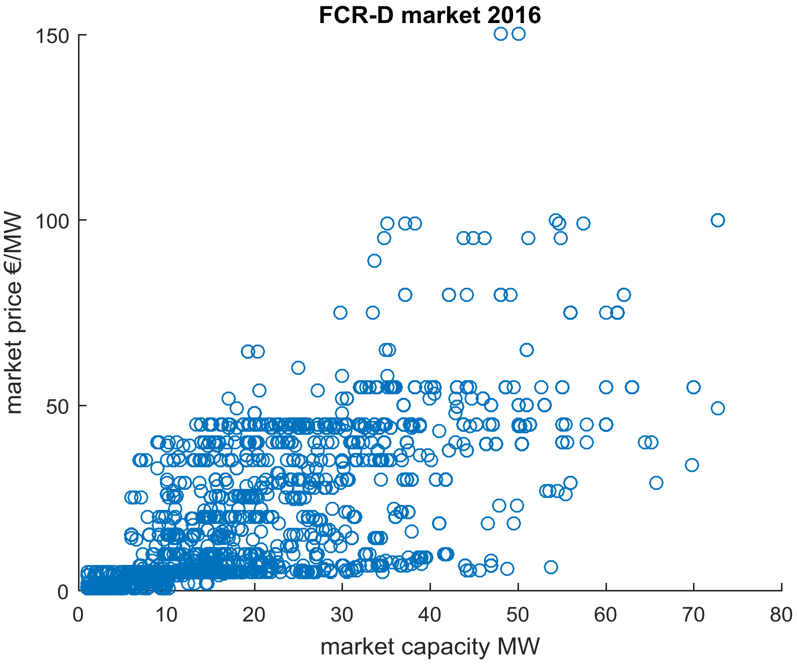


Figure 11
Market data for capacity acquired and respective price in the FCR-D hourly market during 2016

Due to the high availability of yearly market capacity, the utilization of the hourly market was low for 2016, with supplemental capacity being procured through the hourly market for just 23 % of the market hours. The majority of market hours experienced low prices, as over 60 % of the market prices were 10 €/MW or lower. Despite the low mean market price, the market is subject to high price spikes, exceeding 100 €/MW. This leads to a skewed distribution of profits, in which the most profitable 2 % of hours yielded the same profit as the least profitable 67 % in 2016.

Annual values for the FCR-D hourly market are shown in table 7 and values for the yearly market are shown in table 8.

FCR-D	2016	2015	2014	2013	2012
Annual expense M€	1,3	3,1	1,3	3,8	0,5
Mean price €/MW	20	21	17	32	19
Max price €/MW	150	500	420	600	480
Mean overall capacity MW	20	18	13	15	6
Max overall capacity MW	73	115	74	77	46
Hours used N	2049	5827	4089	6358	2822
Utilization rate	23 %	67 %	47 %	73 %	32 %

Table 7
Annual values for FCR-D hourly market

FCR-D	2017	2016	2015	2014	2013	2012
Total capacity MW	455.7	367	297.5	318.7	299.8	346.9
Price €/MW	4.7	4.5	4.13	4.03	3.36	2.8

Table 8
Values for FCR-D yearly market

Along with the FCR-N market, the FCR-D market was also launched in 2011, and has experienced volatility in its first years of operation. Although the average price per MW in the hourly market has consistently been around 20 €/MW, with the exception of 2013 which experienced a higher mean price of 32 €/MW, the overall utilization rates have varied substantially. The hourly market was used for 23 % of the market hours in 2016 despite utilization being as high as 73 % in 2013 and 67 % in 2015. This entails a somewhat high uncertainty in assessing possible annual profits in the hourly market, as it is difficult to forecast the likelihood of bids being activated.

The yearly market price has consistently increased, and the large capacity of participators in the yearly market is likely to further decrease the utilization of the hourly market. Compared to 2013, which experienced the highest values in the hourly market in terms of mean price as well as market utilization, the overall capacity participating the yearly market has increased by more than 50%.

8.3 Balancing Power Market

Bids are made to the balancing power market separately for up- and downregulation based on the system imbalance. If consumption is greater than production, the transmission system operator has the possibility of procuring upregulating power through the balancing power market. Market operators providing upregulating power carry out upregulation by either increasing their production of decreasing their consumption, thereby offsetting the system imbalance between the two. Bids are activated based on their bid price, with the least expensive bids being the first bids activated. The price received for upregulating power is the same for all activated bids, and is equivalent to the highest activated bid, or at the bare minimum equivalent to the corresponding Elspot price of the operation hour. Activated bids receive compensation based on the total energy provided during the operation hour.

If production is greater than demand, the transmission system operator can sell the surplus power to market operators who have bid downregulating power to the balancing power market. Downregulation is carried out by either decreasing production or increasing consumption. Downregulation bids are activated in order of most to least expensive, with the highest activated bid determining the final market price. The price of downregulating power is at most the Elspot market price for the corresponding hour. Figure 12 illustrates the functionality of the balancing power market. The balancing power market prices of 2016 for up- and downregulating power are shown in figures 13 and 14.

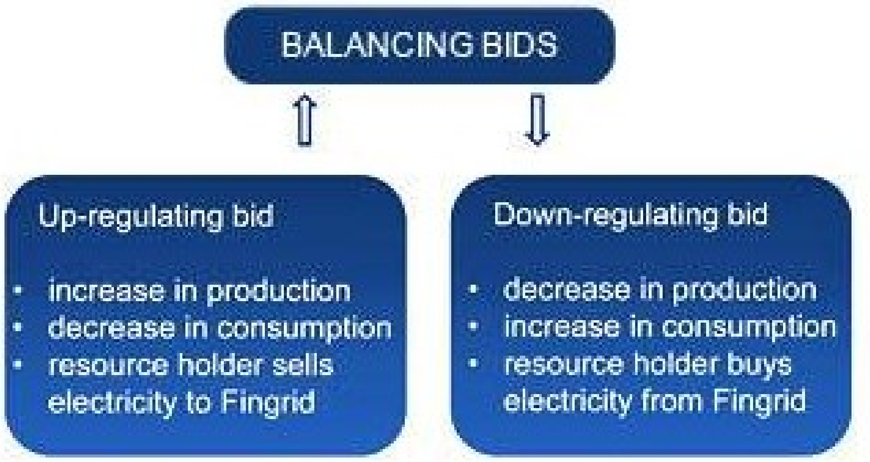


Figure 12 Operation of the balancing power market (Fingrid h)

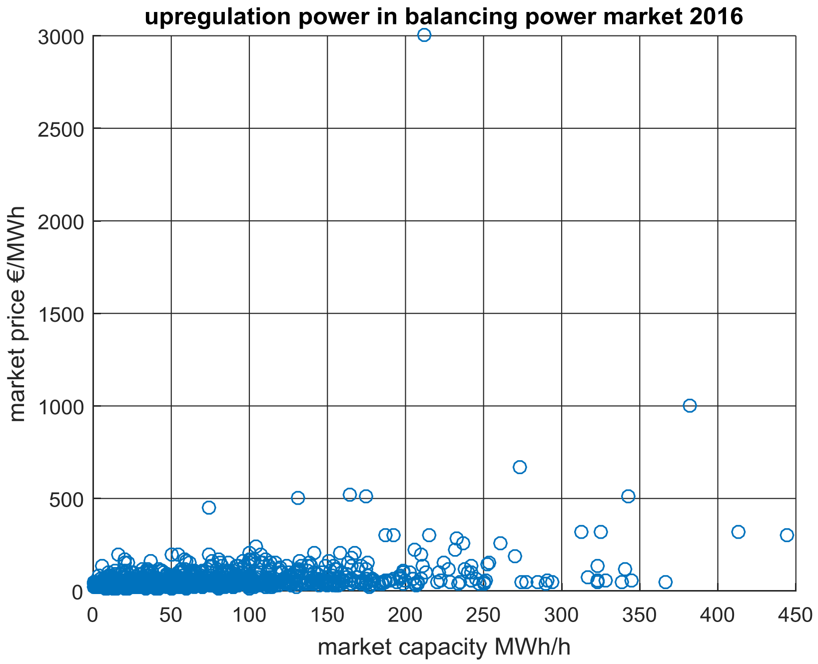


Figure 13
Market data for upregulating power in the balancing power market for 2016

Upregulating power was activated through the balancing power market for a total of 1980 hours during 2016, accounting for a utilization rate of 23 %. The mean price of upregulating power for 2015 was 51.2 €/MWh, and the mean capacity was 58.4 €/MWh/h. The price of upregulation is subject to high price spikes, such as the price spike of 3000 €/MWh experienced on 22.1.2016. The correlation of price and demand is somewhat weak, as several of the peak demand hours did not entail large prices, and correspondingly relatively low demands have the potential to cause significant price spikes.

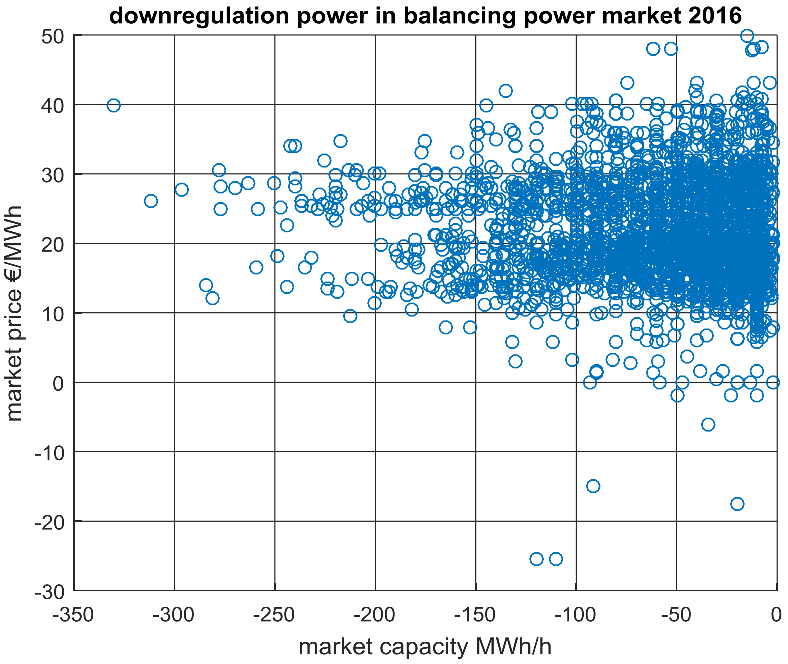


Figure 14
Market data for downregulating power in the balancing power market for 2016

Downregulation provides market operators the possibility to buy surplus energy, allowing them to either consume more or produce less than stated in their balance. The price of downregulating power for 2016 was 22 €/MWh on average. Downregulation is activated somewhat more frequently than upregulation, with bids being activated for a total of 2698 hours in 2016, accounting for a utilization rate of 34 %. The price of downregulation may drop below 0, in which case providers of downregulation are paid for their downregulation. This essentially means that consumers would be paid for consuming electricity, and electricity generators would be paid for cutting down production. 2016 experienced a minimum price of -25.6 €/MWh.

On 7.5.2017, the price of upregulating power fell to an unprecedented low of -1000 €/MWh for a period of 4 hours. The demand for downregulation for this period was between 189 and 444 MWh/h. The irregularly high demand was mainly due to a maintenance break in the transmission line to North Sweden, which would typically provide 1500 MWh/h in transmission capacity. This occurrence serves as a valid reminder of just how vulnerable market prices in Finland are to price spikes when the flexibility of neighbouring countries is not available.

Tables 9 and 10 display information on the behaviour of down- and upregulating power respectively in the balancing power market for the years between 2012 and 2016.

Upregulation	2016	2015	2014	2013	2012
Mean price €/MW	51	53	50	61	81
Max price €/MW	3000	2000	500	2000	2000
Mean overall capacity MW	58	64	66	65	74
Max overall capacity MW	445	435	502	721	767
Hours used N	1980	1963	2088	1850	1851
Utilization rate	23 %	22 %	24 %	21 %	21 %

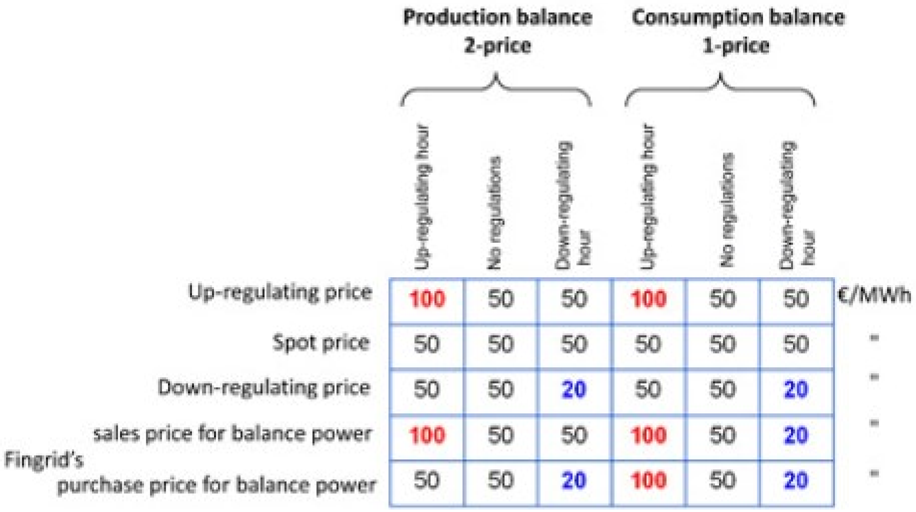
Table 9
Annual values for upregulation in the balancing power market

Downregulation	2016	2015	2014	2013	2012
Mean price €/MW	22	17	25	32	23
Minimum price €/MW	-26	-5	-1	-67	-8
Mean overall capacity MW	-59	-71	-67	-57	-66
Max overall capacity MW	-330	-458	-409	-461	-356
Hours used N	2968	2820	2655	2784	2553
Utilization rate	34 %	32 %	30 %	32 %	29 %

Table 10
Annual values for downregulation in the balancing power market

For the purpose of this paper, we consider the participation of consumers in the balancing power market as a provider of upregulating power, as this is financially the more valuable service. Consumers are assumed to bid upregulating power to the balancing power market at a fixed price. If this bid is activated, the consumer provides upregulation for an unknown duration and receives compensation for the total energy provided in accordance to the upregulation price for the corresponding hour. The provided upregulation causes an energy deficit in the consumption system, and requires an energy payback to be carried out. Although it is assumed that the consumer is capable of delaying the payback effect, it is favourable to limit the length of delay periods, as they may entail drawbacks to the consumer environment. The payback energy is considered as an imbalance in the consumption balance, for which the consumer is responsible for paying the price of imbalance power.

Whereas production follows a 2-price balance model, consumption follows a 1-price model. The significant difference between these models is that the in the case that the imbalance accounted for by consumption is in line with the balance requirement of the power system, this imbalance is essentially regarded as involuntary participation in the balancing power market, adopting the price set by the balancing power market. This is beneficial towards consumers, as they are essentially rewarded for imbalances which correspond with a positive impact on the overall power balance of the system, even when this effect has not been specifically pursued. The 1- and 2-priced balance models are illustrated in figure 15.



	Production balance 2-price			Consumption balance 1-price			
	Up-regulating hour	No regulations	Down-regulating hour	Up-regulating hour	No regulations	Down-regulating hour	
Up-regulating price	100	50	50	100	50	50	€/MWh
Spot price	50	50	50	50	50	50	"
Down-regulating price	50	50	20	50	50	20	"
Fingrid's sales price for balance power	100	50	50	100	50	20	"
Fingrid's purchase price for balance power	50	50	20	100	50	20	"

Figure 15 Required compensation for imbalances in the production balance (2-price) and consumption balance (1-price) (Fingrid f)

The price of imbalance power depends on the usage of balancing power during the operation power. If upregulating power is required, the market hour is considered as an upregulating hour, and the price of imbalances in the consumption balance is determined by the upregulation price of the balancing power market. If the payback occurs during a downregulating power, the price of imbalance power is determined by the downregulating price. If neither upregulation nor downregulation is required, the price is determined by the Elspot price. A 0.5 €/MWh volume fee is added to the price of imbalance power in the consumption balance.

8.4 Elspot Market

The Elspot market is the largest day-ahead market in the world for trading power. In 2013, 88 % of the total electricity consumption in Nordic countries was traded through the Elspot market. As stated previously, the merit order effect leads to an increasing rise in Elspot-prices as demand increases, offering consumers the possibility to increase the economic efficiency of their electricity consumption by transferring electricity from periods of high overall demand to periods of lower overall demand, mitigating the demand for usage of the most expensive production plants.

Unlike previous markets, there is no tangible demand for demand side management in the Elspot market. Instead, the demand for flexibility is in the conceptual benefit of shifting demand. As the market prices are determined in advance, consumers are able to plan the adjustment of their consumption based on these prices. By reacting to the price signals given by the Elspot market, the load shifting achieves the benefit of decreasing consumption during periods of expensive production, and transferring this consumption to periods in which production is more economic.

The relation between price and demand is visualized in figure 16. The production capacity utilized in the Elspot market varies substantially seasonally, as various forms of baseload production are not used during the summer, as the overall consumption remains low. For this reason, prices have been separated based on the season.

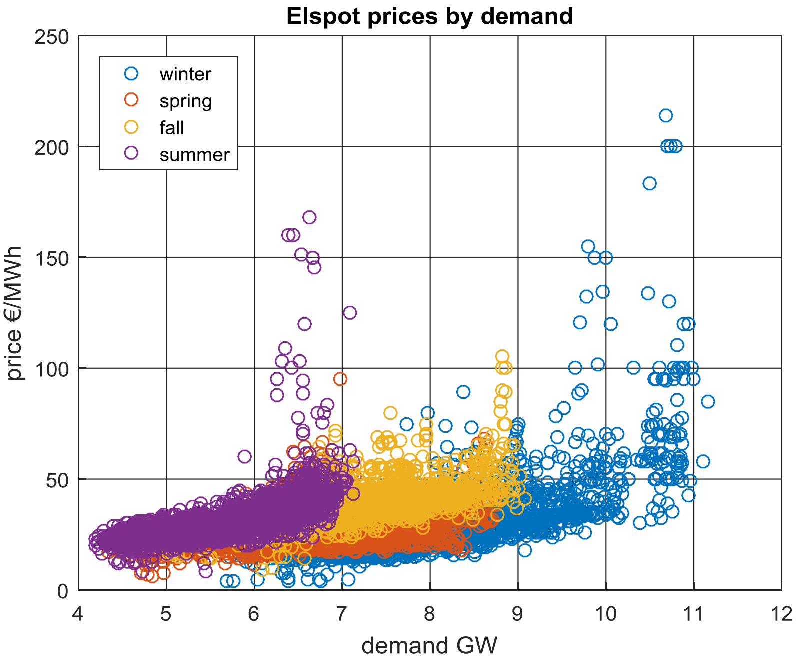


Figure 16
2016 Elspot-prices by demand

Consumers carrying out load shifting do so on an hourly time scale, reacting to price differences experienced during a day. Hourly prices in the Elspot market follow a diurnal pattern, in which prices are highest during morning and evening hours, during which the demand for electricity is high. During the night, the demand for electricity is low, and Elspot-prices for these hours are regularly significantly lower than the daily peak prices. Figure 17 displays the diurnal pattern typically experienced in the Elspot market. Two separate price spikes are often experienced, with on occurring during the morning between the hours of 8 and 12, and the second occurring in the evening during the hours of 17 and 20. Consumers flexibility during the hours most critical in terms of electricity generation are likely to receive the highest reward for carrying out load shifting. In other words, the most essential requirement for Elspot-based load shifting is not the technical capability of flexible consumption (how the flexibility is carried out), but rather the ability to carry out control so that it coincides with the diurnal pattern of market prices (when the flexibility is carried out).

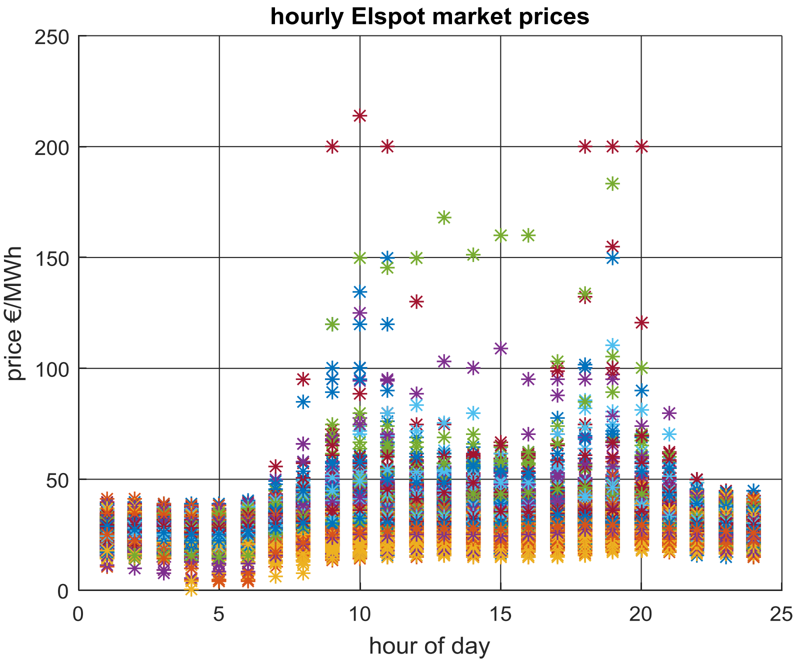


Figure 17
2016 hourly Elspot prices

9 Economic potential

The economic potential for each market is primarily assessed by calculating the annual profit attained based on 2016 market data. The capacity of the flexible load used was 10 MW, as this is the lowest capacity capable of theoretically accessing all marketplaces. Market participators are assumed to bid the available capacity at a constant bid price for all market hours throughout the year. In calculations made on the participation in the balancing power market as well as Elspot-based load shifting, the availability of the flexible capacity is constrained by the system balance constraint, which entails that the flexible capacity is not accessible during an energy imbalance within the consumption system, thereby requiring the carrying out of the energy payback. For the FCR-N and FCR-D markets, the system imbalance is not taken into account. It should be noted that if the imbalance were properly accounted for, participation in the FCR-N market would likely be limited to some degree.

Consumption loads may be restricted from participating in load control due to circumstances unrelated to the market participation. These effects have not been accounted for. In this sense, the values ae theoretical maximums under the assumptions and constraints presented, and actual values are likely to be somewhat smaller due to the consumer loads inability to constantly have the flexible capacity available.

Regulation of the considered markets are likely to develop in the near future, which may cause drastic changes to the market. These developments are not accounted for, but should be kept in mind when considering the accuracy of profit potentials. For the purpose of the research carried out, the market analysis aims to provide insight to the proportional magnitude of profit potential rather than precise values. A key aspect in the analysis performed was to determine and evaluate the factors which contribute to the profitability of these markets. With this in mind, it is not in the interest of this paper to provide accurate economic potentials, but rather to provide a conceptual background to the underlying properties which are most relevant in the pursuit of maximum profitability.

9.1 Frequency Containment Reserves for Normal Operation

The annual profit of a 10 MW load in the frequency containment reserves for normal operation yearly market would have been 1.53 M€, assuming the capacity was available the entire year. Annual profits in the FCR-N hourly market for bid prices of 0-50 €/MWh are shown in figure 18, as well as the number of activated bids over the course of the year.

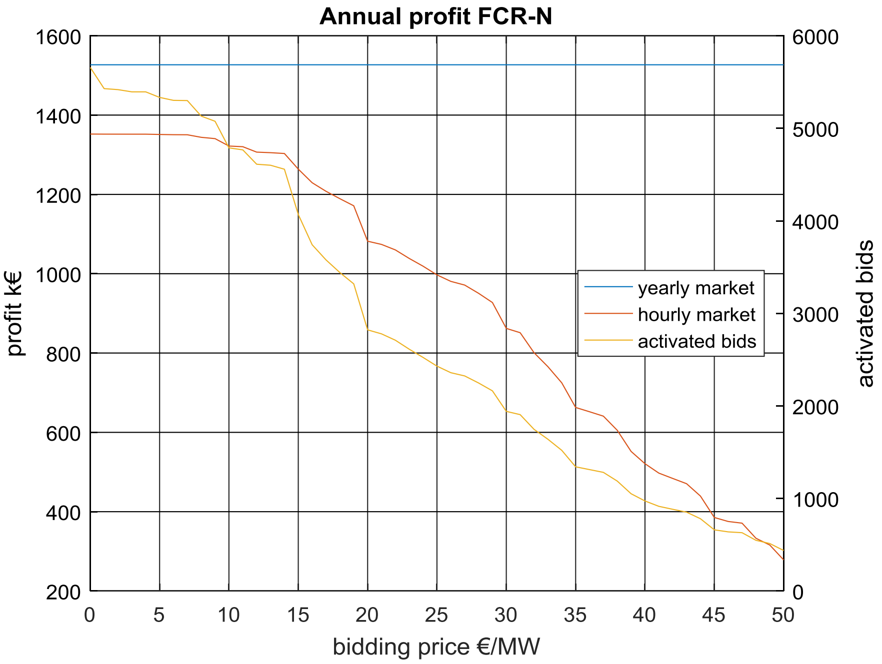


Figure 18
Annual profit of FCR-N hourly market as a function of bidding price for 2016

Profits shown in figure 18 are based on the theoretical profit of a market participator that had participated in the FCR-N yearly or hourly market. This participator would receive compensation based on the hourly market price for all hours in which the bid price was lower than the market price. This would lead to a maximum profit at a bidding price of 0 €/MWh, ensuring that the bid is activated and compensation is received for all hours in which the hourly market is utilized. Participation in the FCR-N is likely to entail costs to the consumer, for example losses in efficiency, increases in operation and maintenance costs, as well as risks related to technical failures. Market participators would be inclined to make bids that ensure the received compensation exceeds the attributed costs of participation.

The amount of capacity procured through the FCR-N hourly market is quite small, averaging just 16 MW in 2016. If large amounts of additional capacity is introduced to the market, this may have a substantial impact on the price level of the market. A highly simplified approach to assessing the impact of additional capacity was used, in which the bids made for each hour were assumed to be perfectly linear, resulting in a linear price drop when additional capacity is introduced. Accurate simulations of price development would require significantly more sophisticated models. Although the assumptions made in the price drop estimation are not necessarily particularly accurate, the motivation for these calculations is to provide insight to how sensitive the markets may be to additional capacity.

Implementing the assumption of a linear price decrease would lead to the results shown in figure 19.

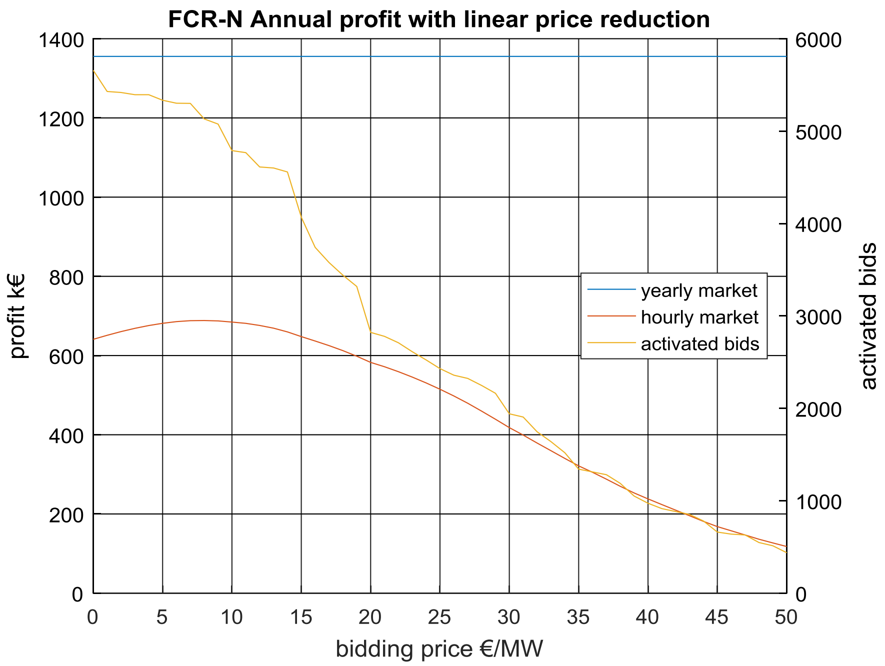


Figure 19
Annual profit of FCR-N hourly market assuming linear reduction of market pics as a function of bidding price for 2016

The effect of the additional capacity is especially evident at low bid prices. This is largely due to the high number of market hours in which demand is very small, less than 10 MW, in which case the price of an additional bid would dictate the final market price altogether. This provides the incentive to bid at a higher price. For the estimations using a linear price drop for the year 2016, a bidding price of 8 €/MWh would yield the highest annual profit, at 688 k€. Compared to the results in figure 18 in which no price drop was taken into account, the results calculated assuming a linear price drop are substantially lower. At bidding prices close to 0 €/MW, the annual profit would drop by more than 50 %. While this may be somewhat discouraging to market participators, as the economic potential is decreased, it is beneficial to the electricity sector as a whole, as the cost of FCR-N is reduced.

The annual profit potentials for 2012-2016 were calculated for both the yearly and hourly markets without taking the price drop into consideration as well as with a linear price drop. Results are shown in table 11.

FCR-N	2016	2015	2014	2013	2012
Yearly market k€					
Annual profit	1527	1421	1385	1259	1049
Profit with price drop	1355	1229	1200	1089	905
Hourly market k€					
Annual profit	1352	1873	2649	2854	2212
Profit with price drop	688	908	1556	1410	953

Table 11
Economic potential of participation in frequency containment reserves for normal operation

9.2 Frequency Containment Reserves for Disturbance

As in FCR-N markets, the overall demand in FCR-D hourly market is quite low, with the average demand in 2016 amounting to 17 MW. In order to estimate the annual profits attainable though FCR-D, we again assume that bidding prices progress linearly, leading to a substantial drop in prices as new capacity is introduced, as displayed in figures 20 and 21.

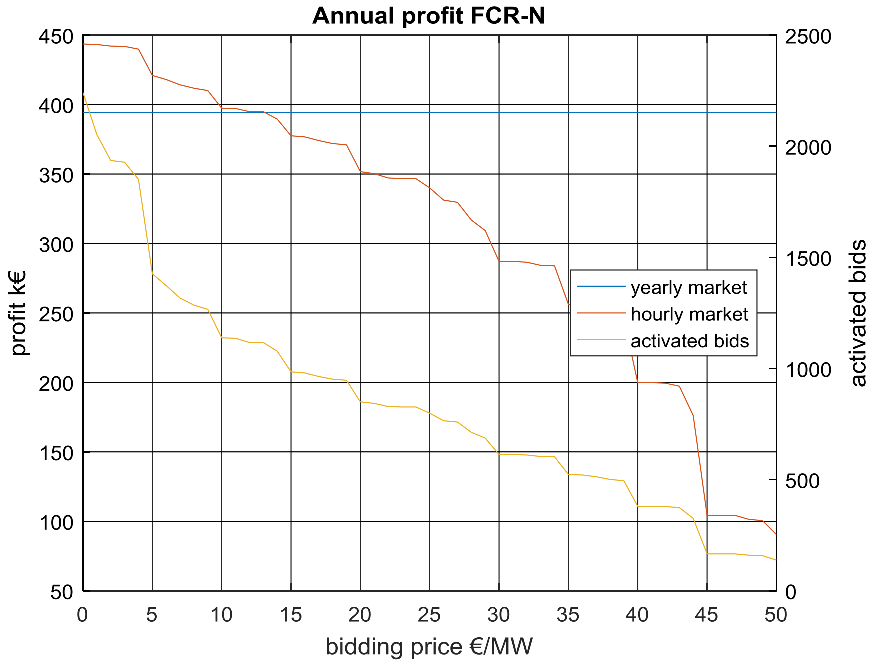


Figure 20
Annual profit of FCR-D hourly market as a function of bidding price for 2016

Compared to the FCR-N market, the utilization of the FCR-D hourly market is considerably less frequent, as the annual market is largely capable of accounting for the entire capacity requirement. Bidding capacity at a price of 10 €/MWh would have led to an annual utilization rate of less than 12 %, whereas the corresponding utilization in the FCR-N market would be roughly 4 times as high.

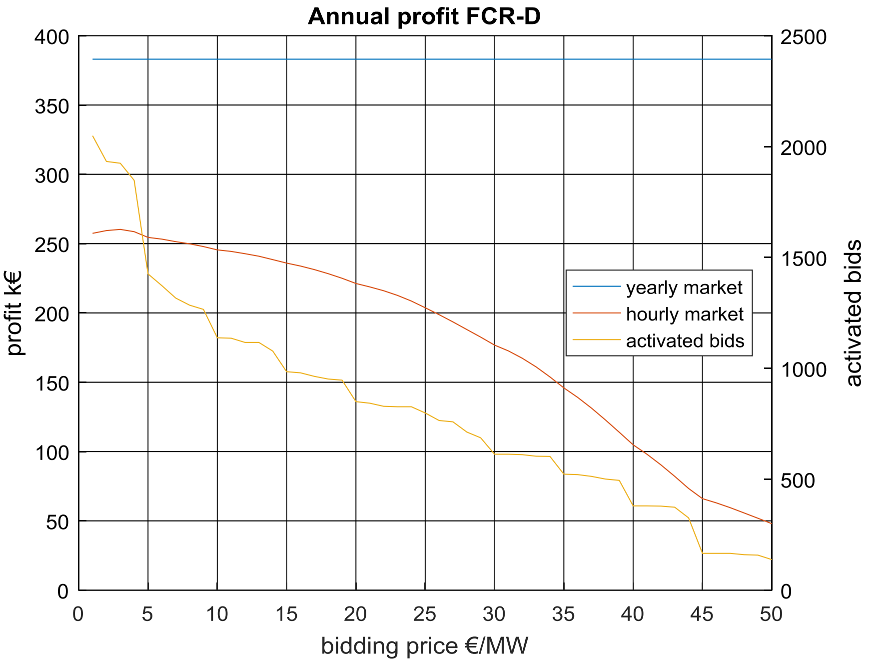


Figure 21
Annual profit of FCR-D hourly market assuming linear reduction of market pics as a function of bidding price for 2016

As shown previously in table 7, the mean demand for FCR-D capacity in the hourly market has remained below 20 MW annually since 2012.Due to the limited demand of the FCR-D hourly market, additional capacity participating in the market is likely to have a large impact on resulting market prices.

FCR-D	2016	2015	2014	2013	2012
Yearly market k€					
Annual profit	394	362	353	295	245
Profit with price drop	384	350	342	285	238
Hourly market k€					
Annual profit	443	1212	637	1743	312
Profit with price drop	260	622	256	724	86

Table 12
Economic potential of participation in frequency containment reserves for disturbances

9.3 Balancing Power Market

The profit of the control carried out based on the balancing power market is determined by the difference between compensation received from the upregulation and the cost of the payback.

$$single\ cycle\ profit = capacity * length\ of\ control * (upregulation\ price_t - cost\ of\ imbalance_{t+1+payback\ delay}) \quad (4)$$

Participating in the balancing power market is somewhat challenging, as neither the upregulation price no cost of imbalance is known by the participator until after the related actions have been carried out. This means that control cycles are carried out based on expected values rather than actual values, and realized control cycles are unlikely to correspond with the theoretical optimum, due to the unavailability of information.

The overall profitability is based on the assumption that the expected value of the upregulation price is greater than the expected value of the cost of imbalance. The expected values can be influenced by both the bidding price, $E[upregulation\,price] \geq bidding\ price$, and by the length of the payback delay. These factors largely dictate the operation of the consumer, and are the most relevant factors when developing a market strategy.

Because both the upregulation price and cost of imbalance are unknown until after the actual control has taken place, there is a risk of a single control cycles being unprofitable, when $cost\ of\ imbalance_{t+1+payback\ delay} > upregulation\,price_t$.

Figure 22 shows the cost of imbalance power for 26.1.2016, illustrating the potential for market participators to carry out control cycles which have a negative profit.

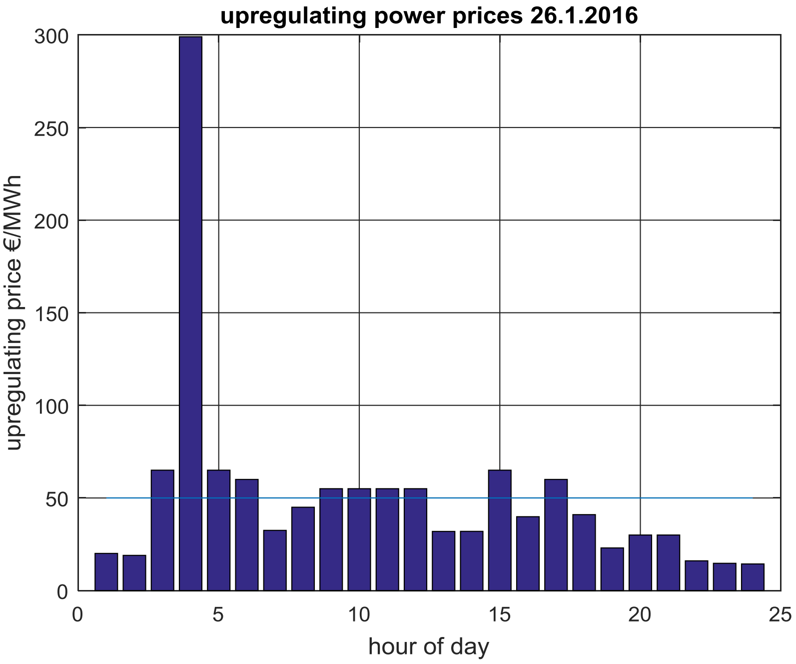


Figure 22
Balancing power market prices for upregulating power for 26.1.2016

We assume a marketing strategy in which the market operator bid upregulating power to the market at a bidding price of 50 €/MWh and carried out the payback immediately after the initial control was carried out. For the hour of 3-4, the uprgeulating bid would have been activated, and the consumer would receive the 65 €/MWh market price for the provided upregulation. The cost of imbalance for the following hour was determined by the upregulating price, leading to a cost of imbalance of 299 €/MWh. The market particiapator would effectively incur a loss of over 230€/MWh for the carried out control. These are clearly very unfavorable scenarios for the consumer, as they result in considerable financial losses, and they are also detrimental to the entire balancing power market, as the initial upregulation is less valuable than the subsequent increase of upregulating demand during the payback hour.

In order to avoid these scenarios, it is in the best interest of the consumer to maintain high bidding prices and delay the payback hour, allowing the market price to develop. If we use the market data of 26.1.2016, the optimal bidding price would have been over 65 €/MWh, and the delay of payback 2 hours. While the market encourages the delay of payback, it is important to keep in mind that this may be detrimental to the operation of the control component. For this reason, the delay of payback periods cannot be considered as arbitrary, but instead as a parameter which should be constrained. Figure 23 shows the annual profits accumulated during 2016 utilzing delay periods of 0, 1 and 2 hours and bidding pices of 0-200 €/MWh. Figure 24 shows the number of control cycles required in each case.

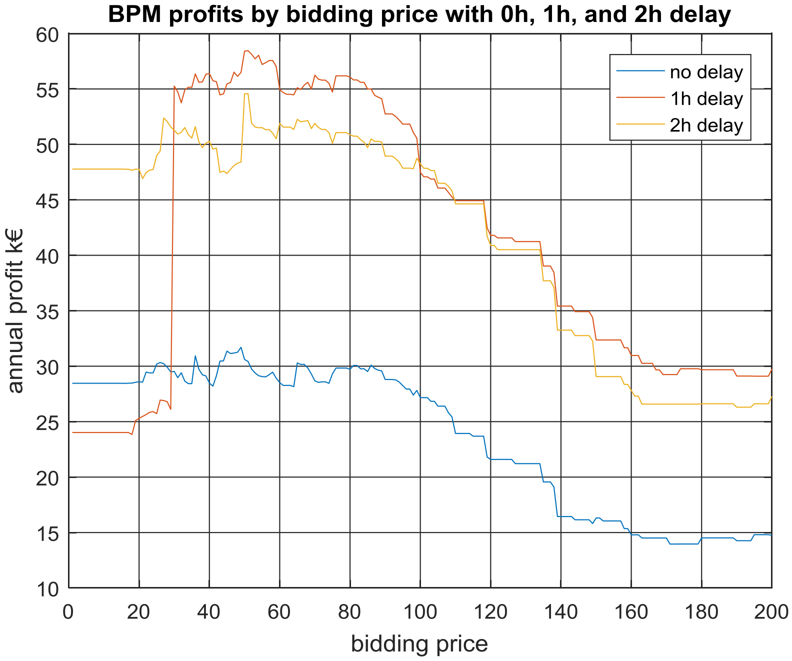


Figure 23
Annual profits through balancing power markets as a function of bidding price for payback delays 0, 1 and 2 hours

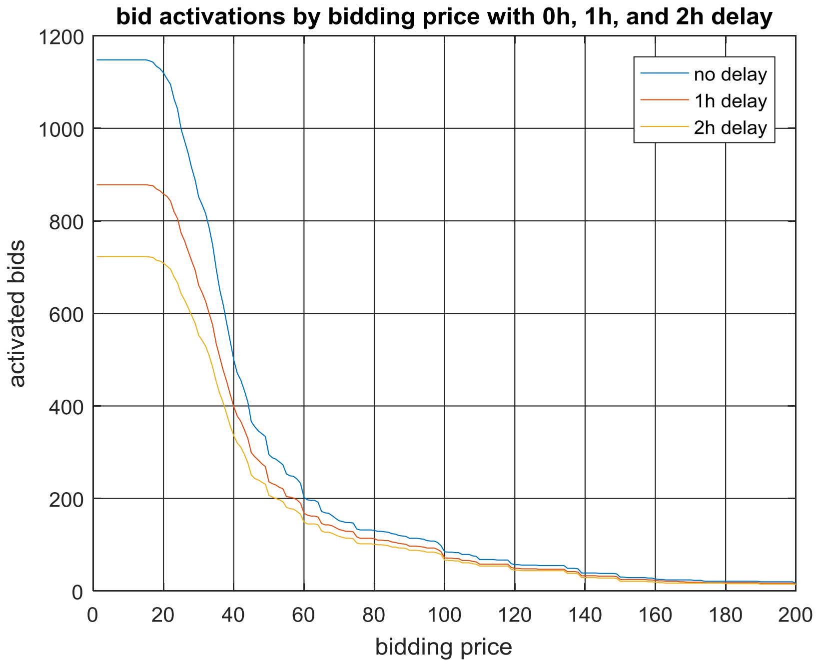


Figure 24
Activated bids in the balancing power markets as a function of bidding price for payback delays 0, 1 and 2 hours

The randomness of single cycle profits in the balancing power market encourages risk averse bidding strategies. Based on 2016 market data, a reasonable market strategy would have been to utilize an 80€/MWh bidding price and 1 hour delay of payback, which would have led to a total of just 113 bid activations over the course of the entire year. It seems that annual profits rely heavily on the extreme market conditions, with a large share of the annual profits coming from isolated price spikes. Out of the profit acquired over the course of the entire year, the profit attained through the most profitable cycle which occurred during the 8.1.2016 price spike of 3000 €/MWh accounted for over 24%. More than 50% of the total annual profits would have been attainable through the 10 most profitable cycles. An hourly breakdown of single cycle profits is shown in figure 25.

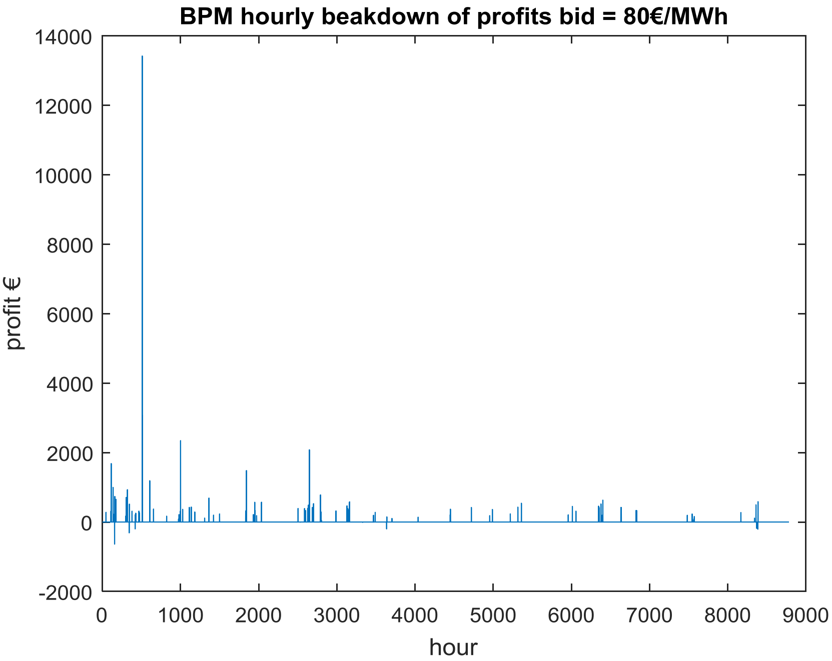


Figure 25
Hourly breakdown of balancing power market profits using a bidding price of 80 €/MWh and payback delay of 1 hour

Based on the results found using 2016 data, participation of consumers in the balancing power market is likely to be very limited, as both the interest of mitigating the risk of unprofitable control cycles as well as the pursuit of maximum profits with minimal impact on the consumer environment favour marketing strategies in which the upregulating potential is reserved for extreme price spikes.

9.3.1 Elspot-based balancing power market payback

Forecasting the price development of the balancing power market is highly challenging, as the very demand of the market itself is based on factors which were not forecasted. One simplistic forecasting strategy would be to base payback hours on Elspot prices. The rationale behind this strategy is the fact that during hours in which neither up- nor down-regulation is not used, the price of imbalance power is the Elspot price. However, during hours in which regulating power is used, the price of balancing power does not correlate strongly with Elspot prices, and therefor there is little upside to using this strategy. Looking at the extreme scenarios that happened during 2016 provides an interesting insight to just how unpredictable the balancing power market prices are. The balancing power market experienced a historical price spike on 22.1.2016 during the hour from 6-7 AM, reaching a price of 3000 €/MWh. All upregulating bids made to the BPM for that hour were activated. The Elspot market price for this hour was 42.75 €/MWh, which is not an extraordinary price for that hour and time of year. 4 hours later, the Elspot price was nearly three times what it had been during the balancing power market price spike, while the imbalance prices had dropped to less than 5 % of what it had been, to 134.14 €/MWh. Figure 26 shows the correlation (or lack thereof) of imbalance prices and Elspot prices for 2016.

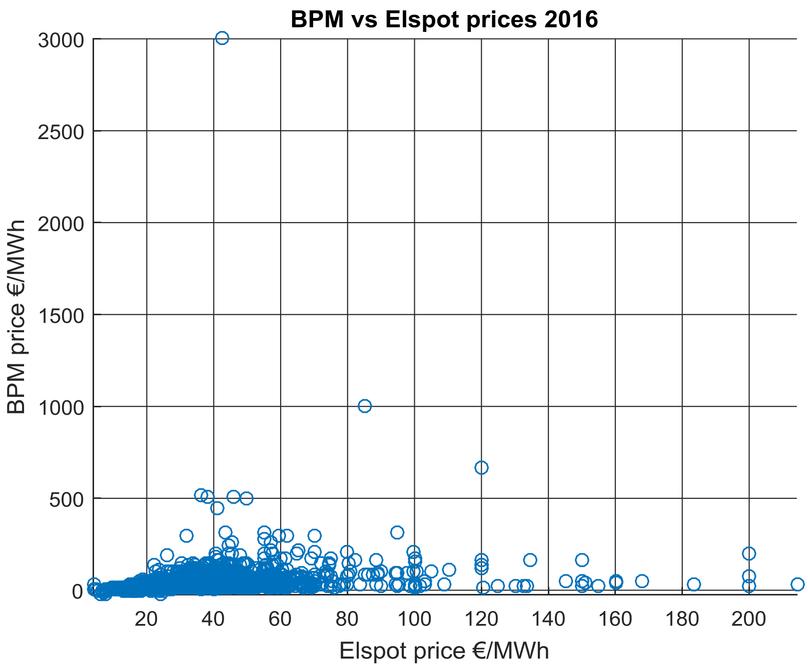


Figure 26
Balancing power market prices and corresponding Elspot market prices for 2016

It seems that other than the fact that both Elspot and imbalance prices are highest during winter periods, it is uncommon for the price spikes to coincide with each other. In fact, during the highest Elspot prices of 2016, peaking at 214.32 €/MWh during 21.1.2016 for the hour from 9-10, the price of buying imbalance power was very low, at just 29.00 €/MWh. Interestingly, only 18.33 MWh of downregulation was activated for the given hour, which indicates the highly sensitive nature of the market. These extreme scenarios serve as a reminder that the factors which dictate price development in the balancing power market are very different to those in the Elspot market.

Overall, there is some benefit to following Elspot prices, as a considerable portion of payback periods occur during hours where there is no regulation, in which case the price of imbalance power is dictated by the Elspot price. Figure 27 shows annual profits using a payback strategy in which the payback hour is chosen based on the lowest Elspot price within the 6 hours following the upregulation hour.

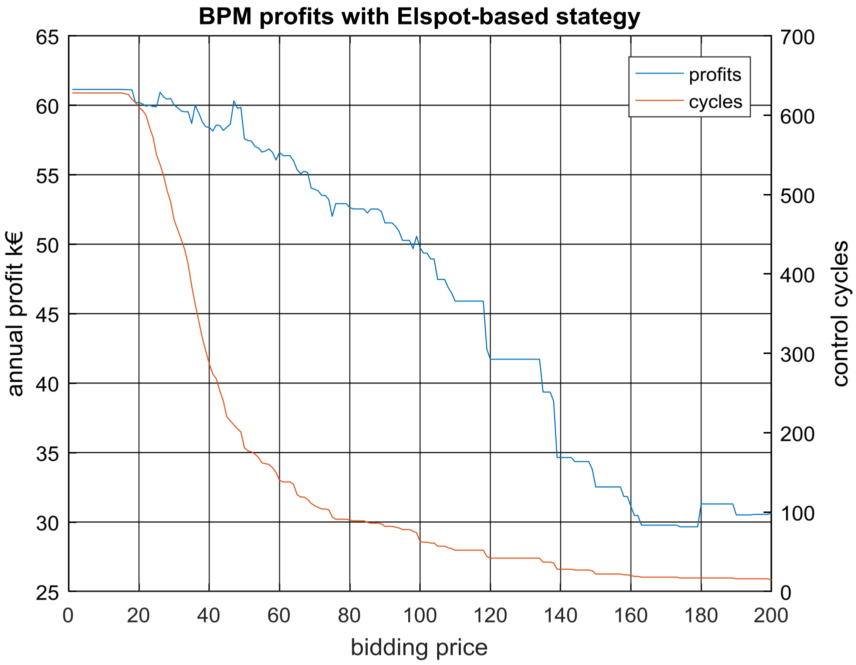


Figure 27
Annual profits through the balancing power market utilizing Elspot-based payback delay

Compared to the profits made with a predetermined payback delay, the increase in profits is moderate, offering at most around 10 k€ more annually. The distribution of delays heavily favours longer delay periods, as can be seen in the figure 28. When considering the drawback of having extended delay periods, it is unlikely this will be seen as the best option for the consumer.

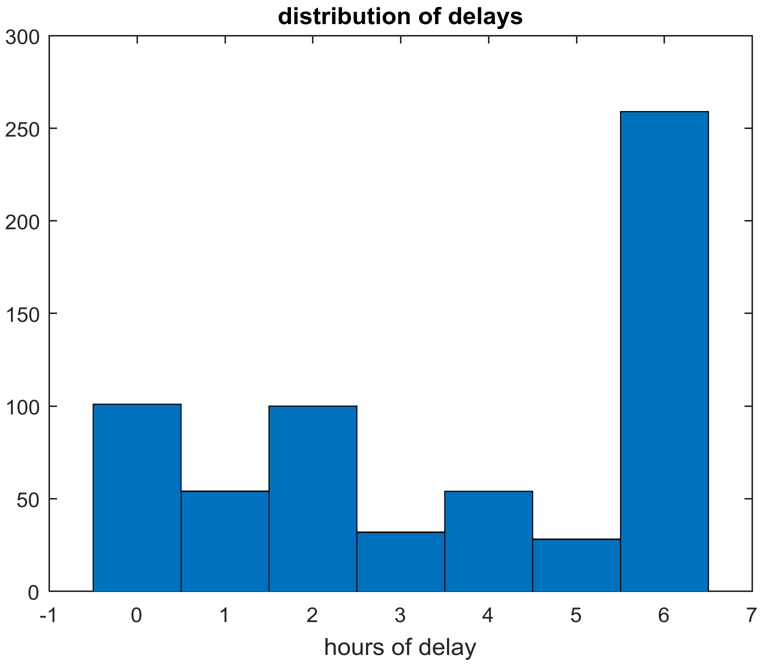


Figure 28
Distribution of payback delay length utilizing Elspot-based payback

Previous research has addressed the challenge of delaying with the payback issue in the BPM. Although it presents a challenge to consumers participating in the market, it is hardly the underlying constraint to attaining substantial income. In fact, simulations utilizing perfect knowledge of price development still fall short of the economic potential of other marketplaces. Annual profits assuming perfect information are shown in figure 29.

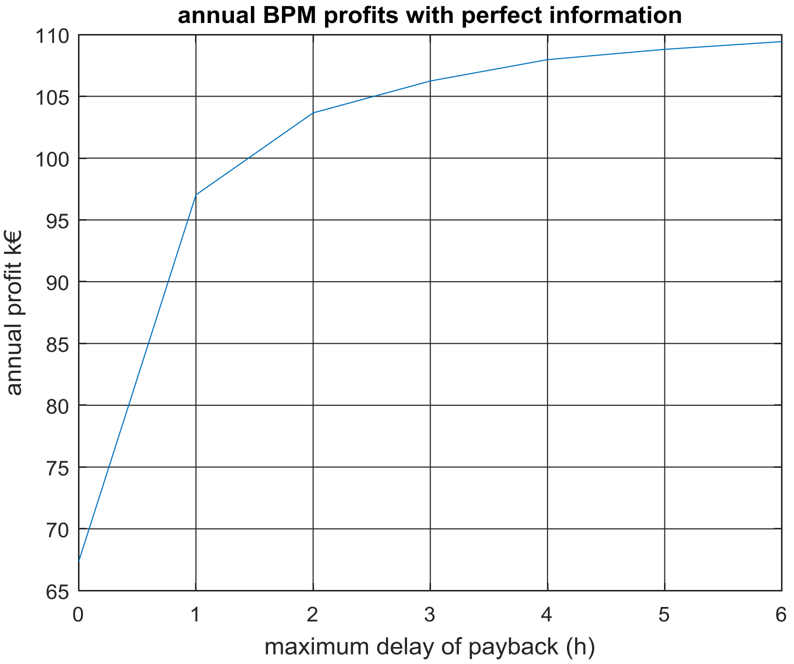


Figure 29
Annual profits through bidding of upregulating to the balancing power market assuming the availability of perfect information for maximum delay periods of 0-6 hours

Due to the random nature of the balancing power market, profit estimations based on perfect information are effectively irrelevant, as market participators have no way of attaining dependable information. However, it does give some insight to the theoretical potential of the market. Simulations were run assuming that market participators would have access to nearly perfect market information, allowing them to choose the control cycles which would yield the maximum profit over the year. The information was merely nearly perfect, as the run time (which of course pays a large part in dictating the compensation) was not known, and therefore assumed to be constant at 0.5 hours, as in previous simulations.

Results show that even if perfect information were available, the annual profits do not compete with other marketplaces. This is in large part due to the fact that the utilization of the upregulation remains low, with upregulation being provided for just a total of 741 hours in 2016.

The fundamental challenges of participating in the balancing power market make it largely unattractive for consumers. Compared to other methods of utilizing control, annual paybacks are modest, while the effect control cycles have on the consumer environment are substantial. These are largely due to the nature of the balancing power market in itself, making them difficult to mitigate through sophisticated market strategies. Future developments in the BPM will likely aim to better facilitate the participation of consumption. However, most consumption partaking in the BPM will likely be consumption that is not mandatory, allowing participation in the market without the major drawback of the uncertainty of imbalance costs and extended periods of energy deficit. Figure 30 shows the annual profit formation from the initial income of the upregulation and cost of payback using a 1 hour delay of payback.

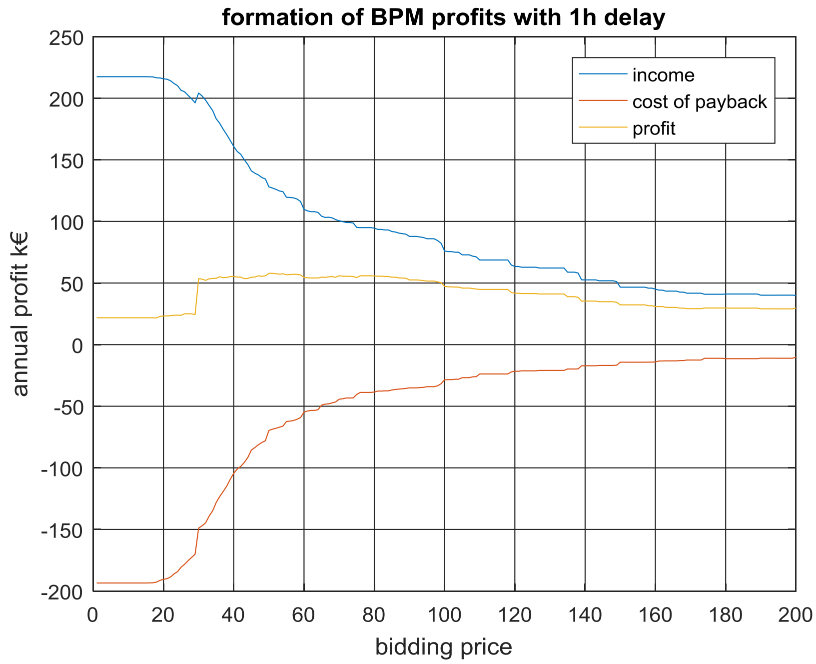


Figure 30
Formation of annual profits (upregulation income – cost of payback) as a function of bidding price using a 1 hour delay of payback

9.4 Elspot Market

In calculating the potential profits attainable through Elspot based load shifting, a constant flexible load of the magnitude of 10 MW was assumed to be in use, as in previous calculations. This load is essentially a buffer, which the consumer is able to add to or decrease from its normal consumption during low market prices, creating a corresponding energy imbalance within the load component of 10 MWh. This energy imbalance is accounted for through the payback process, with the control cycle yielding profit relative to the difference in prices from the hour the excess electricity was consumed to the hour in which consumption was reduced.

Consumers carrying out load shifting are able to do so on their own terms, as the control is not regulated in any mater, and is purely incentivized by the consumers ability to alter their consumption based on the price signals of the Elspot market. As the control required has no technical requirements other than the ability to alter consumption, the impact of Elspot-based load shifting on the consumer is determined by the system energy imbalance caused by the control. In order to properly manage the impact of the system imbalance, consumers are likely to limit the length of control and length of payback delay in order to limit the magnitude of the imbalance as well as the length of imbalance.

The single cycle profit of carrying out load shifting is determined as

$$Single\ cycle\ profit = capacity * \Delta Elspot\ price \tag{5}$$

If consumption is initially decreased, $\Delta Elspot\ price$ is determined as

$$\Delta Elspot\ price = \ Elspot\ price_t - Elspot\ price_{t+1+payback\ delay} \tag{6}$$

Alternatively, consumption can be initially decreased, in which case $\Delta Elspot\ price$ is determined as

$$\Delta Elspot\ price = \ -Elspot\ price_t + Elspot\ price_{t+1+payback\ delay} \tag{7}$$

The overall profit over an extended period does not depend on whether consumption in initially decreased of increased, but this has a significant impact on the imbalance caused. Naturally, carrying out the consumption increase initially will cause an energy surplus in the energy system, which may be favourable to the consumer. Additionally, payback periods were found to be shorter if consumption was initially increased, as the time required for prices to increase to a local maximum from a local minimum is shorter than the time required for prices to drop from a local maximum to a local minimum.

Using 2016 prices, a maximum theoretical profit of 119 k€ was found for the 10 MW flexible load. A total of 1291 control cycles were required to reach this profit. When considering the most likely market strategy, there are certain constraints which are likely to cause consumers to choose a different strategy to the maximum profit strategy. A weakness of maximizing annual profits is that this strategy utilizes even the slightest variations in Elspot prices, often leading to rather insignificant increases in profits. This is illustrated in the figure 31, which shows the profit curve of singular control cycles.

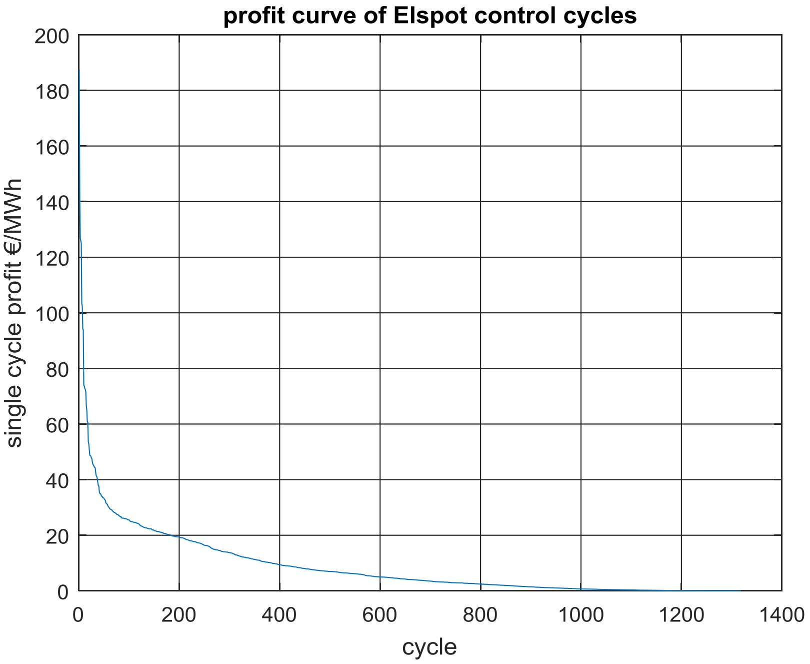


Figure 31
Profit curve of Elspot-based load shift cycles for maximum profits

The control profit curve shows that a small number of control cycles provide substantial profits, while the majority of control cycles provide only a marginal profit increase. For the control strategy providing maximum profits, only 166 of the 1291 control cycles are require to attain half of the total annual profits. As consumers are likely to aim to restrict the number of control cycles carried out, a constraint may be introduced which sets a requirement to the profit increase provided by a single control cycle. This constraint cannot however be introduced on its own, as it affects the nature of the control cycles, mainly the length of delay periods between load shifts. The histogram below shows delay periods required for the maximum profit case, with a delay period of 0 meaning that the load is shifted form one hour to the following hour.

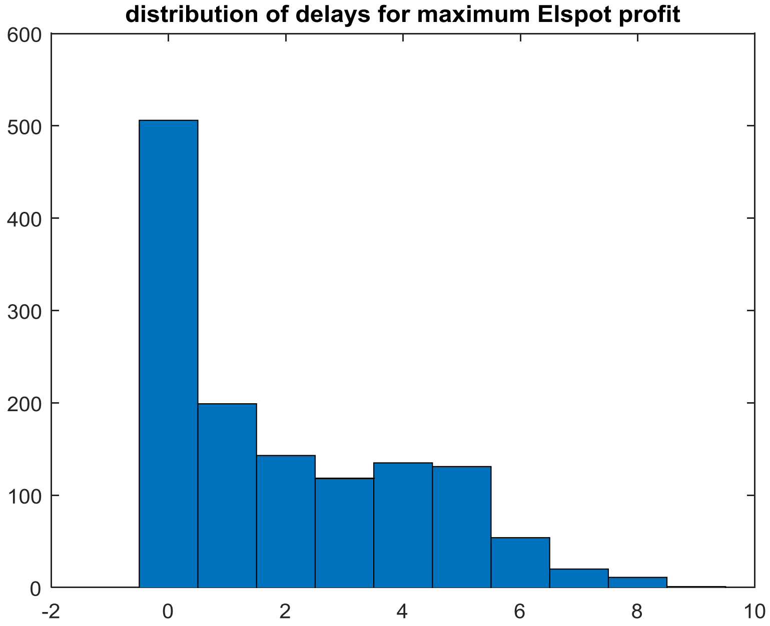


Figure 32
Distribution of payback delay length in Elspot market for maximum profit

The distribution of delays displayed in figure 32 is quite favourable, as the majority of delays are less than 6 hours, and do not exceed 9 hours at any point. Thanks to the availability of perfect information, the control cycles can be sequenced in a way that crates an energy surplus in the control environment, rather than an energy deficit. This is often favourable to consumers, as it does not limit the functionality of a thermal load. However, as discussed earlier, an energy surplus entails greater heat transfer losses, and the delay period must be constrained to mitigate this effect.

Based on these factors, profits were calculated using a more viable market strategy, in which a minimum cycle profit constraint was introduced as well as a maximum delay constraint, ensuring that the losses caused by the delay periods are limited. Figure 33 shows annual profits as well as the number of control cycles required to gain these profits using minimum control profits of 0 to 20 €/MWh. The maximum delay period was set to 12 hours.

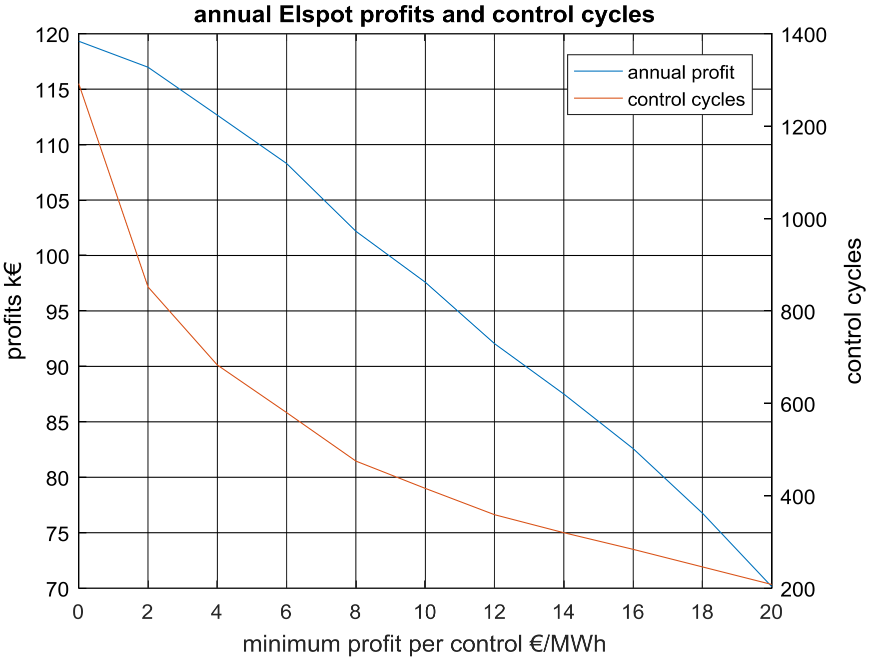


Figure 33
Annual profit through Elspot-based load shifting as a function of single cycle minimum profit

The number of control cycles decreases rapidly as the minimum control profit is increased, while the effect on profits a far less substantial. Comparing results using a 10 €/MWh minimum to a 0 €/MWh minimum, we see that the profits decrease by 19 %, while the number of control cycles required drops by 68 %. The number of required control cycles in this case was 416. If we assume that under normal operation the consumption would be carried out as a constant load, the load shifting would reduce the energy cost of electricity by 9.7 %. The relative overall savings would be only roughly a third of this, as the payments made for transmission and taxes, which make up roughly two thirds of the final electricity bill of consumers, are based on overall consumption and would therefore not decrease as a results of the load shifting under current regulation.

While the limitation of control cycles encourages implementing a minimum cycle profit constraint, this would have an impact on the length of delay periods. Figure 34 shows the distribution of delay periods resulting from a minimum cycle profit of 10 €/MWh and figure 35 shows the corresponding distribution using a 20 €/MWh minimum single cycle profit.

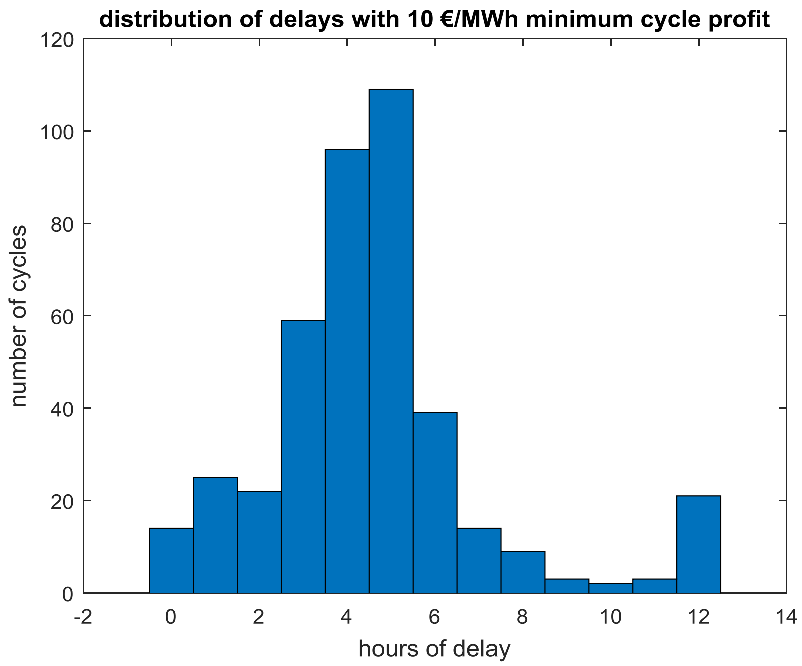


Figure 34
Distribution of payback delay length utilizing 10 €/MWh minimum single cycle profit

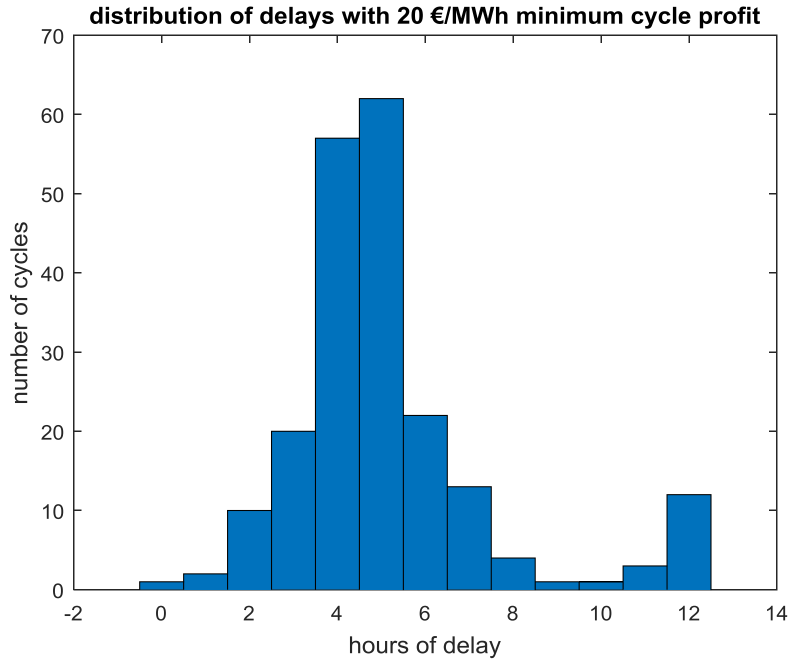


Figure 35
Distribution of payback delay length utilizing 20 €/MWh minimum single cycle profit

Although the average delay period increases slightly as the minimum single cycle profit is increased, this cannot directly be considered an inconvenience. Comparing the 10 €/MWh distribution to the distribution in which no single cycle profit constraint was used we see that although the 10 €/MWh market strategy is more likely to require delay periods of 3-6 hours, the total number of cycles requiring these delay periods is in fact less than in the 0 €/MWh case. The distributions show that increasing the minimum cycle profit does not in fact cause an increase in delay periods, but rather cuts down on the number of short cycles, which causes the increase in average delay periods. This favours consumers unable to maintain energy deviation for extended periods of time, as a 6 h payback delay is sufficient for carrying out most control cycles regardless of the minimum cycle profit constraint.

9.5 Combining multiple markets

FCR-N is by far the most profitable market for consumers to utilize flexible consumption loads. However, due to the stringent demands it sets for the control capability, the majority of flexible loads are unlikely to be qualified for FCR-N markets. Participation in FCR-D and the balancing power market as well as Elspot-based control are less demanding from the consumers point of view, and a large capacity of loads are likely to be eligible to participate in all of these markets. As the markets are not strictly contradictory, it is possible for consumers to concurrently participate in all 3. In practice this would mean that consumers would initially bid the available capacity to the FCR-D markets, for which the profit per control cycle is high. Consumers receive verification of the bid activations for a given market day the preceding evening, after which the hours that are not designated to FCR-D can be utilized for Elspot based control. The market hours in which the flexible load is not being utilized in either of these markets (including the payback periods), flexible capacity can be offered to the balancing power market.

The market strategy used for Elspot based controls utilized a minimum control profit of 10 €/MWh and maximum payback delay of 12 hours. The market strategy for the balancing power market was to bid capacity at 50 €/MWh and have a uniform delay of 1 hour before the payback hour. The breakdown of profits from each of these markets and be seen in figure 36.

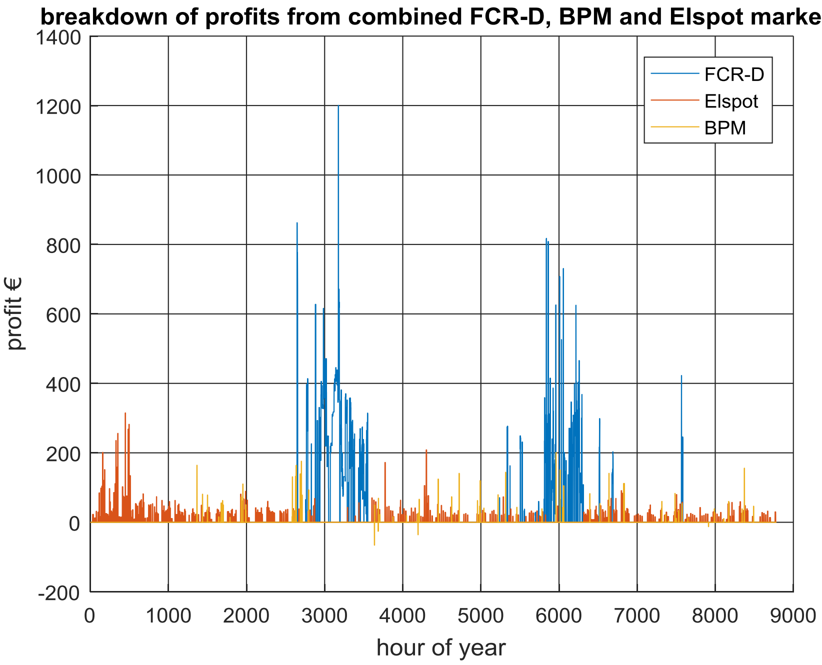


Figure 36
Hourly profits through combined participation in FCR-D, Elspot and balancing power market

	Profits k€	**Cycles N**	**Total hours h**
FCR-D	221	850	850
Elspot	84	356	2133
BPM	14	80	240
total	**319**	**1286**	**3223**

Table 13
Composition of annual profits through combined participation in FCR-D, Elspot and balancing power market

The combination of multiple markets provides substantial profits. Because the capacity is initially offered to the FCR-D market, the profit potential for FCR-D is fully utilized. As the utilization factor for the FCR-D hourly market is small, less than 10 %, the capacity was available for use in the Elspot market for the majority of the year, resulting in considerable profits. The profits accumulated through Elspot markets increase annual profits by 38 %. Elspot based control cycles required an average of 6 hours for the initial downregulation delay of payback and payback hour. The lengthiness of Elspot-based load shifting significantly limits the possibility of providing upregulation power to the balancing power market. Over the course of the year, upregulation was provided for a total of 80 hours, accounting for a profit increase of 14 k€. This is equivalent to a 6 % increase compared to participating solely in the FCR-D market. In total, profits from the combine market participation are 319 k€, 44 % more than the FCR-D only case. This falls below the current profitability of the FCR-D yearly market, which indicates the lack of initiative provided to consumers to participate in both the Elspot market and balancing power market.

10 Impact of market participation

This section aims to provide an assessment of the benefit achieved through the participation of consumers in the discussed markets. The desired impact of integrating consumption as market operators is to increase the economic and technical efficiency of the electricity sector. Evaluating these benefits is a difficult task, as the operation of the electricity system is highly multi- dimensional and subject to changes based on a multitude of factors. Analysis based on current market structures and prices may lose relevance as these markets are developed. However, the provided analysis aims to provide insight to the factors that currently impact the technical effectiveness of consumption-based control, as well as assess the potential magnitude of economic benefits.

10.1 Frequency Containment Reserves

The system benefit of utilizing consumption in FCR markets is mainly financial. As reserve capacities are predetermined on a national level, introducing additional capacity does not increase the amount of reserves in use. Instead, adding new sources of FCR would substitute the more expensive FCR units currently in use. The impact of additional capacity depends on the difference in functionality (reliability) as well as cost compared to the sources it would replace. If we assume that DSM-based reserves maintain the same reliability as the component they are substituting, the benefit is purely financial. Annually the procurement of FCR-N has come at a cost 18-28 M€, or 0.22-0.33 €/MWh, and the FCR-D procurement has entailed costs of 10-14 M€, or 0.12-0.16 €/MWh. Introducing consumption to the FCR markets at low market prices can decrease the cost of FCR procurements, and cut back on balance service and grid service costs, which are used to finance the procurement of reserves. This will cause a marginal decrease on the price of electricity to consumers. Although the realized decrease is somewhat insignificant, the price volatility of FCR markets can be considered a notable risk, especially considering future developments of the market structure, and mitigating this risk can consequently be seen as a valuable service. (Fingrid g)

When it comes to the procurement of FCR, Finland is highly dependent on the availability of reserves through external links. In 2013, Russia/Estonia, Sweden, and Norway accounted for 22 %, 22 %, and 8 % respectively of the total procurements of FCR-N, accounting for a combined 52 % of the overall payments made. In the procurement of FCR-D for 2013, Sweden received 29 % of the total funds used, and Norway received 5 %. (Fingrid i) Consumers provide a domestic resource for both FCR-N and FCR-D, which would increase the self-sufficiency of the Finnish electricity sector.

10.2 Balancing Power Market

When consumption loads offer upregulating power to the balancing power market, they provide a valuable service in reducing the power imbalance during the operation hour. However, as the consumption system ultimately requires the provided electricity to be consumed, the component unit does not effectively offer upregulating power, but rather transfers the demand for upregulation to a later period, operating under the assumption that the value of upregulating power during the initial control hour is greater than during the payback hour. Ultimately the value of the provided control is therefore not guaranteed through the palpable value provided during the operation hour, but is instead determined by the value provided in postponing upregulation from the hour in which the consumer provides upregulation to the hour in which it carries out the energy payback.

In the best case scenario, the payback hour occurs during a downregulating hour, in which case the payback would effectively be beneficial to the overall state of the market. If the payback hour requires neither up-or downregulating power, the payback can be considered to have a negligible effect on the market. However, if the payback occurs during another upregulation hour, it is questionable whether the provided control was of value. In the worst case, the price of upregulation during the payback hour is greater than during the initial upregulation, leading to a financial loss on behalf of the consumer while also incurring additional strain on the balancing power market. It should also be considered that the added demand for upregulation during the payback hour by the market operator should be taken into account, although due to the difficulty of simulating balancing power market prices this is not accounted for in this paper.

The fact that the participation in the balancing power market is profitable entails that the provided service is in fact of value, $E[price\ of\ upregulation] > E[cost\ of\ imbalance]$. However, the somewhat minimal profit potential raises question over just how much is achieved through postponing the upregulation demand. In order to provide further insight to this subject, the state of the balancing power market was observed for the potential payback hours. Results for 2016 are shown in figure 38.

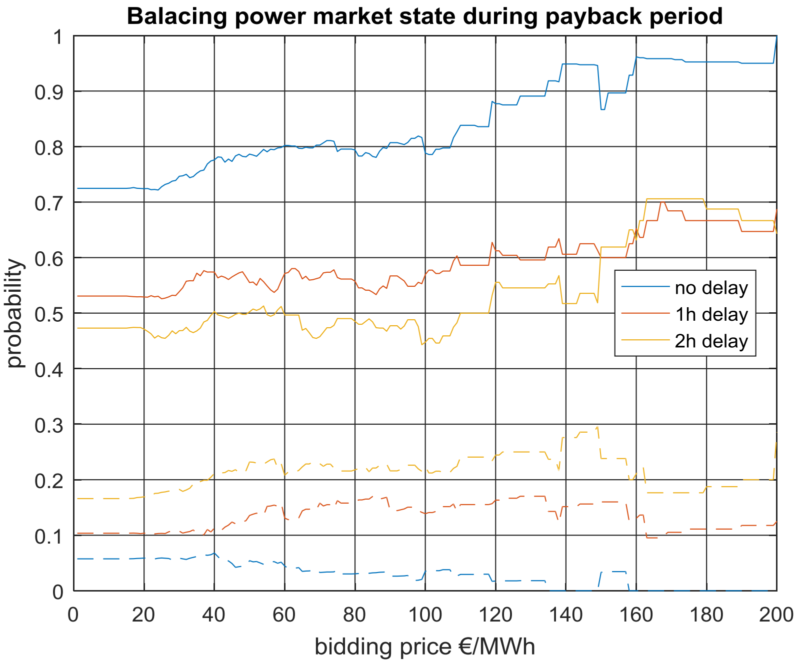


Figure 37
Probability of payback hour occurring during an upregulating market hour (solid line) and downregulating hour (dashed line)

The solid lines represent the probability of the payback occurring during an upregulating hour and the dashed lines represent the probability of the payback occurring during a downregulating hour. When payback hours are not delayed, the probability of the market experiencing an upregulating hour during payback is over 70 % for all bidding prices, indicating that upregulation periods primarily last for multiple hours. Delaying payback by one or two hours leads to a considerable drop in the probability of the payback occurring during an upregulating hour, and the probability of the payback occurring during a downregulating hour becomes substantial. The probabilities show that if payback is not delayed, it is unlikely the provided control is beneficial, whereas slightly longer periods of delay are much more probable to prove to be valuable.

The worst case scenario for consumers acting in the Elspot market is for the cost of payback to be more expensive than the income received for provided upregulation. This is problematic for the market participator, leading to financial losses, while also causing additional strain on the balancing power market, as the provided control ultimately leads to increasing the difficulty of providing balancing power. In figure 39 the probability of a single control cycle being unprofitable is shown for the delay periods of 0, 1 and 2 hours.

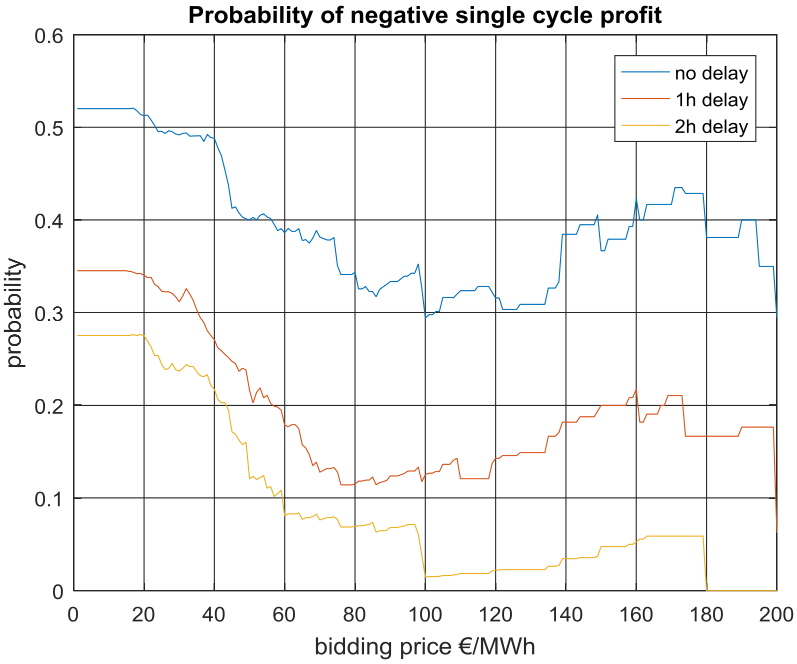


Figure 38
Probability of single cycle being unprofitable (payback cost > upregulating compensation)

A considerable share of cycles are ultimately disadvantageous when carried out without the delay of payback. Even when payback periods are delayed by one or two hours, the likelihood of a control cycle being unprofitable remains a significant risk unless the bidding price is high. Based on 2016 market values, the risk of unprofitable control cycles would be largely avoided by using a two hour delay of payback periods at a bidding price of at least 100 €/MWh. Under these constraints, the likelihood of control cycles entailing losses is less than 6 %, while the likelihood for the best case scenario in which the payback period occurs during a downregulating hour is over 18 %.

Overall, operation in the balancing power market is clearly prone to the risk of provided control entailing less provided benefit than the hindrance caused by the payback. Based on the results shown here, it is arguable that the service provided by consumers in the balancing power market in postponing upregulating demand is unlikely to provide a sustainable valuable service, and under the assumptions made in the framework of this paper, consumers are unlikely to succeed in the current balancing power market when obligated to carry out the energy payback.

10.3 Elspot Market

Unlike the previously discussed markets, Elspot-based control does not necessarily require active participation in the Elspot market. Instead, consumers have the possibility to use an Elspot-based contract, and autonomously consume electricity in a manner that yields the best economic savings. As the amount of electricity procured though the Elspot market is massive, the effect of singular consumers does not have an effect on the market. However, as demand-side management becomes more accessible and gains popularity, these effects may have substantial impacts on the Elspot market.

Consumers participating in the Elspot market-based DSM do so in order to gain a financial benefit, and base their actions solely on the state of the market. By definition, the impact of Elspot-based load shifting is decreased consumption during hours in which the price of electricity is high, and the subsequent increase of consumption during hours in which the price of electricity is low. This in itself can be seen as a valuable service. However, this benefit is not always as trivial as it may seem, and this section aims to provide a more detailed analysis of how the participation in Elspot-based demand-side management may affect the demand curve on a national level.

The nature of consumption loads considered in this paper are typically part of the base consumption load, as thermal loads are effectively used constantly in order to maintain cooling or heating. The amount of capacity available for load shifting was set as 5 % of the daily base load, with the base load being approximated as the daily minimum load. This is a large quantity of capacity, ranging from 218 to 647 MW, with an average of 418 MW. Although these values will likely not be met for some time, they provide a substantial enough impact on the system for proper analysis. The effect control cycles would have on the demand load were calculated by calculating hourly averages for demand with and without the demand-side management.

The criteria set by the consumer have a sizable effect on the impact of DSM control on the demand curve, and are subject to review when assessing these impacts. Results were calculated using a market strategy incorporating a 10 MW/h minimum cycle profit and maximum 12 hour delay period. Hourly national consumption averages are shown in figure 40.

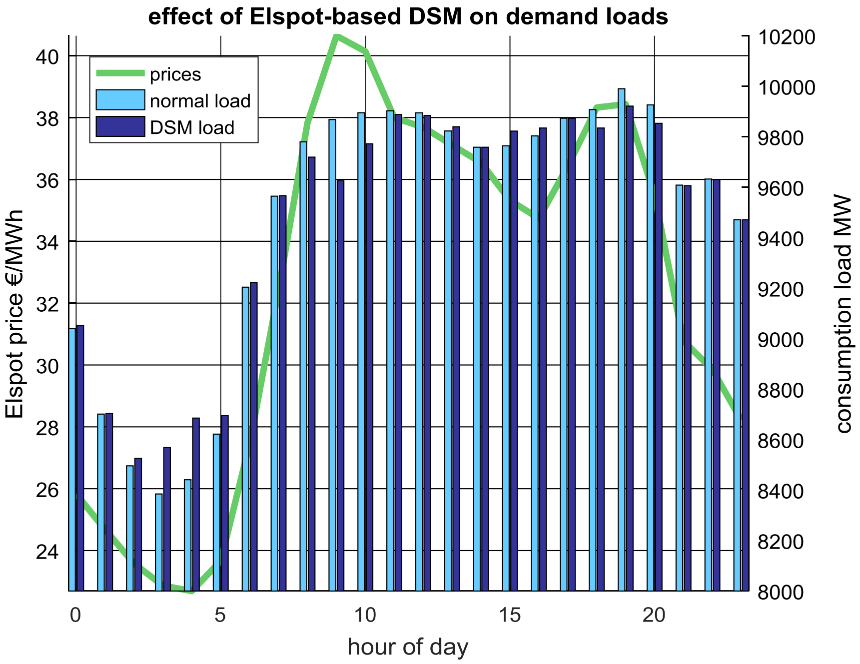


Figure 37
Annual averages for hourly electricity demand with and without Elspot-based load shifting utilizing minimum 10 €MWh single cycle profit

The effect of DSM is quite significant during night hours, primarily the hours form 3-4 and 4-5, for which the DSM load is considerably higher than normal, as well as for morning peak hours, primarily the hours from 9 -10 an 10-11, in which the DSM loads are substantially lower than normal. This is to be expected, as these periods often experience the daily maximum and minimum prices. On average, there is a nearly 18 €/MWh difference in the price from the market hour 4-5 to the market hour 9-10. A less significant shift in loads can be seen in the afternoon peak, with the hours from 15-17 receiving slightly larger demand loads than normal from the DSM, and the hours 18-20 experiencing slightly smaller demand.

In order to assess the effectiveness of the DSM, it is necessary to define the desired impact. One of the primary desired impacts is a decrease in peak loads. In some sense, the simulated DSM effect can be seen as positive, as many of the peak demand hours experience smaller loads on average, while hours of low demand, during which ample capacity is likely to be available, experience higher demand. However, the average peak load is not significantly affected, dropping from 9.99 GW to 9.92 GW. This is largely due to the fact that while the peak demand typically spans for a period of 2-4 hours, the DSM will only affect one of these hours. In light of receiving maximum payment for load shifting, consumers have no incentive to spread out the up-and downregulation of consumption, but are rather inclined to fully commit to the singular hours which yield the highest margin.

This is evident in figure 39. While the hour from 9-10 typically experiences the same amount of demand as the hour from 12-13, the load is far more likely to be shifted away from the hour from 9-10, as prices are considerably higher for this period. This results in a considerable drop in demand for the hour from 9-10, while the demand for the hour from 12-13 is largely unaffected. This ultimately means that although sections of the peak demand are cut down, the overall effect on the peak demand is small.

Although Elspot prices depend strongly on the overall demand, the merit order effect, which entails that prices increase more aggressively as demand is increased, may lead to scenarios in which relatively insignificant development in demand may cause drastic developments in the Elspot price. These exaggerated price signals may lead to undesired load shifting. An example of this can be seen on 8.1.2016 illustrated in figure 41, during which the electricity demand was very high throughout the day, ranging from 1290 MW to 1530 MW.

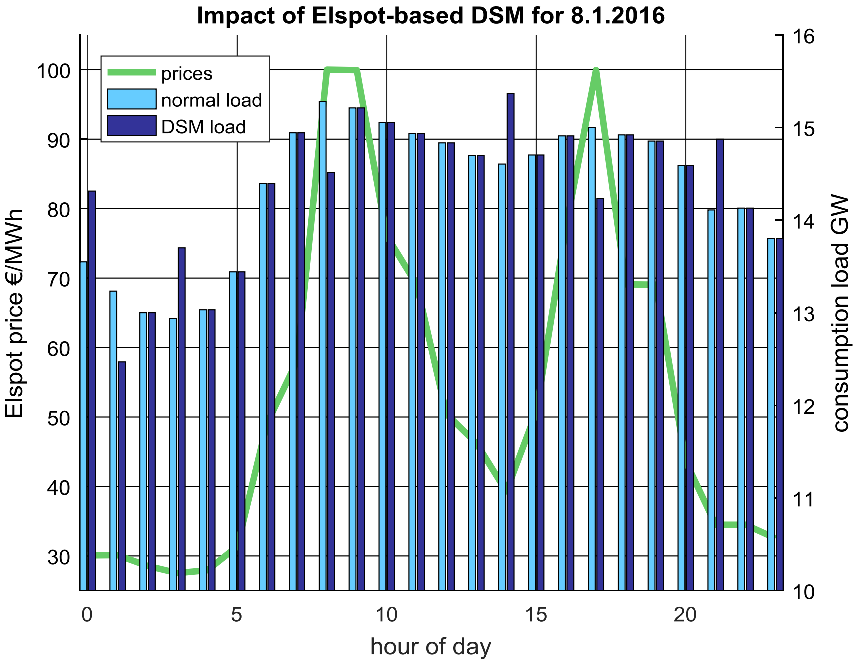


Figure 38
Hourly electricity demand with and without Elspot-based load shifting utilizing minimum 10 €MWh single cycle profit for 8.1.2016

Although the increase in consumption loads between the market hour for 14-15 and the market hour from 18-19 is almost negligible, at just 2.7 %, the difference in prices is quite massive, exceeding 150 %. Consumers inclined to utilize load shifting base on Elspot prices would naturally use this price difference to their advantage, causing an increase in demand in the hour from 14-15. An increase in demand equal to 5 % of the base load during this hour would result in a demand higher than the peak consumption for the entire year of 2016, a result which can hardly be considered as desirable. Figure 40 also illustrates the dilemma of consumers being encouraged to designate their available capacity to singular price peak hours, rather than distribute the control over the span of the peak and low demand periods, which are considerably longer than the peak periods experienced in market price.

It is important to note that certain factors such as the wind power production and cross-border transmission capacities can cause large variations in price without changes in demand. However, for the 8.1.2016 case, the availability of imported capacity as well as the availability of wind power were virtually identical for the hours in question.

The underlying dilemma is that the price difference between potential load shifting hours does not reflect the difference in consumption between the two hours. In this sense, the price difference between two hours does not portray the magnitude of load shifting demand. The price curve of electricity becomes increasingly steep as demand increases, and at high demands seemingly marginal differences in demand may often cause drastic price changes, a result of the merit order effect. When the overall demand of electricity is high, minor differences in demand may entail major price differences. If a large share of consumer loads are shifted based on Elspot prices, radical price increases may be misunderstood as a high demand for load shifting, although this is not always the case, leading to cases in which the supply for load shifting is based on the perceived demand, which is high, when in reality it may be very small. This misinterpretation poses the risk for overcompensating for the demand difference, which would cause additional strain to electricity generators rather than alleviating it. The negative correlation between the value of load shifting and the conceptual demand for load shifting does not directly cause a problem if the capacity of load shifting consumers is small. However, if substantial quantities of consumption loads are implemented, the risk of overreacting to price signals may become significant.

10.3.1 Impact on demand fluctuation

Based on the results shown above, although load shifting may indeed lead to a decrease in peak hour consumption, it may often lead to abrupt changes in the demand curve. When considering the generation of electricity, this volatility is problematic, as it entails the ramping up and down of power generation. In light of this fact, it is reasonable to favour demand curves with less volatility. The nature of Elspot based DSM does not support this goal, due to the fact that consumers are likely to shift consumption from one specific hour to another, resulting in irregular fluctuations in the demand curve.

To illustrate the rate of changes in the demand load, a differential value was calculated to indicate the average change in demand between consecutive hours. Results are shown in figure 42. The value used to determine the smoothness of the demand curve was calculated using the formula below.

$$\overline{d\imath ff} = \frac{1}{N-1}\sum_{1=2}^{N}|C_i - C_{i-1}| \qquad (8)$$

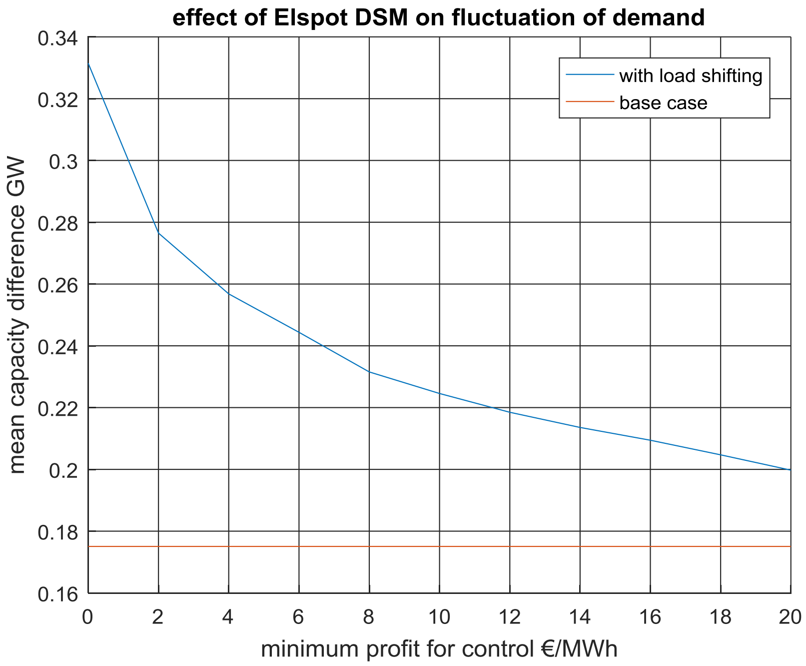


Figure 39
Mean differential of consecutive electricity demand as a function of minimum single cycle profit utilized in Elspot-based load shifting for 2016

When flexible consumer react to low price variations, the increase in demand fluctuation is substantial, with the mean demand differential between consecutive hours increasing from 175 MW to 330 MW. The fluctuation of demand decreases as load shifting is reserved for period with higher price differences. However, as discussed previously, the price differences do not correlate with the capacity differences, and load shifting entails the risk of overcompensating for the capacity differences even at high price differences. An additional factor accounting for the large fluctuation of demand curves due to load shifting is the concentration of load shifts to short periods, in this case 1 hour. As prices overemphasize differences in demand, hours of minimum and maximum prices are likely to have similar demand as the hours directly preceding and following these hours, and substantially increasing or decreasing demand for one of the given hours leads to increases in fluctuation.

10.3.2 Impact on balancing power market

One of the most crucial factors in a well-functioning electricity system is that ability to accurately forecast both demand and generation, enabling electricity producers to prepare available production capacity. If consumers are inclined to deviate from their normal consumption patterns, accounting for these deviations may cause additional challenges for balance responsible parties in accurately accruing electricity. The difficulty of taking into account the effect Elspot prices may have on demand is increased by the fact that accounting for the presumed load shifts has an effect on the realized prices of the market, which ultimately dictate the load shifting. This recursive interaction may be difficult for market operators to forecast, especially when consumers may base their load shifting on a variety of different strategies.

The impact of failing to account for the impact of load shifting on demand curves is difficult to gauge. However, certain expectations can be made as to how this may affect the imbalances of balance settlements and more importantly the consequences of the imbalances on the balancing power market.

If the capacity of load shifting is assumed to be marginal, the impact of imbalances on the market party are likely to be small, as they would receive downregulating power during the low-price periods at prices close to the low Elspot price of that hour, and correspondingly be able to sell upregulating power during peak prices, receiving compensation often close to the high Elspot price of that hour. This would results in an income for the market party, as the value of the sold upregulating power is higher than the downregulating power procured. The overall cost to the market party is determined by the difference between the amount of income lost due to the consumer load shifting and the income received through the resulting imbalances.

However, prices in the balancing power market are sensitive to considerable changes even at low capacities. If a low price hour were to experience consumption well above the forecasted amount, the demand for imbalance power would increase substantially, which may lead to high prices for imbalance power. Likewise an unexpected decrease in consumption for peak price hours would lead to substantial amount of surplus capacity. As it is unlikely that there would be a corresponding demand for upregulation, the value of the upregulation would decrease considerably.

As the magnitude of the Elspot market far exceeds the capacity of the balancing power market, systematic deviations in consumption caused by consumers reacting to the Elspot prices may lead to extensive increases in demand in the balancing power market. These deviations present a risk to the economic operation of the balance responsible party, and may cause further strain to electricity generators, as additional flexibility is required to account for the increase in forecast errors caused by load shifting.

For these reasons it is imperative for BRPs to play an active role in the load shifting of the consumers they are responsible for, ensuring that the effect of load shifting does not cause a burden on the balancing power market. This requires BRPs to develop methods of accurately aggregating and determining the effect load shifting, a feat best achieved by actively participating in the operation of the demand-side management.

11 Conclusions

In this thesis the potential for consumers to utilize flexible consumption in the currently available marketplaces has been reviewed. The main objective of the research carried out was to determine whether current market structures provide the means to fulfil the targets set for demand-side management as a productive component in the energy system of Finland. The research method consisted of a market review based on actual market data from 2016 for the frequency containment reserves for normal operation, frequency containment reserves, balancing power market and Elspot market. The analysis aimed to determine the market potential of these respective markets, optimal market strategies, as well as analysis on various constraints that effect the results. By comparing the impacts involvement in these markets would have on the energy system, the effectiveness of the market strategies was assessed.

From the consumers point of view, FCR-N markets provide the best possible profit potential, ranging from 70 to 280 k€/MW annually. This market is technically demanding, and therefore only attainable for a restricted share of flexible loads. FCR-D markets provide attractive profit potential, ranging from 25-170 k€/MW annually. Although the market requires very fast activation, it is a potential marketplace for large shares of consumption. The effectiveness of FCR-markets is secured through their functionality, which is to directly manage the control of consumption to be beneficial to the stability of the grid. Additional participation of consumers in the FCR-N and FCR-D markets is likely to cut down on the cost of procuring reserves, while also reducing the volatility of the hourly market and increasing the self-sufficiency of providing reserves.

The balancing power market offers modest profit potential, around 3-6 k€/MW. By participating in the balancing power market, consumers aim to improve the availability of upregulating power, and thereby compensate for energy imbalances. A consumer’s ability to succeed in this task is subject to scrutiny, as the unpredictability of the state of the market leads to considerable uncertainty in terms of the benefit provided by control cycles. Consumers bound by the payback requirement are likely to struggle in providing a sustainable service through the balancing power market, and due to the high risk aversion required in managing the impacts of the payback effect, consumption based upregulation is unlikely to be utilized regularly.

Elspot-based control offers a somewhat attractive profit margin, ranging from 10-12 k€/MW. By performing Elspot-based load shifting, consumers can potentially decrease peak loads. This paper has highlighted various factors that may hinder the effectiveness of these controls. In order for the potential Elspot-based load shifting to be reached, market mechanisms must be developed that incentivize market strategies that are in line with the desired impacts. Current market structures may lead to undesired load profiles as well as increase the demand for balancing power, as the accuracy of demand forecasts is decreased. In order to sustainably incorporate load shifting without entailing risks to BRPs, more sophisticated management of load shifting is required, capable of adequately taking into account the effect of demand-side management in Elspot-trading.

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