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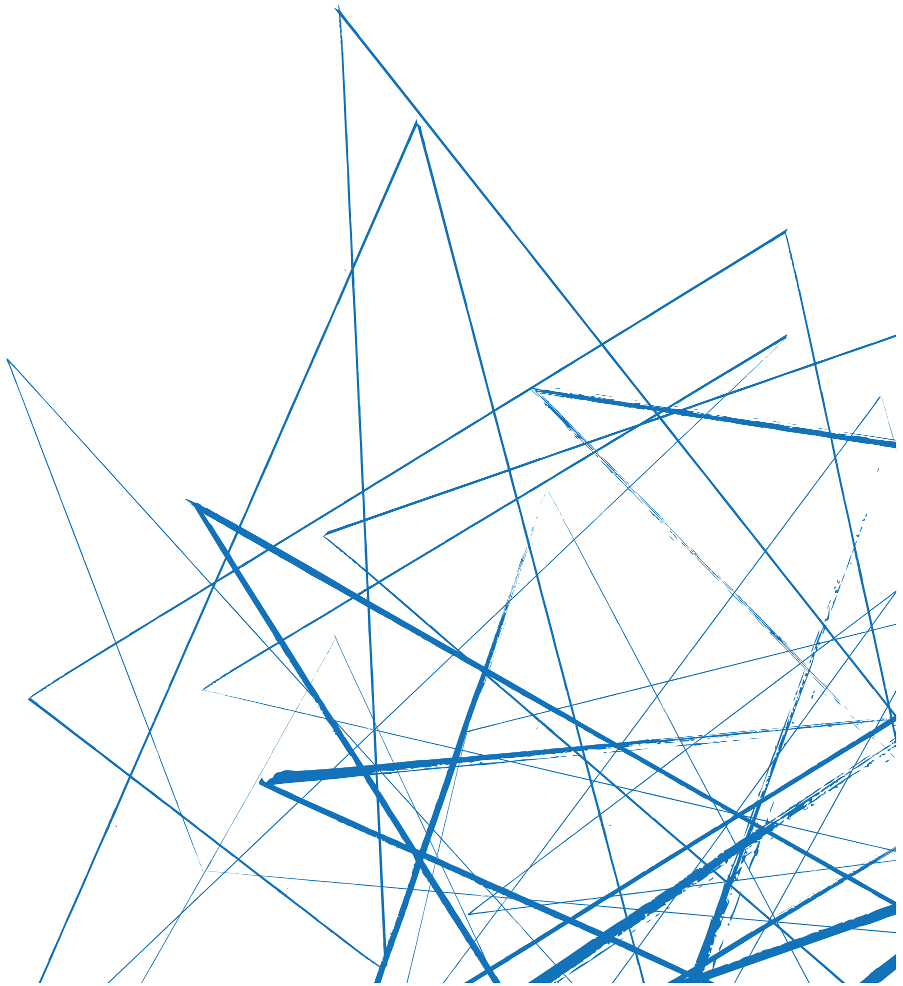
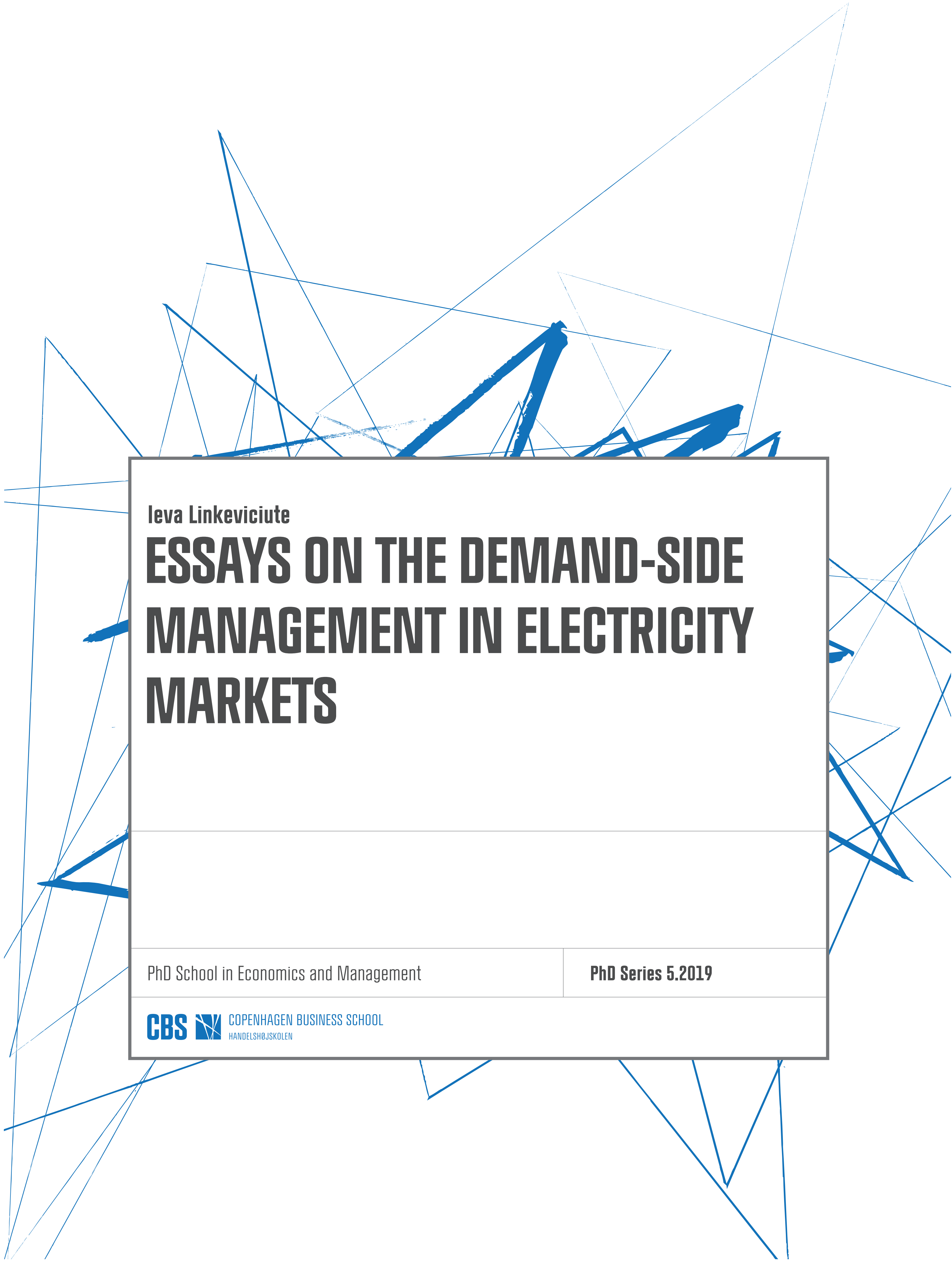


ESSAYS ON THE DEMAND-SIDE MANAGEMENT IN ELECTRICITY MARKETS

PhD Series 5-2019



Ieva Linkeviciute

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Essays on the Demand-Side Management in Electricity Markets

Ieva Linkeviciute

Supervisor: Cédric Schneider

PhD School in Economics and Management
Copenhagen Business School

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The PhD School in Economics and Management is an active national and international research environment at CBS for research degree students who deal with economics and management at business, industry and country level in a theoretical and empirical manner.

Preface

This thesis is the result of my work as a Ph.D. Fellow at the Department of Economics at Copenhagen Business School. I am grateful for the funding I received through a research project '5s' – Future Electricity Markets, supported by the Danish Strategic Research Council (DSF), and for other financial support of the department that allowed me to complete my doctoral studies.

I would like to thank several people who have supported me in the last few years. First and foremost, I wish to express my gratitude to my primary supervisor Cédric Schneider for all his help, advice and encouragement throughout my studies. I would also like to thank my secondary supervisor Peter Bogetoft for his valuable comments and for organising my stay at the Center for Operations Research and Econometrics (CORE) at the Université catholique de Louvain in Belgium. I am equally grateful to my first supervisor Peter Møllgaard who gave me the opportunity to join the project '5s' and the Department of Economics and helped me get on track during the first few months of my Ph.D.

I would like to thank my co-author Per Joakim Agrell for our collaboration and a warm welcome to the CORE center. I am very grateful for the useful comments I received from Anette Boom and Pierre Pinson during my closing seminar. I also thank all the members of the Department of Economics and the members of the CORE center for their feedback during the Brown Bag seminars.

Finally, I am especially thankful to my mother, father and brother for always supporting and believing in me, friends, for making these years much more cheerful, Kamile, for our friendship and encouraging words, and Benjamin, for being there for me.

Summary (English)

This Ph.D. thesis focuses on the demand-side management in electricity markets and a new player in the market – an aggregator of flexible demand. The thesis consists of three independent chapters investigating the entrance of this new player in the power markets from different angles: focusing on the aggregator, a large power consumer and a producer.

The first chapter, “Aggregation of demand-side flexibility in electricity markets: the effects of portfolio choice”, analyses the performance of the aggregator depending on its portfolio choice. I have investigated several portfolios of different flexibility sources: electrical vehicles, heat pumps and/or home appliances like washing machines, dryers and dish washers. I have used Nord Pool power market data for Denmark’s bidding area DK2 to identify the effects of the portfolio choice on the imbalance payments and compensations to consumers that provide flexibility. The results show that different compositions of flexibility sources lead to different imbalance payments and compensations to consumers. However, there is no significant additional value of having an access to all types of flexibility sources unless there is a fixed contract cost. This suggests that the aggregator would choose to specialise in certain types of flexibility sources. Also, I find that the incentives for consumers to participate in demand-side management programs might be not sufficient, since the compensation for the provided flexibility is very low.

The second chapter, “Cooperative governance structures in flexible electricity demand aggregation”, written together with Per J. Agrell, focuses on the aggregator’s presence in the intraday power market from a perspective of a large power consumer that has flexible load. We examined whether the cooperative governance structures could bring value to the market participants and final power consumers compared to the situations where demand flexibility is traded individually or via the investor owned aggregator. We found that if a large consumer has a possibility to form a cooperative with other large consumers and share fixed flexible demand coordination and market access cost, the consumer would receive the highest profit. When there is no such possibility, a large consumer would offer its flexibility to the aggregator, since the transaction cost related to trading the flexibility individually is too high. In this case, the aggregator would absorb the profit. The results show that cooperative governance structures lead to lower equilibrium market prices and the highest consumer surplus.

The third chapter, “Flexible electricity demand aggregator in the intraday market: Who gains?”, studies the aggregator’s presence in the intraday market from the producer’s perspective. I investigated whether the flexible demand aggregator’s presence in the intraday market can lead to a lower consumer surplus of power buyers and a higher profit for the producer. I found that under certain market conditions and producer’s marginal cost in different hours, the producer benefits from being in a competition with the aggregator and the consumer surplus is lower compared to the situation when the producer is a monopolist. However, under favourable market conditions, all market participants can benefit from the aggregator’s presence in the intraday market.

Resumé (Danish)

Denne ph.d.-afhandling fokuserer på efterspørgselsstyring på elektricitetsmarkedet og en ny spiller på markedet – en aggregator for fleksibel efterspørgsel. Afhandlingen består af tre selvstændige kapitler, der undersøger den nye spillers indtræden på elektricitetsmarkederne med et anderledes fokus, nemlig på aggregatoren, storforbrugeren af el og producenten af energi.

Det første kapitel, “Aggregeringen af efterspørgselssfleksibilitet på elektricitetsmarkederne: Effekter af porteføljevalg”, analyserer aggregatorens ydelse afhængig af porteføljevalget. Jeg undersøger flere porteføljer inden for forskellige kilder til fleksibilitet; elektriske køretøjer, varmepumper og/eller hårde hvidevarer som fx vaskemaskiner, tørretumblere og opvaskemaskiner. Jeg anvender Nord Pools markedsdata for Danmarks prisområde DK2 til at identificere de effekter, porteføjevalget har på afvikling af ubalancer og kompensation til fleksible kunder. Resultaterne viser, at forskellige sammensætninger af kilder til fleksibilitet fører til forskellige afviklinger af ubalancer og kompensation til forbrugerne. Der er derimod ingen betydelig merværdi i at have adgang til alle typer af kilder til fleksibilitet, medmindre aftaleomkostningerne er faste. Dette antyder, at aggregatoren ville vælge at specialisere sig i bestemte typer af kilder til fleksibilitet. Derudover konstaterer jeg, at incitamenterne for forbrugernes deltagelse i programmer for efterspørgselsstyring ikke er tilstrækkelige, da kompensationen for forbrugernes fleksibilitet er meget lav.

Det andet kapitel, “Selskabskonstruktioner inden for aggregeret fleksibel efterspørgsel på elektricitet”, skrevet i samarbejde med Per J. Agrell, fokuserer på aggregatorens tilstedeværelse i intraday-elektricitetsmarkederne fra den fleksible storforbrugers synsvinkel. Vi undersøger, hvorvidt selskabskonstruktionerne kan tilføre værdi til markedsdeltagerne og slutbrugerne sammenlignet med de situationer, hvor fleksibiliteten handles individuelt eller via den investorejede aggregator. Vi konstaterer, at hvis en storforbruger har mulighed for at skabe et kooperativ med andre storforbrugere og koordinere den fleksible efterspørgsel og markedsadgangsomkostningerne, vil det generere det størst mulige overskud. Når der ikke er mulighed herfor, vil storforbrugeren tilbyde sin fleksibilitet til aggregatoren, da transaktionsomkostningerne for at forhandle fleksibiliteten individuelt er for høj. I dette tilfælde

sluger aggregatoren overskuddet. Resultaterne viser, at selskabskonstruktioner fører til lavere ligevægtsmarkedspriser og det højeste konsumentoverskud.

Det tredje kapitel, “Aggregator for fleksibel elektricitetsefterspørgsel på et intraday-marked: Hvem vinder?”, undersøger aggregatorens tilstedeværelse på intraday-markedet fra et forbrugerperspektiv. Jeg undersøger, hvorvidt aggregatoren for fleksibel efterspørgsel kan føre til et lavere konsumentoverskud for elforbrugere og et højere overskud for producenten. Jeg konstaterer, at under visse markedsforhold og producentens grænseomkostninger på forskellige tidspunkter taget i betragtning, vil producenten drage nytte af at konkurrere mod aggregatoren, og konsumentoverskuddet er lavere sammenlignet med, hvis producenten havde monopol. Alle markedsdeltagere kan dog under gunstige markedsforhold drage nytte af aggregatorens tilstedværelse på intraday-markedet.

Contents

Introduction

Worldwide attention and discussions on climate change has increased the importance of further development of the energy sector, which has become one of the key topics of the governments' agendas. The EU 2030 Energy Strategy has set a target to increase the share of renewable energy as a proportion of final power consumption at least up to 27% (European Commission, 2014). This will contribute to reducing green house gas emissions, but also create new issues for the power system stability due to large share of variable wind and solar production. Smart grid and electricity demand-side management is seen as one of the ways to deal with the system stability problems and, therefore, is widely discussed among practitioners, academics and policy makers.

There is a great number of finished or ongoing smart grid projects in Europe. According to the Joint Research Centre, the European Commission's science and knowledge service (2017), there are 950 Research & Development (R&D) and Demonstration projects with a total budget of 4,97 billion Euros. One fourth of this amount represents the financing of demand-side management projects. According to the same source, among the biggest investors are distribution system operators, information and communications technology companies and universities. Consumers' flexibility is the focal point of such projects as *eFlex* carried by DONG Energy Eldistribution A/S, *TotalFlex* under the Energinet.dk's *ForskEL* programme, *EcoGrid EU* by Energinet.dk and *iPower* (DONG Energy Eldistribution A/S, 2012; TotalFlex, 2017; Energinet.dk, 2014; iPower, 2017; Hansen and Borup, 2014).

This Ph.D. thesis consists of three independent chapters on energy economics and a general conclusion. Even though each chapter is written as an independent research paper, all of them focus on electricity demand-side management and a new player in the electricity markets – an aggregator[1] of flexible demand. Each chapter analyses the entrance of this new player in the market from different perspectives. The first chapter takes the aggregator's perspective and investigates the effects of different compositions of flexibility sources in the aggregator's portfolio on its performance. The second chapter takes a large electricity consumer's perspective and analyses three options to trade flexibility: offer flexibility directly

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[1] Eurelectric (2014) defines an aggregator as "a market participant that combines multiple customer loads or generated electricity for sale, for purchase or auction in any organised energy market".

to the market, offer it to the aggregator, which would trade on the large consumer's behalf, or join a cooperative of other large electricity consumers willing to engage in flexibility trading and share related market costs. The third chapter takes a power producer's and other electricity market participants' perspective and examines market equilibrium outcomes and the resulting changes due to the aggregator's entrance to the market. All three chapters use a game theoretic approach and provide numerical estimations based on Nord Pool power markets, in particular Denmark's bidding area DK2.

In 2014, The Council of European Energy Regulators (CEER) presented an advice paper contributing to "assistance for NRAs [National Regulatory Authorities] and MS [Member States] on how to encourage the participation of demand-side resources in their markets and networks" (CEER, 2014). It highlights the aggregator's importance in enabling demand-side management to participate in wholesale markets and indicates that the aggregator's role is not clearly defined yet. Since then a lot of studies have had the aggregator as a central figure pooling certain types of flexibility sources, such as electric vehicles (EVs) in Finn et al. (2012), Di Giorgio et al. (2014), Neaimeh et al. (2015) or Bessa and Matos (2014), or heat pumps (HPs) in Rankin et al. (2004), Papaefthymiou et al. (2012), Alahäivälä et al. (2017) or Arteconi et al. (2016). The first chapter supplements the ongoing discussion about the aggregator's role in electricity markets and, unlike other studies, investigates whether targeting several types of small flexibility providers could bring additional value in terms of balance management and excess flexibility selling for balancing purposes. Results suggest that with no fixed contract cost there is no significant value in combining all flexibility sources in one portfolio, thus, the aggregators are likely to specialise.

The second chapter, coauthored with Per J. Agrell, examines cooperative governance structures in the intraday electricity market. The main difference between a cooperative and an investor owned firm is that a cooperative does not have a profit maximisation motive of its own, but instead it represents several individual interests of its members (Trifon, 1961). According to Bonus (1986), being a member of a cooperative allows lower transaction cost, which leads to increased benefits compared to the individual activities in the market. Thus, another way to pool the flexibility of large consumers is to allow them to form a cooperative. We have investigated the intraday market outcomes under two flexibility pooling options:

the aggregator and the cooperative. Similarly like Zugno et al. (2013), we found that the aggregator absorbs the profit of large consumers offering their flexibility to the aggregator unless they have an option to form a cooperative and compete with the aggregator. Finally, the possibility to bid directly in the intraday market is not attractive to large consumers since the market barriers are too high – relatively large transactions cost and high minimum bid sizes.

The third chapter reveals that the aggregator's presence at the intraday market may have both positive and negative effects on the rest of the market players. In contrast to many studies, for example, Hatziargyriou et al. (2010), Adika and Wang (2014), Frew et al. (2016) or Alahäivälä et al. (2017), focusing only on the benefits of flexible demand aggregation, I found that under certain market conditions, i.e. certain demand and marginal cost of power production in different hours, the market participants, including power buyers, may be better off in a monopoly of the producer than under the producer's and the aggregator's competition.

This dissertation contributes to a better understanding of the flexible demand aggregator's effects on the power markets and welfare of electricity consumers. The scale of interest in the demand-side management topics only confirms its importance for future power systems. However, there are still many aspects that need to be analysed, such as consumer compensation schemes, and all possible advantages and disadvantages should be determined before the demand flexibility can be successfully used guaranteeing the stability to the power system and lower prices to power consumers.

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Chapter 1

Aggregation of demand-side flexibility in electricity markets: the effects of portfolio choice

Aggregation of Demand-Side Flexibility in Electricity Markets: the Effects of Portfolio Choice

Ieva Linkeviciute[*]

September 27, 2018

Abstract

Aggregation of demand-side flexibility for balancing purposes is seen as a way to cope with the challenges imposed by increasing share of renewable energy sources in the future power system. The value of demand-side flexibility attracted attention of researchers and industry some time ago. However, there is still a lack of discussion whether the composition of various flexibility sources could bring additional value in optimising schedules of flexible load. This paper examines the role of flexible demand aggregators and the effects of their portfolio choice on imbalance payments and compensations to flexibility providers. It also proposes a game theoretical model, which allows to determine optimal flexible load schedules ensuring the highest savings on imbalance payments. Seven scenarios, representing portfolios with different compositions of flexibility sources, were set to investigate the Nordic power market. Results show that the aggregator's payments in balancing market and compensations to consumers for provided flexibility depend on the type of flexibility sources in the portfolio. Also, the difference between forecasted and actual reductions in imbalance payments is affected by the portfolio composition. However, with no fixed contract cost, there is no significant value in combining all flexibility sources in the portfolio. This means that in order to maximise the value of flexible demand the aggregators might choose to specialise in certain types of flexibility sources.

Keywords: demand-side management, flexibility, aggregation, electricity market
JEL classification: C61, C63, C72, L94

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1 Introduction and literature review

Increasing share of variable renewable energy sources in power systems, lower generation predictability and related balancing issues have heightened the need for enabling demand-side flexibility in electricity markets. Today, small residential and commercial consumers are still facing a number of barriers in accessing markets where they could trade their flexibility – quantities are too small to meet the bidding requirements at the intraday or balancing markets, market membership fees are too high for a small consumer and the lack of knowledge and time for trading prevents from entering these markets. Therefore, aggregation of demand-side flexibility has become an important topic among academics, policy makers and businesses. This paper examines the role of flexible demand aggregators and the effects of their portfolio choice on imbalance payments and compensations to flexibility providers.

The European network of transmission system operators for electricity (ENTSO-E) defines balancing as “all actions and processes, on all timelines, through which TSOs ensure, in a continuous way, to maintain the system frequency within a predefined stability range [...]” (ENTSO-E, 2014*a*). Everyone, who is connected to the grid, is responsible for their own imbalance and pays imbalance payments for any discrepancies between scheduled and actual consumption (production). However, small consumers delegate this task to the retailer, who either handles it himself or finds a Balance Responsible Party (BRP). In the end, final consumers are charged for this service accordingly (Eurelectric, 2014).

Balancing services can mean both balancing energy, which is energy used by a TSO to balance the power system, and balancing capacity, which is a reserved capacity hold by a balancing service provider, which has an agreement with a TSO to bid a corresponding volume of regulating energy for an agreed period of time. Balancing services can be provided by flexible producers, energy storage facilities, as well as flexible consumers. Thus, flexible demand is one of the competing flexibility sources, extending the list of possible flexibility providers.

One could argue that small consumers cannot provide all types of flexibility. The balancing of production and consumption can be differentiated by time, i.e. hours-ahead (replacement reserves, activation within hours), minutes ahead (frequency restoration reserve, activation within 15 minutes) and seconds ahead (frequency containment reserves, activation within 30 seconds). These reserves can be provided by generators, storage and demand response. Small flexible consumers might find it challenging to react within seconds. However, if the consumption is based on thermal storage, such like refrigerators, ovens or heat pumps, this type of reserve can be served by small consumers too.

Currently, the traditional suppliers of flexibility in the balancing market are thermal power plants. In the future, these conventional sources of flexibility might become more costly since they would be utilised at lower rates due to an increasing share of renewable energy sources (Katz, 2014). Thus, new flexibility sources should be introduced into the power system. In order to do that, ENTSO-E is preparing the European network code on electricity balancing, which should facilitate the participation of all flexibility providers, including demand-side response, in the balancing market (ENTSO-E, 2014*a*).

Studies show that flexible consumption of households can contribute to the power system balancing. Heating, ventilation and air-conditioning have high potential in providing fast demand response (Ali et al., 2015; Lu, 2012). Electric vehicles and refrigerators are also good candidates for flexible demand (Short et al., 2007; Nguyen and Le, 2014).

Although smart metering installation will eliminate one of the main barriers to use small consumers' flexibility, there are more obstacles to overcome. For example, it is important for the consumers to accept this new technology, understand it and have their anxiety about risks of participation mitigated (Park et al., 2014). Also, informational links between the power market and consumers' meters should be created (Katz, 2014). For further discussion about demand response challenges and benefits see O'Connell et al. (2014).

In the recent years, a number of studies have focused on optimisation frameworks for flexible demand aggregators participating in power markets. In some of these studies, the aggregator is an existing player in the market, for example supplier, which requires only minor adjustments to the current market model (Katz, 2014); in others, it is a newly introduced player acting as an intermediary between the flexibility providers and the power market (Agnetis et al., 2011).

The value of aggregation has been estimated in the current Nordic power market framework by Roos et al. (2014), in addition, real life demonstrations have been performed to show the value of aggregated flexibility by Biegel et al. (2014a). So far, however, little discussion exists about the effects of the aggregator's portfolio composition, i.e. combination of various sources of flexibility, like electric vehicles (EVs), heat pumps (HPs), and smaller home appliances. It is still not clear, whether the aggregator should specialise in certain types of flexibility or if it should construct a diversified portfolio to maximise the value.

There are two ways to modify the demand curve. The first is to shift the consumption to other periods of time; the second is to curtail the consumption during peak hours.[1] In this paper, the former approach has been chosen to optimise consumption schedules, as it is not straightforward to determine consumers' opportunity cost of lowering the consumption without an option to restore it later. In some cases, for example, changing the load of thermal units like refrigerators or heat pumps, shifting the consumption may increase total consumption due to restoring the required temperature levels. However, in others cases, shifted consumption of such appliances as washing machines or dish washers does not depend on the time of consumption.

In this study, the analysis of portfolio choice is based on game theory, which has been widely applied in demand-side management models by, for example, Saad et al. (2012); Fadlullah et al. (2013); Mohesian-Rad et al. (2010); Zugno et al. (2013); Kim (2014). Game theory has a great potential to analyse demand-side management problems, because optimal load schedules can be obtained by analysing the best strategies of all participants in the system that have different objectives. Thus, game-theoretical tools are very useful for designing incentive schemes for consumers.

The interactions between two main players, i.e. the aggregator, which is also the balance responsible party, and the consumer, include information sharing about flexible consumption schedules and sending price incentives for load shifting. Both players solve their optimisation problems: the aggregator maximises the expected market profits by using demand-side flexibility to lower imbalance payments and selling the excess flexibility in the market, while the consumer minimises the cost of consumed electricity. The aggregator does not have

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[1] One should be aware that demand response may also increase the consumption when power prices are low due to increased renewable energy generation.

complete market information about regulating energy prices, nor imbalances for the next hour, which means that the actual gain and the expected result of the optimisation differ. All flexibility sources have different characteristics and it is impossible to rank them without a deeper analysis and actual real life simulations. Therefore, seven scenarios with different portfolio compositions were set to investigate the effects of portfolio choice in the Nordic power market.

The rest of the paper is organised as follows. Section 2 discusses the role of the aggregator in the power market. Section 3 introduces the model setup: the aggregator and consumer optimisation problems, forecasting and uncertainty issues. Section 4 describes analysed cases and scenarios, as well as the data used in simulations, while Section 5 provides simulation results and discusses the characteristics of demand shifting in each portfolio and the aggregators' ability to trade flexibility. Finally, Section 6 concludes and suggests future research directions.

2 Aggregator's role

Now, some balance responsible parties have already taken the aggregator's role and provide different types of ancillary services aggregating smaller CHP (combined heat and power plant) units (Energinet.dk and Danish Energy Agency, 2012). In the future, the main task of the aggregator will be to connect small consumers offering flexibility to the power markets. The aggregation of dispersed flexibility of households enables to use this flexibility source, because only by aggregation it can be formed into wholesale market products (Koponen et al., 2012). Thus, the aggregator acts as a central figure coordinating and changing consumption schedules according to the agreed terms or by sending price signals in order to minimise energy costs.

In some optimisation frameworks, like in Agnetis et al. (2011), the aggregator uses an optimal schedule to place bids in the day-ahead market. Its decisions are based on forecasts of the power price in the market and expected changes in the consumption schedules due to price and volume signals sent to the consumer. In other frameworks, like in Biegel et al. (2014*b*), the aggregator places bids in the ancillary service market for primary and secondary

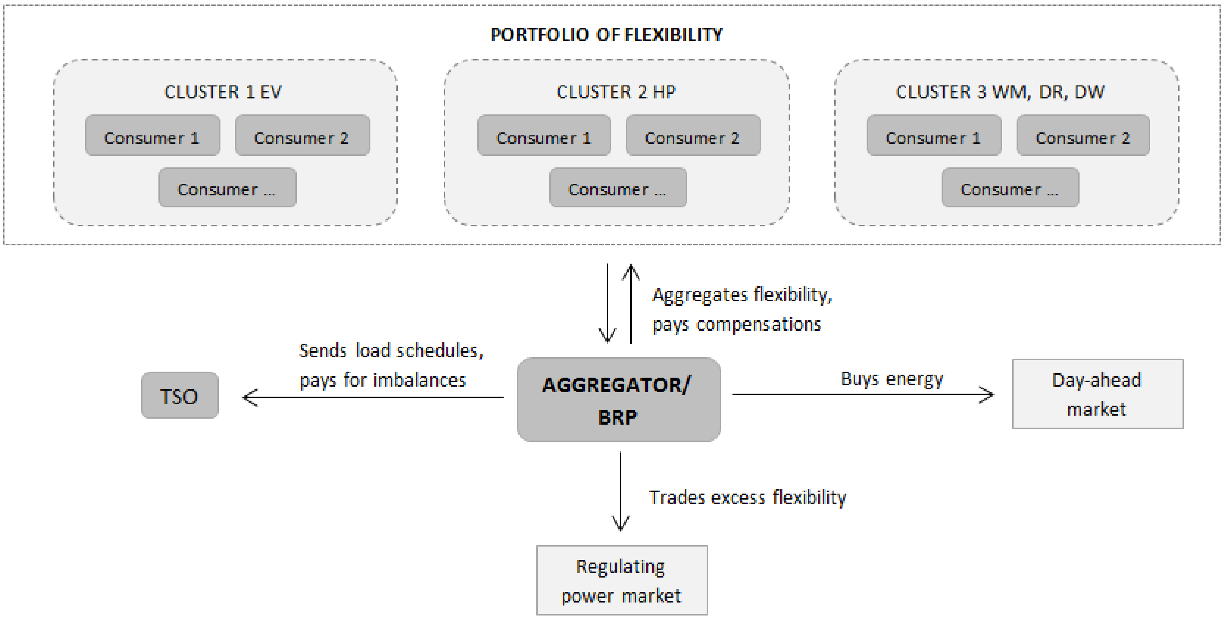

Figure 1: Aggregator's role and its tasks in the power market: energy purchase at the day-ahead market, formation of the flexibility portfolio, compensations to consumers for used flexibility, information about load schedules and payments for imbalances to a TSO and the excess flexibility provision to the regulating power market

reserves. This paper presents a model where the aggregator buys energy at the day-ahead market before the optimisation of consumption schedules. Information about the flexible consumption amounts and the time interval for load shifting is not always available before the gate closure in the day-ahead market. Thus, flexibility sources are used for minimising imbalance payments and selling flexibility at the regulating power market.

In cases where a balance responsible party also manages production side and has flexible consumption sources, generating units can be kept in an optimal operating state. Consumers' flexibility helps to reduce deviations in the system and allows to avoid high start-up cost improving the efficiency rates of running power plants (Harbo and Biegel, 2012). However, this paper focuses on the consumption side and the aggregator does not have generating units in its portfolio. This also means that the aggregator faces only the regulating energy price for consumption and, unlike in production side management case, can be compensated for having the imbalance in the opposite direction than the system's total imbalance.

In this model there is only one aggregator and many consumers divided in clusters depending on the flexibility source (see Figure 1). Even though the clusters can also be formed according to the number of people at the premises, the geographical area and their habits, like argue Koponen et al. (2012), the model focuses on typical Danish households and the type of appliances they own. The optimisation is carried out for all consumers individually, but their behaviour is determined by common rules of the cluster. Although the aggregator provides services to many consumers, the portfolio is relatively small; therefore, the aggregator does not influence the regulating energy price.

If the aggregator had a bigger portfolio, it would start influencing regulating energy prices and revenues would increase at a decreasing rate. Meanwhile, the compensation to consumers would stay at the same rate of increase, as there is no impact to day-ahead prices. The total portfolio fixed contract cost would increase with every additional contract, as it is an increasing step function. Thus, the aggregator should carefully choose the size of its portfolio.

If other aggregators would enter the market, the revenues from trading the excess flexibility at the market are likely to diminish, because the supply of energy would increase and strengthen competition. In addition, the consumers would get an opportunity to switch between the aggregators which focus on the same source of flexibility and in this way try to increase their compensations.[2] All of this would lead to lower aggregator's profits. However, the aggregator's imbalance cost might decrease due to lower regulating power prices. The aggregator's behaviour in the presence of other aggregators and the value of demand flexibility depending on the portfolio size are interesting topics that deserve a separate study. As this paper focuses on different sources of flexibility and its value to the aggregator, the model setting is chosen to be relatively simple and reflects only the effects of different compositions of the aggregator's portfolio.

The optimisation of flexible consumption is a continuous process as it does not depend on a particular event in the system, such as a sudden shut down of a power plant or a very high spot market price, but rather minimises the cost of energy every time the appliance is used. Even though the aggregator has more information about the power system conditions than the consumer, it still faces various uncertainties and calculates the expected value

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[2] This could be another reason encouraging the aggregators to specialise in certain types of flexibility.

of flexibility. This means that there is a risk of changing a consumption schedule in the opposite direction than it is optimal. However, the aggregator's portfolio consists of many dispersed flexibility offers during the year, which allows diversifying risk of losses caused by inaccurate forecasts. Thus, this is another quality of aggregation, which makes it preferable to a single consumer trading small and infrequent flexibility amounts at the market.

It is hard to estimate the baseline of consumption, i.e. consumption without the flexibility involved, when the usage of appliances depends on the consumer behaviour. For example, the aggregator cannot make accurate forecasts of a dishwasher activation time unless the consumer sends a notice to the aggregator that the dishes must be done within a certain period of time. Naturally, the baseline consumption would coincide with hours when the notice is sent, i.e. consumer's initial thought of using an appliance. Introducing flexibility allows the consumer to adjust consumption according to the lowest electricity spot prices. In this case the baseline consumption (or "original schedule", as it is called further in the paper) for the aggregator is the consumption schedule optimised by the consumer according to the day-ahead prices (see section 4.2 Data and Figure 6 for more details). Based on this consumption schedule, the aggregator determines compensations for the shifted load.

The aggregator and flexibility providers enter into a contract, where they state the obligations for both parties, including compensation terms, constraints under which the aggregator is allowed to change the consumption schedule and consumer's obligation to provide flexibility, similarly like in Harbo and Biegel (2012).

In terms of contract cost, the most favourable situation for the aggregator would be to have one infinitely flexible consumer that could provide all energy needed to eliminate its imbalance. However, each consumer has a limited flexibility and the aggregator has to form a portfolio of flexible demand, where the number of consumers depends on the flexibility source. Thus, contract cost affects the ranking of the aggregator's portfolios and a high number of contracts may reduce the value of otherwise effective flexibility source.

Compensation rates for the consumer's provided flexibility can be flat or flexible. A flat rate, or a capacity payment, means that the aggregator pays a fixed compensation for a specified time period for a specified capacity of flexibility. Meanwhile, a flexible rate, or an energy payment, is used when the aggregator compensates only for the flexibility that has been actually used. Also, consumers can be offered a combination of these two payments. In the model, a flexible rate regime is chosen to reflect the market value of flexibility.

According to Broberg and Persson (2016), consumers want to be compensated differently depending on the flexibility source and time during the day. For example, consumers are more willing to allow direct control of their heating systems instead of other home appliances, such as washing machines, dryers and dish washers. Evening peak consumption hours are less flexible and need larger compensation. Also, age, gender, income and the number of persons in a household also affect their compensation preferences. However, to determine exact disutility functions reflecting all these variables would require a thorough analysis of consumers' behaviour.

3 Model setup

The model is set using a leader-follower structure that is a characteristic of Stackelberg games (von Stackelberg, 2011)[3]. In this hierarchical game, the leader, i.e. the consumer, announces his or her strategy in advance. After receiving this information, the aggregator maximises its utility. Thus, the consumer's task is to choose a strategy such that the aggregator's response yields the largest possible payoff for him or her. When the equilibrium is reached, neither the consumer nor the aggregator is willing to change the load scheduling strategy. The nomenclature is presented in Table 1.

The process of aggregating and trading the flexibility of consumption is illustrated in Figure 2. It includes the following stages:

- **Initial state** The aggregator has already purchased energy at the day-ahead market E_t^s to cover the demand for the next day. Decisions about the amount of energy are based on consumption forecasts.

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[3] Translation from the German language edition: "Marktform und Gleichgewicht" (1934), Springer-Verlag Wien

Table 1: Nomenclature

Nomenclature	
T	total number of time periods in the optimisation (total number of hours)
t	time index (a number of hour), $t \in (1, 2, \ldots, T)$
K	total number of consumers in the aggregator's portfolio
i	consumer index, $i \in (1, 2, \ldots, K)$
J	total number of flexibility sources in the portfolio
j	index of flexibility source, $j \in (1, 2, \ldots, J)$
$l_{i,t}$	total load of the i'th consumer in hour t
$l_{i,t}^{inf}$	inflexible load of the i'th consumer in hour t
$l_{i,t}^{f}$	flexible load of the i'th consumer in hour t
p_t^s	day-ahead price in hour t
$U_{i,j,t}^a$	i'th consumer's utility of using j type of appliance in hour t
$V_{i,j,t}^a$	i'th consumer's value of using j type of appliance in hour t
$\gamma_{i,j,t}$	compensation factor for i'th consumer's j type of appliance, $\gamma_{i,j} \in [1; 2]$
$m_{i,j,t}$	number of times the aggregator has used the i'th consumer's flexibility of type j in the whole optimisation period up to and including hour t
C_i	total consumer's cost of consumed electricity in the optimisation period
$p_{i,j,t}^f$	price of j type flexibility in hour t for consumer i
E_t^s	energy purchased by the aggregator at the spot market for period t
p_t^u	electricity up regulation price in period t
p_t^d	electricity down regulation price in period t
E_t^u	up regulation energy purchased by the aggregator from a TSO for period t
E_t^d	down regulation energy purchased by the aggregator from a TSO for period t
l_t^u	up regulation energy sold by the aggregator at the ancillary services market in period t
l_t^d	down regulation energy sold by the aggregator at the ancillary services market in period t
I_t	imbalance the aggregator has in period t
c_c	the aggregator's fixed contract cost
C_c	total fixed contract cost for the aggregator's portfolio
$p_{forecast,t}^u$	the aggregator's electricity up regulation price forecast for time period t
$p_{forecast,t}^d$	the aggregator's electricity down regulation price forecast for time period t
$p_{actual,t}^u$	actual electricity up regulation price for time period t
$p_{actual,t}^d$	actual electricity down regulation price for time period t
e_t^u	random error variable for up regulation price in period t, $e_t^u \in [-0,05; 0,05]$
e_t^d	random error variable for down regulation price in period t, $e_t^d \in [-0,05; 0,05]$
$I_{forecast,t}$	the aggregator's forecasted imbalance in period t
$I_{actual,t}$	actual aggregator's imbalance in period t
$e_{i,t}$	random error variable for the imbalance in period t, $e_{i,t} \in [-0,1; 0,1]$

- **Stage 1** The consumer optimises his/her flexible consumption according to the known day-ahead prices and sends a notice to the aggregator indicating the amount of available flexibility in consumption, i.e. the amount of energy and time when this energy should be used, together with the time interval for allowed deviations.

- **Nature** After the gate closure of the day-ahead market, some unexpected events lead to deviations from the aggregator's forecasted demand schedules. This causes imbalances for the aggregator.

- **Stage 2** After receiving the consumer's notice with the "original" consumption schedule, the aggregator optimises it according to the expected imbalance situation it forecasted (imbalance amounts I_t depending on the actual consumption l_t, up and down regulating prices p_t^u and p_t^d, and the dominating direction of the system's total imbalance). If there are deviations from the "original" consumption schedule sent by the consumer, the aggregator sends a notice to the consumer with desired changes in the "original" consumption schedule and offers of compensations (flexibility price $p_{i,j,t}^f$). The aggregator knows the consumer's utility function.[4]

- **Stage 3** The consumer decides whether to accept the offer, i.e. the flexibility price for all offered flexibility and changes in the "original" consumption schedule. The consumer does not have information about the aggregator's expected imbalance situation. The consumer always fulfils his/her obligation to provide flexibility, there are no penalty fees.[5]

- **Stage 4** The aggregator uses flexibility to minimise its imbalance payments, sells the excess flexibility at the ancillary services market and pays compensations to consumers.

- **Stage 5** Revelation of actual aggregator's imbalances I_t, regulating energy prices p_t^u and p_t^d, and the dominating direction of the system's total imbalance.

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[4] The consumer and the aggregator reach an agreement about compensation rates when signing the flexibility provision contract. Thus, $\gamma_{i,j,t}$ is known in advance and depends on the number of times when the flexibility was used. Nevertheless, the aggregator can never be completely sure about its consumers real disutility of shifting the consumption which is hard to evaluate in monetary terms. Therefore, the consumer could use this asymmetric information to increase his/her compensation rates.

[5] As the load shifting processes are assumed to be automated, the probability of the consumer violating the agreement is relatively low. However, introduction of penalty fees is quite common in load shifting simulations.

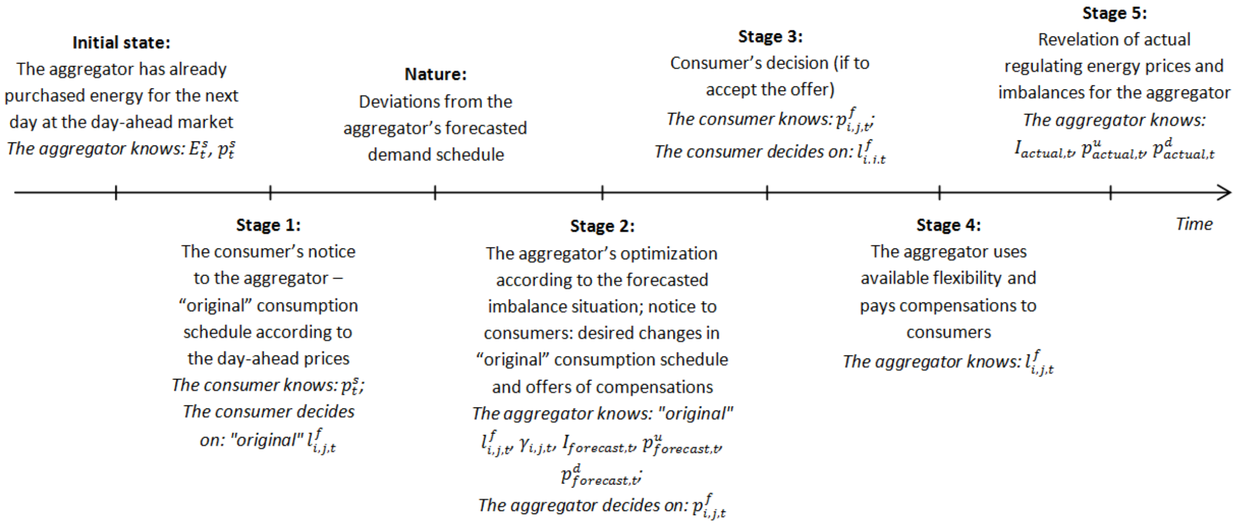

Figure 2: Timeline: stages reflecting the process of aggregating, optimising and trading demand flexibility

The algorithm of the model is presented in Figure 3 and illustrates the stages of the model. The following sections focus on a consumer's and the aggregator's optimisation problems, also discuss uncertainties and forecasting issues.

3.1 Consumer

Let i, $i \in (1, 2, \ldots, K)$ be the set of consumers in the aggregator's portfolio, where K is the total number of consumers. The total load $l_{i,t}$ of the i'th consumer in hour t is composed of two parts: inflexible load $l_{i,t}^{inf}$ and flexible load $l_{i,t}^f$, i.e. $l_{i,t} = l_{i,t}^{inf} + l_{i,t}^f$. Since the inflexible load cannot be shifted, I have focused only on the flexible part $l_{i,t}^f$. Each consumer is charged the day-ahead price p_t^s for each kilowatt hour of his/her consumed electricity.

3.1.1 Sources of flexibility

The consumer offers the flexibility of consumption of five flexibility sources: washing machines, clothes dryers, dish washers, heat pumps and electric vehicles. All of them have different consumption patterns, i.e. time when the flexibility is offered, the amount of flexibility and the time interval for possible shifting of consumption. Based on the characteristics of flexibility sources, the consumers are divided into three clusters:

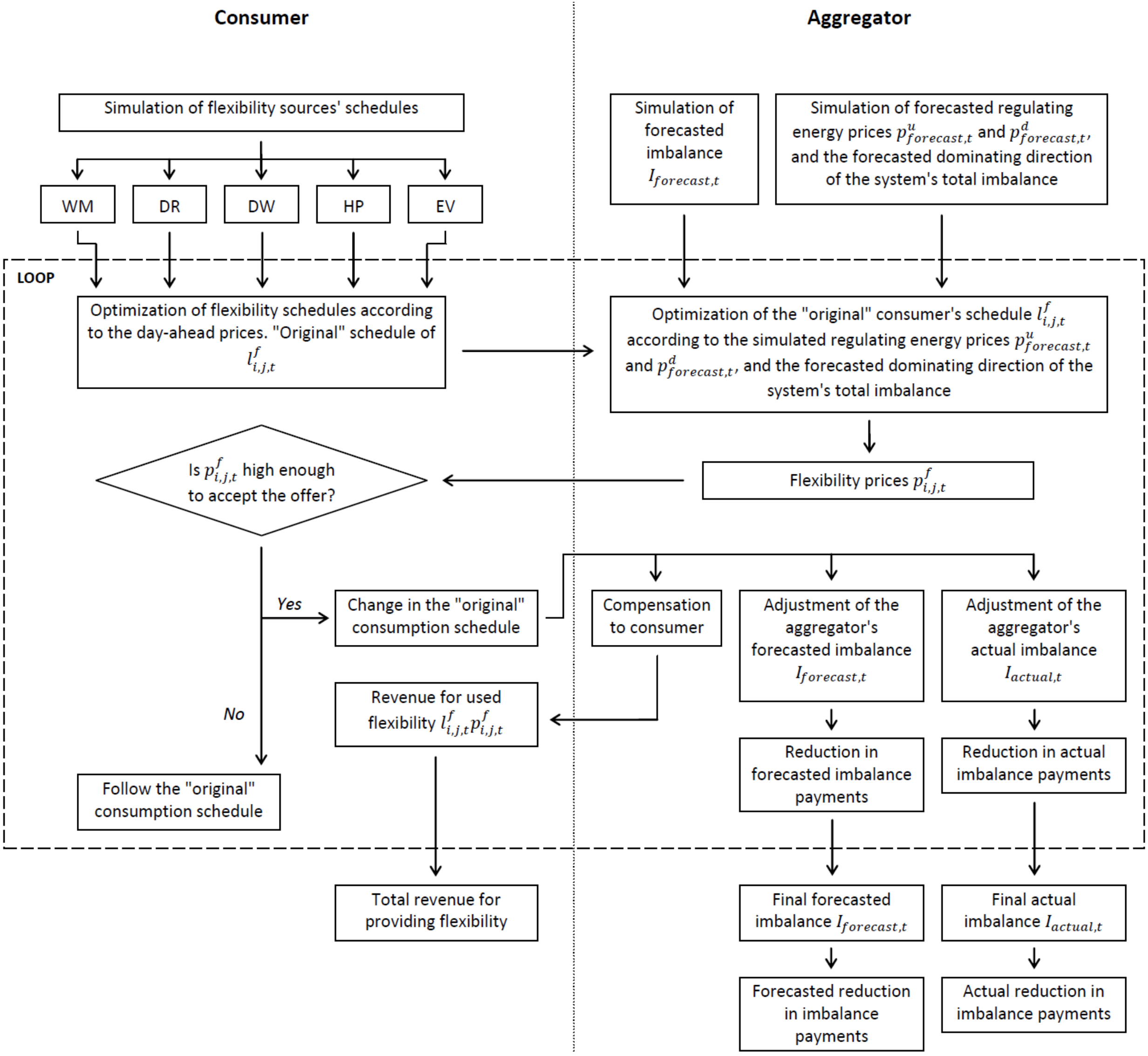

Figure 3: The algorithm of the simulations reflecting the sequence of forecasting processes and actors' decisions

- those who offer the flexibility of small home appliances: washing machines, clothes dryers and dish washers (the need to use these appliances is stochastic, the amount of offered flexibility of one appliance is relatively small, appliances are usually used during the day time and the time interval for possible shifting of consumption is medium, 3-6 hours);
- those who offer the flexibility of heat pumps (available only seven months per year, 24 hours per day, the amount of available flexibility is correlated with outside temperature, the time interval for shifting the consumption is relatively shorter, 3 hours);
- and those who offer the flexibility of their electric vehicles (the flexibility is available only at night, the offered amount is relatively large and time period for shifting is the longest, 10 hours).

In the model, the source of flexibility is denoted by j, $j \in (1, \ldots, J)$. The values of j depend on a particular scenario and the flexibility sources included in the aggregator's portfolio and J indicates the total number of flexibility sources in the portfolio.

3.1.2 Consumer's utility

The i'th consumer's utility of using an appliance that provides flexibility is denoted by $U^a_{i,j,t}$ and the cost of using the appliance in hour t is the product of electricity day-ahead price and the amount of energy used in hour t, i.e. $p^s_t l^f_{i,j,t}$. Thus, the value of using an appliance in hour t is

$$V^a_{i,j,t} = U^a_{i,j,t} - p^s_t l^f_{i,j,t}. \tag{1}$$

Since the focus is on consumption shifting but not on consumption curtailment, the exact utility of using the appliance $U^a_{i,j,t}$ is not important. For example, if the consumer wants to wash dishes, the satisfaction of clean dishes will be the same and will not depend on the particular time within the allowed time interval for shifting the consumption. This means that if the washing is moved by n, $n \in (0, 1, \ldots, N)$, hours, where N is the maximum number of hours indicating the interval within the consumption can be moved, the utilities $U^a_{i,j,t}$ and $U^a_{i,j,t\pm n}$ will be equal. Instead we should analyse the disutility of shifting the consumption within the indicated period of time. Unlike the utility of using the appliance $U^a_{i,j,t}$, the value $V^a_{i,j,t}$ differs for every hour within the shifting period, because the cost of energy $p^s_t l^f_{i,j,t}$ depends on consumption hour t. When the consumer optimises his/her consumption schedule, he or she chooses the highest value of using the appliance $V^a_{i,j,t}$ within the allowed time interval for shifting the consumption. Due to shifting the consumption by n hours to hour $t \pm n$, the change in consumption value can be written as

$$V^a_{i,j,t} - V^a_{i,j,t\pm n} = (U^a_{i,j,t} - p^s_t l^f_{i,j,t}) - (U^a_{i,j,t\pm n} - p^s_{t\pm n} l^f_{i,j,t\pm n}). \tag{2}$$

Since $U^a_{i,j,t} = U^a_{i,j,t\pm n}$ and $l^f_{i,j,t} = l^f_{i,j,t\pm n}$ [6], we get

$$V^a_{i,j,t} - V^a_{i,j,t\pm n} = (p^s_t - p^s_{t\pm n}) l^f_{i,j,t}. \tag{3}$$

This difference in values can be seen as a disutility of shifting the consumption. However, due to shifting the consumption, the consumer not only incurs higher cost of energy, but also experiences some level of discomfort, for example, uncertainty of the exact time when the dishes are washed. The level of discomfort increases with the increasing number of times when the consumption has been shifted.[7] To account for the increasing discomfort, I have introduced a compensation factor $\gamma_{i,j,t}$, $\gamma_{i,j,t} \in [1;2]$. Let $m_{i,j,t}$ be the number of times the aggregator has used the i'th consumer's flexibility in the whole optimisation period up to and including hour t. $\gamma_{i,j,t}$ can be written as

$$\gamma_{i,j,t} = 1 + \frac{1}{M_{i,j}} m_{i,j,t}, \tag{4}$$

where $M_{i,j}$ is the total number of times the i'th consumer can offer his or her flexibility in the whole optimisation period. Thus, every time the aggregator uses the flexibility, the consumer's discomfort and, therefore, compensation factor to the consumer is increasing at a constant rate $1/M_{i,j}$. This means that the compensation factor is $1/M_{i,j} \times 100$ percent higher comparing to the previous time of shifting the consumption. The compensation to consumer for shifting his/her consumption for the $m_{i,j,t}$'th time can be written as

$$l^f_{i,j,t} p^f_{i,j,t} = l^f_{i,j,t} (p^s_t - p^s_{t\pm n}) \gamma_{i,j,t}, \tag{5}$$

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[6] Here, it is assumed that due to consumption shifting the required amounts of energy are the same in both hours for all flexibility sources including the heat pumps.

[7] Harbo and Biegel (2012) also argue that contract settlement cost may depend on the flexibility utilisation extent.

where $p^f_{i,j,t}$ is the flexibility price offered to the i'th consumer for the flexibility source j. From (5):

$$p^f_{i,j,t} = (p^s_t - p^s_{t\pm n})\gamma_{i,j,t}. \tag{6}$$

One one hand, if compensations are too low, consumers have no incentive to offer their flexibility of consumption. On the other hand, if compensations get too high, the aggregator cannot use the offered flexibility because the cost of shifting load exceeds its value. Thus, the higher compensation factor would encourage consumers' participation, but also would result in lower use of flexibility. In the results section of this study one can see that with the current form of compensation factor only half of the available flexibility is actually used, while the compensation amounts to consumers are very small. Therefore, changing the compensation factor to one or another direction would either diminish already low compensations to consumers or reduce the actual use of flexibility even further.

The presented concept is similar to the proposal by Harbo and Biegel (2012), where they suggest the "N-curtailment contract". This contract has a limited number of activations, n, and a compensation for curtailment is increasing with the number of activations. Thus, the consumer is compensated progressively with activation. Harbo and Biegel (2012) also propose a fixed reservation payment at x_0 DKK after which follows an activation fee of $(x_1, \ldots, x_n)$ for the following n activations.

3.1.3 Consumer's optimisation problem

The objective function of the i'th consumer offering flexibility of the source j is the minimisation of the cost of the electricity consumed by providing as much flexibility of the consumption as possible, given by

$$C_i(l^f_{i,j,t}) = \sum_{t=1}^{T} p^s_t l_{i,t} - p^f_{i,j,t} l^f_{i,j,t}. \tag{7}$$

Here, the cost of consumed electricity is equal to the sum of hourly consumed energy at spot prices $p^s_t l_{i,t}$ less the revenue from the provided flexibility $p^f_{i,j,t} l^f_{i,j,t}$. The consumer has no information about the flexibility price $p^f_{i,j,t}$ he or she will be offered while making the initial load schedule decision. Therefore, the consumer's optimisation problem becomes a simple exercise of finding the lowest electricity spot prices for the time intervals with flexible consumption. After solving this problem, the aggregator is provided with the flexible consumption schedule. Based on this schedule and estimated savings in imbalance payments, the aggregator offers flexibility prices for changing the initial schedule and the consumer minimises the cost by accepting or rejecting the offer for a particular time period.

The consumer's optimisation problem has several constraints. First, the total consumption consists of inflexible and flexible parts:

$$l_{i,t} = l_{i,t}^{inf} + l_{i,j,t}^{f}. \tag{8}$$

Second, flexibility can be provided only by certain home appliances, HPs and/or EVs. This means that the amount of flexible consumption $l_{i,j,t}^{f}$ depends on the power of those appliances and the need to use them. In addition, the source of flexibility determines the time interval for possible consumption shifting. For more details on flexibility sources see section 4.2 Data.

3.2 Aggregator

The aggregator enters into a contract with the consumer and uses demand-side flexibility to reduce its imbalance payments and maximise the profit. In addition to the compensations to its consumers, the aggregator faces some fixed contract cost that diminishes benefits from the enabled flexibility. The aggregator's optimisation problem and related contract cost, as well as forecasting procedures are discussed in the following subsections.

3.2.1 Aggregator's optimisation problem

The objective function of the aggregator is the maximisation of the expected market profit, given by

$$\Pi(\mathbf{x}, \mathbf{y}) = \mathbb{E}\Big\{ \sum_{i=1}^{K} \sum_{j=1}^{J} \sum_{t=1}^{T} p_t^s l_{i,t} - p_t^s E_t^s - p_t^u E_t^u - p_t^d E_t^d - p_{i,j,t}^f l_{i,j,t}^f + p_t^u l_t^u + p_t^d l_t^d \Big\} \tag{9}$$

where T is time periods in the optimisation, t – index of the time period, p_t^s – electricity spot price in period t, $l_{i,t}$ – total consumption of the consumer in period t, E_t^s is energy purchased at the spot market for period t, p_t^u and p_t^d – electricity up and down regulation prices in period t, E_t^u and E_t^d – up and down regulation energy purchased from a transmission system operator (TSO), $p^f_{i,j,t}$ – price offered to the i'th consumer for flexible consumption of flexibility source j in period t, $l^f_{i,j,t}$ is flexible consumption of flexibility source j of the i'th consumer in period t, l_t^u and l_t^d are up and down regulation energy sold by the aggregator at the ancillary services market.

The aggregator's expected market profit in hour t is equal to the revenue from the consumers for supplied electricity $\sum_{i=1}^{K} p_t^s l_{i,t}$ minus the cost for buying energy at the spot market $p_t^s E_t^s$ minus the cost for up or down regulation energy purchased from the TSO $p_t^u E_t^u + p_t^d E_t^d$, minus the payment to the consumer for the provided flexibility $\sum_{i=1}^{K} \sum_{j=1}^{J} p^f_{i,j,t} l^f_{i,j,t}$, plus the revenue for the excess up and down regulation energy sold at the regulating energy market $p_t^u l_t^u + p_t^d l_t^d$. In a one-price balance settlement system, a load balance responsible party may profit from its imbalance if it helps to reduce a system imbalance. Therefore, just by having an imbalance in the opposite direction than the system's total imbalance, the aggregator yields profit without actually trading the flexibility with other market players. In addition, shifted flexible demand does not influence regulating energy prices, because the aggregator's flexibility portfolio is relatively small.

By simplifying (9), we get

$$\Pi(\mathbf{x},\mathbf{y}) = \mathbb{E}\Big\{ \sum_{i=1}^{K} \sum_{j=1}^{J} \sum_{t=1}^{T} p_t^s (l_{i,t} - E_t^s) - p^f_{i,j,t} l^f_{i,j,t} + p_t^u (l_t^u - E_t^u) + p_t^d (l_t^d - E_t^d) \Big\}, \tag{10}$$

$$\Pi(\mathbf{x},\mathbf{y}) = \mathbb{E}\Big\{ \sum_{i=1}^{K} \sum_{j=1}^{J} \sum_{t=1}^{T} p_t^s I_t - p^f_{i,j,t} l^f_{i,j,t} + p_t^u (l_t^u - E_t^u) + p_t^d (l_t^d - E_t^d) \Big\}, \tag{11}$$

where $I_t = l_t - E_t^s$, $l_t = \sum_{i=1}^{K} l_{i,t}$, is the imbalance that the aggregator has in period t. Here $\mathbf{x} = \{p^f_{i,j,t}, E_t^u, E_t^d, l_t^u, l_t^d\}$ is the aggregator's set of decision variables and $\mathbf{y} = \{l^f_{j,t}\}$ is the i'th consumer's one.

To solve the optimisation problem the aggregator has to take the following constraints into account:

$$E_t^u = \begin{cases} E_t^s - l_t & \text{if } E_t^s - l_t \leq 0 \\ 0 & \text{if } E_s^t - l_t > 0 \end{cases} \tag{12}$$

$$E_t^d = \begin{cases} E_t^s - l_t & \text{if } E_t^s - l_t \geq 0 \\ 0 & \text{if } E_s^t - l_t < 0 \end{cases} \tag{13}$$

(12) and (13) reflect imbalance definition, which says that if the planned consumption E_t^s purchased at the spot market is less than the actual consumption l_t, i.e. the imbalance is negative, the aggregator must buy up regulation power. If the imbalance is positive and the actual consumption is smaller than expected, then the aggregator must buy down regulation power (Energinet.dk, 2008). Other constraints, such as time intervals for potential shifting of consumption and flexibility amounts, depend on a particular flexibility source. More detailed information is provided in section 4.2 Data.

Final problem formulation, including the consumer's problem, can be written as

$$\begin{aligned} \max_{\mathbf{x}} \quad & \Pi(\mathbf{x}, \mathbf{y}) \\ \text{s.t.} \quad & (12), (13) \\ & \mathbf{y} \text{ solves} \quad \begin{aligned} \min_{\mathbf{y}} \quad & C(\mathbf{x}, \mathbf{y}) \\ \text{s.t.} \quad & (8), \\ & \text{specific flexibility source constraints.} \end{aligned} \end{aligned} \tag{14}$$

The Stackelberg game can be formulated mathematically using bilevel programmes, which are mathematical programmes that contain optimisation problems in their constraints. The leader's, the aggregator's, problem is called the upper-level problem and the follower's, the consumer's, problem is called the lower-level problem. One solution method of this bilevel problem is to use Extended Mathematical Programming (EMP) tool, which formulates the bilevel problem as a Mathematical Program with Equilibrium Constraints (MPEC). The reformulation is made by replacing the lower-level problem by its Karush-Kuhn-Tucker conditions. Afterwards, such problem can be solved using already existing solvers, for example, those available within GAMS (GAMS, 2018).[8]

In this study, due to the model complexity, the solution is obtained numerically. The chosen approach allows to track all changes in the system during the simulation and provides the whole system's view at any point in time.

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[8] For similar problems see Zugno et al. (2013) and Luo et al. (1996).

3.2.2 Contract cost

The aggregator pays compensations to its consumers based on the market value of the flexible consumption and the amount of used flexibility. This means that, unlike in the flat tariff case where the consumers are offered a fixed payment every month, the flexible tariff requires more aggregator's resources for settlement process and maintaining transparency (Harbo and Biegel, 2012).

Let c_c be the aggregator's fixed contract cost. Thus, the total contract cost for the portfolio of consumers is equal to the product of the contract cost c_c and the total number of consumers in the portfolio K, $C_c = c_c K$.[9] As a result, the aggregator's profit in each scenario is reduced by the total contract cost of the portfolio.

3.2.3 Uncertainty and forecasting

While maximising its profits, the aggregator faces uncertainty in regulating energy prices, the direction of regulating energy for the whole system and its imbalance amounts. Thus, in order to make an optimal flexible load scheduling decision it uses forecasts.

The aggregator's forecasts for up and down regulating prices are simulated using the following formulas:

$$p^u_{forecast,t} = (1 + e_{u,t}) p^u_{actual,t} \tag{15}$$

$$p^d_{forecast,t} = (1 + e_{d,t}) p^d_{actual,t} \tag{16}$$

where $p^u_{forecast,t}$ and $p^d_{forecast,t}$ are up and down regulating energy prices for the time period t, $p^u_{actual,t}$ and $p^d_{actual,t}$ – actual up and down regulating prices for the time period t, $e_{u,t}$ and $e_{d,t}$ – error variables for up and down regulating prices, which are random variables uniformly distributed in the interval [-0.05, 0.05] for the time period t. Thus, it means that the forecast has a maximum error of 5%.

Often the dominating direction of the system's total imbalance does not change for several hours. Therefore, the aggregator's forecast is based on the information about the dominating

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[9] It is assumed that the consumer needs a contract for every source of flexibility he or she is offering.

direction in previous hours. For example, if the whole system needed up regulation in the previous hour, the aggregator expects that the system will need up regulation in the current hour, too. However, the aggregator may predict the coming change in the system's imbalance direction from up and down regulation prices and their movement towards the spot price for that hour. So, when there is a change in the dominating direction, the system's total imbalance direction is predicted correctly with a probability of 1/3, as there are three possible outcomes: the system might need up regulation, down regulation or it is balanced. In a one-price system, the imbalance price for consumption depends on the dominating direction of the system's total imbalance but not the aggregator's imbalance. In case the system is balanced, the imbalance price for consumption is equal to the spot price.

It is also assumed that the aggregator forecasts its imbalance with a maximum deviation of 10% from the actual imbalance for every hour. The aggregator's forecast is simulated using the following formula:

$$I_{forecast,t} = (1 + e_{i,t}) I_{actual,t} \tag{17}$$

where $I_{forecast,t}$ and $I_{actual,t}$ are the aggregator's forecasted and actual imbalance in the period t, and $e_{i,t}$ is a random variable for the imbalance error, which is uniformly distributed in the interval [-0.1, 0.1] for the time period t.

Even though forecasting the imbalances and regulating prices for the next hours is a complicated task for the aggregator, the errors in obtaining these values are chosen to be low. The reason is that the expected and the actual imbalance payments differ significantly when higher error values are chosen for simulation, which leads to a situation when the aggregator is incapable to reduce its actual imbalance. Figure B.4 and Figure B.5 in Appendix B provide results for four scenarios with a larger imbalance price forecasting error.

4 Case study description

The following case study description defines cases and scenarios for flexible demand simulations and provides all necessary data.

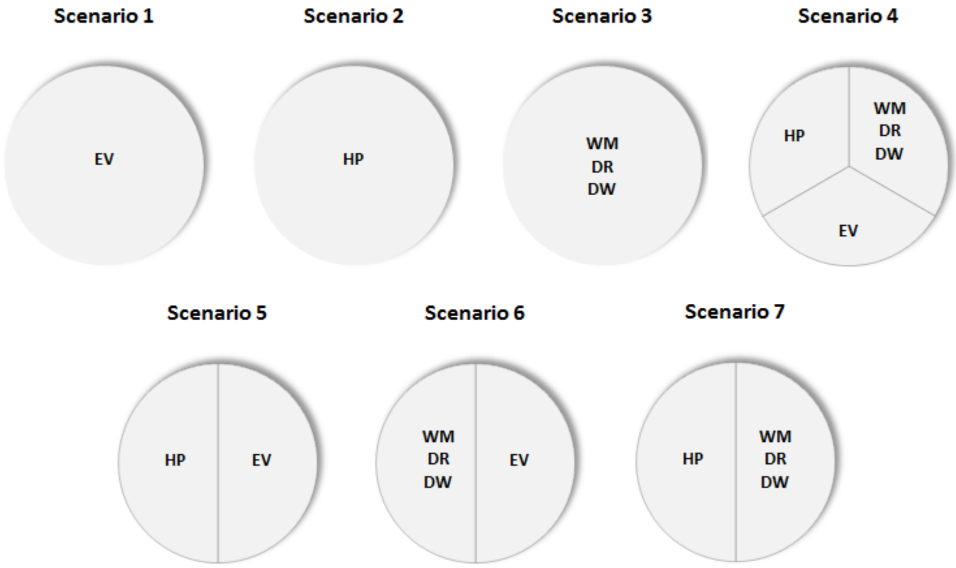

Figure 4: Scenarios reflecting different compositions of the aggregator's portfolio

4.1 Cases and scenarios

Simulations are run for two cases. Case 1 examines the variations in consumption and available flexibility during the year. However, time for running the optimisation for the whole year increases significantly with every additional appliance. Thus, Case 2 with a shorter period of one week is used to investigate the effects of a higher number of flexibility sources. The week is chosen to reflect the winter maximum when the consumption and, therefore, imbalances are highest. According to the ENTSO-E guidelines for the system adequacy forecasts (ENTSO-E, 2014*b*), the winter peak is calculated for the third Wednesday in January (the third week in 2014). However, in 2014, weather temperature was lower in week 4, which results in higher consumption of electricity. Thus, week 4 was used for one week simulations in Case 2. In the model, the cases are reflected in T, which is the total number of time periods in the optimisation: in Case 1, $T = 8760$; in Case 2, $T = 168$.

Seven scenarios are used in order to analyse the effects of different portfolio compositions on the value created by enabling demand flexibility. All scenarios are presented in Figure 4. The total amount of flexible consumption in the portfolio is divided equally between three consumer clusters providing flexibility from various sources. For example, in Scenario 1 the aggregator has only those consumers who have EVs. Scenario 2 includes only those, who have HPs. Scenario 3 analyses flexibility provided by smaller home appliances, where it is again divided equally between washing machines (WMs), clothes dryers (DRs) and dish washers (DWs). Scenario 4 comprises all types of flexibility: here one third of flexibility comes from EVs cluster, one third from HPs cluster and the rest from the small home appliances cluster. In the model, the source of flexibility is denoted by j, while J reflects the total number of flexibility sources types in the portfolio. For instance, in Scenario 1, the flexibility is provided only EVs, therefore, $J = 1$. Meanwhile, in Scenario 4, the aggregator has an access to all five types of flexibility sources and $J = 5$.

4.2 Data

The model was applied using the Nordic power market and Denmark's bidding area DK2 data for 2014. Electricity spot and regulating energy prices, the dominating direction of the system's total imbalance, as well as the hourly consumption for each bidding area, are available on the Nord Pool website.

Total annual consumption and its distribution between various household appliances determine the amount of flexible demand. An average Danish household of three persons living in a house consumes approximately 4500 kWh per year (Dong Energy, 2013). Flexible consumption of washing machines, clothes dryers and dish washers is a part of this total consumption. However, electric vehicles and heat pumps are still used moderately; therefore, the energy used for transportation and heating purposes is not reflected in data from 2014 (see Appendix A Figure A.2). This is corrected by increasing the average annual total consumption of 4500 kWh by the average consumption of electric vehicles and heat pumps. An average annual consumption of one unit of each flexibility source is presented in Figure 5.

The value of aggregated demand flexibility depends not only on the total annual flexible consumption, but also on hourly consumption patterns during the year. Table 2 shows flexibility sources' consumption patterns and time periods for possible shifts in consumption schedules.

According to the Dong Energy household's consumption report (Dong Energy, 2013), on

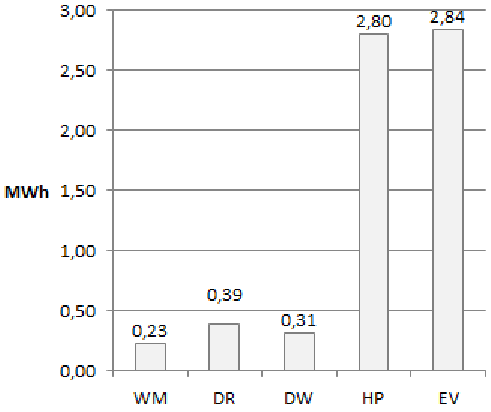

Figure 5: Average annual consumption of one unit of flexibility source (Case 1)

Table 2: Flexible consumption patterns, amounts and time periods for potential shifting

Flex. source	Consumption pattern	Flexibility amount per time	Flexibility time period
WM	5 loads per week	0,87 kWh	6 hours per load
DR	Correlated with washing machine's schedule, 3 loads per week	2,5 kWh	3 hours per load
DW	3 loads per week	1,98 kWh	6 hours per load
HP	Correlated with outside temp., turns on 8 times per 24 hours, 7 months per year	varies with temp.	3 hours
EV	Plugged-in for 10 hours every night	7,8 kWh	10 hours per night

average, a washing machine is used 5 times per week and it requires around 0,87 kWh of electricity per load. Since the washing cannot be interrupted, 0,87 kWh corresponds to flexibility provided in a block of two hours t and $t+1$ ($l^f_{i,j,t} = 0,5$ kWh and $l^f_{i,j,t+1} = 0,37$ kWh). In this model, it is assumed that the consumer may accept to delay washing, however, the clothes must be washed no later than six hours after the notice of washing was sent. This means that there is a six hour time period within which the aggregator can shift the consumption. Similarly, a clothes dryer is, on average, used three times per week and consumes 2,5 kWh per load ($l^f_{i,j,t} = 2,5$ kWh). Its usage is correlated with the schedule of a washing machine. A dish washer uses 1,98 kWh of electricity per load ($l^f_{i,j,t} = 1,98$ kWh), three times per week, with a six-hour period of flexibility.

Consumption schedules for washing machines, clothes dryers and dish washers during the week are generated using a random variable. However, there are some constraints that must be satisfied. For example, the consumer cannot send the consumption notice for the aggregator during the night hours, i.e. from 12:00 a.m. to 6:00 a.m.; a clothes dryer must be loaded no later than two hours after the washing is done, or, if it was finished during the night, between 6:00 to 8:00 a.m..[10]

An HP is turned on only seven months per year, i.e. from October until May. On average a 120 m2 house for heating uses 2800 kWh per year. Unlike with other appliances, the hourly consumption varies and depends on the outside temperature: cold winter days significantly increase the need for heating. Thus, the load curve is negatively correlated with the outside temperature (see Appendix A Figure A.3). It is assumed, that the HP is turned on for one hour in a three-hour interval and there are no changes in total consumption level of the HP due to moving heating processes in time.

The consumer agrees to keep an EV plugged-in for ten hours, from 9:00 p.m. till 7:00 a.m.. According to Denmark's Ministry of Transport (2012), the average Dane travels 39 km a day. An electric vehicle consumes about 20 kWh/100 km, which means that the aggregator has 7-8 kWh of flexible demand each night and about 2840 kWh per year. An EV must charge for approximately 4 hours ($l^f_{i,j,t} = 1,95$ kWh in each hour), as the maximum

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[10] Other rules guarantee that there cannot be more than two loads per day for washing machines and only one load per day for a dish washer. Also, there cannot be more than three days without washing dishes and more than two days in a row of using a dish washer.

Table 3: The number of appliances in each scenario in Case 1 (Case 2)

Scenario	EV	HP	WM	DR	DW
1	18 (214)	-	-	-	-
2	-	18 (68)	-	-	-
3	-	-	73 (764)	43 (444)	54 (561)
4	6 (71)	6 (23)	24 (255)	14 (148)	18 (187)
5	9 (107)	9 (34)	-	-	-
6	9 (107)	-	36 (382)	21 (222)	27 (280)
7	-	9 (34)	36 (382)	21 (222)	27 (280)

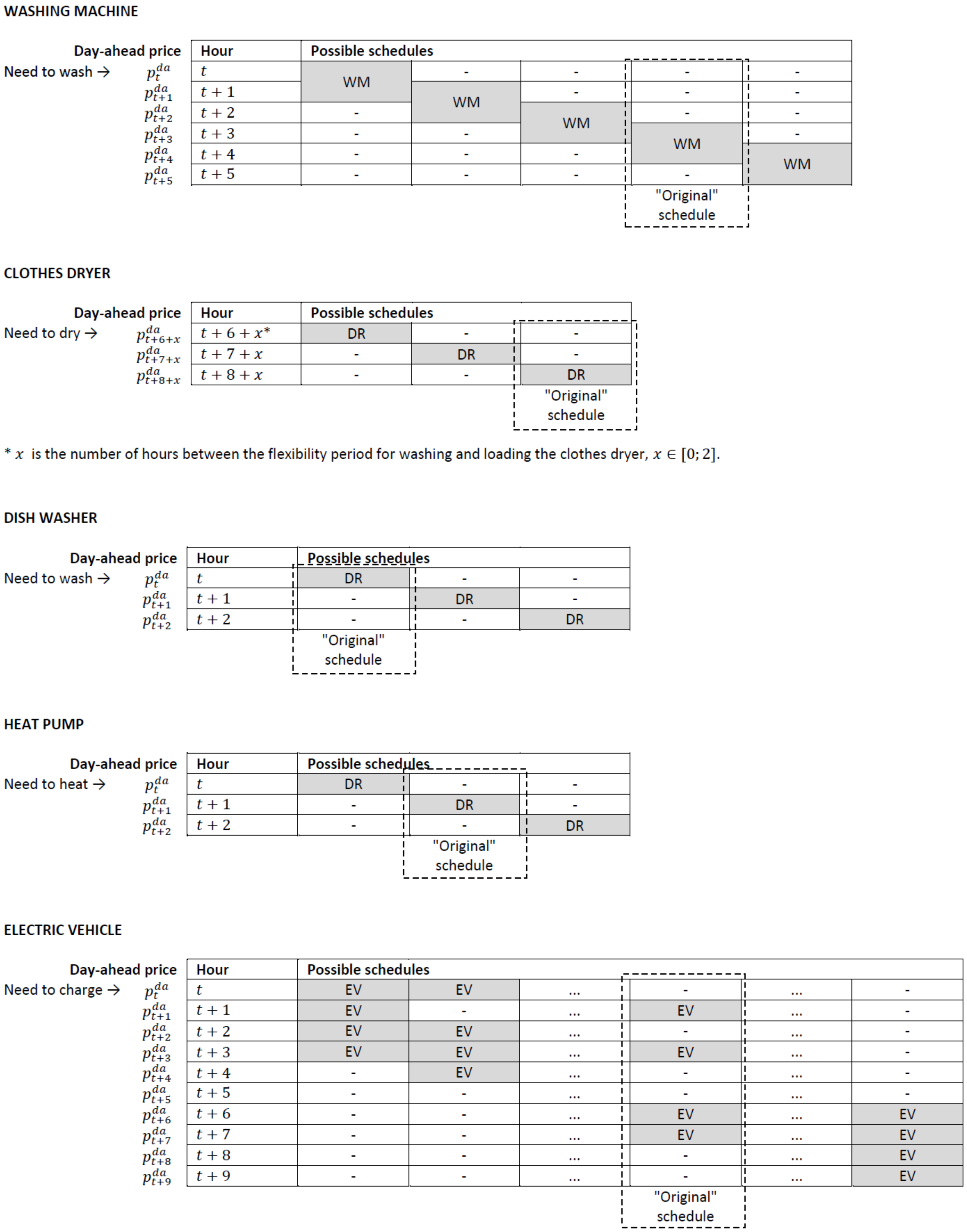
boundary for charging is 2.2 kW (Hennings et al., 2013). However, the charging of EVs can be interrupted, which means that the consumer will choose four hours during the night, when the day-ahead prices are the lowest.

The scheme for possible schedules for each flexibility source type is presented in Figure 6. For example, there are 5 possible schedules for washing. Let's assume that, according to the day ahead prices, the cheapest option to wash clothes is in hours $t+3$ and $t+4$. Then, the schedule with the lowest cost of using the flexibility source is called the "original" schedule and is sent to the aggregator. Each consumer has his/her individual consumption schedule.

Case 1 and 2 represent two portfolio options with different total flexibility amounts. In Case 1 the aggregator has an access to 50 MWh of flexibility per year, while in Case 2 it gathers 10 MWh per week, which allows for a larger number of flexibility sources. The number of appliances is determined by each unit's annual and weekly consumption accordingly. As HPs use much more energy during week 4 in winter, the number of HPs is relatively lower in Case 2 (see Figure 7 and Table 3).

It is assumed, that the aggregator has 1000 households. Hourly consumption of one household is derived using the load curve and the annual electricity consumption in the DK2 bidding area. The load curve is corrected for increased consumption due to HPs and EVs. Further, the load curve is used to model the aggregator's imbalance, which is equal to 2% of its consumers' consumption (see Appendix A Figure A.4). Usually, the aggregator's imbalance is in the same direction as the whole system. Therefore, in imbalance simulations it is assumed that it may be in the opposite direction only 5% of the time.

In Denmark, a fixed supply contract charge for a typical household (4.000 kWh/year) is



WASHING MACHINE

	Day-ahead price	Hour	Possible schedules				
Need to wash →	p_t^{da}	t	WM	-	-	-	-
	p_{t+1}^{da}	$t+1$		WM	-	-	-
	p_{t+2}^{da}	$t+2$	-		WM	-	-
	p_{t+3}^{da}	$t+3$	-	-		WM	-
	p_{t+4}^{da}	$t+4$	-	-	-		WM
	p_{t+5}^{da}	$t+5$	-	-	-	-	
						"Original" schedule	

CLOTHES DRYER

	Day-ahead price	Hour	Possible schedules		
Need to dry →	p_{t+6+x}^{da}	$t+6+x$*	DR	-	-
	p_{t+7+x}^{da}	$t+7+x$	-	DR	-
	p_{t+8+x}^{da}	$t+8+x$	-	-	DR
					"Original" schedule

* x is the number of hours between the flexibility period for washing and loading the clothes dryer, $x \in [0; 2]$.

DISH WASHER

	Day-ahead price	Hour	Possible schedules		
Need to wash →	p_t^{da}	t	DR	-	-
	p_{t+1}^{da}	$t+1$	-	DR	-
	p_{t+2}^{da}	$t+2$	-	-	DR
			"Original" schedule		

HEAT PUMP

	Day-ahead price	Hour	Possible schedules		
Need to heat →	p_t^{da}	t	DR	-	-
	p_{t+1}^{da}	$t+1$	-	DR	-
	p_{t+2}^{da}	$t+2$	-	-	DR
				"Original" schedule	

ELECTRIC VEHICLE

	Day-ahead price	Hour	Possible schedules					
Need to charge →	p_t^{da}	t	EV	EV	...	-	...	-
	p_{t+1}^{da}	$t+1$	EV	-	...	EV	...	-
	p_{t+2}^{da}	$t+2$	EV	EV	...	-	...	-
	p_{t+3}^{da}	$t+3$	EV	EV	...	EV	...	-
	p_{t+4}^{da}	$t+4$	-	EV	...	-	...	-
	p_{t+5}^{da}	$t+5$	-	-	...	-	...	-
	p_{t+6}^{da}	$t+6$	-	-	...	EV	...	EV
	p_{t+7}^{da}	$t+7$	-	-	...	EV	...	EV
	p_{t+8}^{da}	$t+8$	-	-	...	-	...	EV
	p_{t+9}^{da}	$t+9$	-	-	...	-	...	EV
						"Original" schedule		

Figure 6: Possible schedules for each flexibility source type

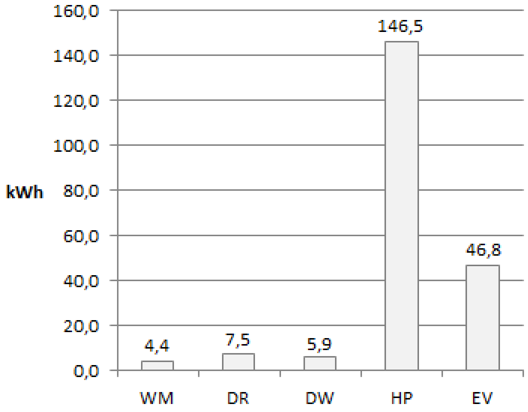


Figure 7: Average weekly consumption of one unit of flexibility source (Case 2)

Table 4: Total number of contracts in each scenario, Case 1 and Case 2

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Case 1	18	18	170	68	18	93	93
Case 2	214	68	1769	684	141	991	918

around 9 DKK per month (€0-28 per week or €14-52 per year) (Kitzing et al., 2016). However, the aggregator is already billing its consumers and an increase in the fixed contract cost should account only for additional resources used to track offered flexibility amounts and calculate compensations according to the market prices. Therefore, the fixed contract cost for flexibility (further – fixed contract cost) is relatively small compared to the total fixed supply contract cost.

To investigate the effect of fixed contract cost on the aggregator's profit in each scenario, I used a range of fixed contract cost per consumer: €0,00-€0,015 per week in Case 2; and €0,00-€0.55 per year in Case 1. The total fixed contract cost depends on the total number of contracts in a portfolio, presented in Table 4.

5 Results

Simulations are run on a laptop with an Intel Core i3 1.70 GHz processor and 4 GB memory using *Wolfram Mathematica 10.3*. The output for Case 1 and Case 2 includes hourly payments for regulating energy before and after the optimisation, compensations to consumers,

Table 5: Actual and forecasted reductions in total imbalance payments (Case 1 and Case 2)

Case 1	1	2	3	4	5	6	7
Actual reduction in total imb. payments, %	5,1	4,7	7,4	5,7	4,9	6,4	6,2
Forecasted reduction in total imb. payments, %	7,3	8,1	10,2	8,5	7,7	8,8	9,2
Actual reduction in total imb. payments, €	57,1	52,1	81,8	63,8	54,6	70,9	68,4
Forecasted reduction in total imb. payments, €	71,78	79,53	100,53	83,73	75,66	87,06	90,93
Difference in differences, €	14,68	27,38	18,74	19,88	21,03	16,15	22,50
Case 2	1	2	3	4	5	6	7
Actual reduction in total imb. payments, %	3,0	5,1	3,4	3,9	4,1	3,1	4,2
Forecasted reduction in total imb. payments, %	3,8	12,1	4,4	6,7	7,9	4,1	8,2
Actual reduction in total imb. payments, €	1,06	1,80	1,20	1,36	1,43	1,09	1,47
Forecasted reduction in total imb. payments, €	1,21	3,85	1,42	2,14	2,53	1,29	2,61
Difference in differences, €	0,15	2,05	0,21	0,78	1,10	0,20	1,15

consumers' profit, shifted energy amounts and optimised consumption schedules for each flexibility source unit. Also, simulations reflect the difference between forecasted and actual outcomes of the optimisation. In the following sections the results do not include fixed contract cost incurred by the aggregator. This allows to compare different compositions of portfolios based on provided flexibility characteristics only. The impact of the fixed contract cost on the imbalance payments reduction is analysed in the last section.

5.1 Reductions in imbalance cost

Results show that in all scenarios for Case 1 and Case 2 the imbalance payments after the optimisation are lower than before (see Figure 8). In Case 1, the actual total imbalance payment for year 2014 before the optimisation is equal to €1112,31, and after the optimisation it varies between €1030,52 and €1060,16 depending on the scenario. In simulations for one week the number of appliances is larger, so the percentage drop is even higher – from €35,29 to €21,23 – €28,21 (see Table 5).

Figure 8 also shows that different compositions of flexibility sources – EVs, HPs, washing machines, clothes dryers and dish washers – influence the aggregator's payments in balancing market. The results in Case 1 and Case 2 are consistent – the best choice for the aggregator seems to be a portfolio with consumers that have small home appliances, which corresponds to Scenario 3, and the least attractive is a portfolio with those that have HPs, i.e. Scenario 2. In further analysis, the focus is set on Case 2, where the number of appliances is higher.

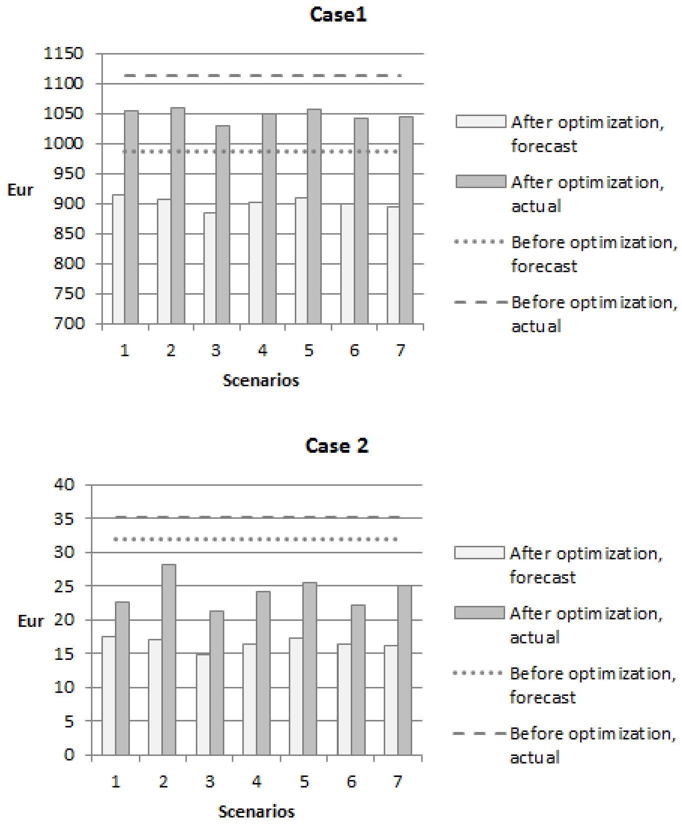


Figure 8: Total imbalance cost before and after optimisation (Case 1 and Case 2)

In Scenario 3, the actual total imbalance payment is lowered by 40%, while in Scenario 2 the reduction is only 20%. Using the flexibility of consumers that have EVs, i.e. Scenario 1, imbalance payments are 36% lower. All other scenarios are combinations of flexibility sources and their results are close to the average outcomes of the first three scenarios. This means that there is no obvious benefit from the portfolio diversification. Even though combining various flexibility sources with different patterns of flexible demand in one portfolio increases time when flexibility is available for reducing imbalances, it does not bring additional value. Therefore, the aggregator might find it beneficial to specialise in certain types of flexibility sources.

5.2 Compensations to consumers

Only less than half of available flexible consumption is actually shifted (see Table 6): of 10 MWh, available during one winter week, the aggregator moves only 4,229 – 4,989 MWh. During the whole year, the percentage share is even lower. The reason for this low usage of available flexibility is that the compensation exceeds the imbalance payment savings or the consumption schedule is in line with the optimal schedule in the first place.

Table 6: The amount and a number of hours of shifted flexible consumption, imbalance savings-shifted consumption and compensation-shifted consumption ratios (Case 1 and Case 2)

Case 1	1	2	3	4	5	6	7
Shifted consumption, kWh	16988	20208	15926	17270	18277	16427	17693
Number of hours with shifted consumption	968	1316	5313	5083	2051	5235	5120
Imbalance savings-shifted consumption ratio, €/MWh	6,63	4,26	8,13	6,34	5,44	7,45	6,16
Compensation-shifted consumption ratio, €/MWh	3,27	1,68	3,00	2,64	2,45	3,13	2,29
Case 2	1	2	3	4	5	6	7
Shifted consumption, kWh	4590	4989	4229	4464	4687	4427	4443
Number of hours with shifted consumption	22	56	122	126	62	124	125
Imbalance savings-shifted consumption ratio, €/MWh	4,26	3,06	7,37	4,90	3,72	5,64	5,14
Compensation-shifted consumption ratio, €/MWh	1,51	1,64	4,04	2,41	1,61	2,71	2,84

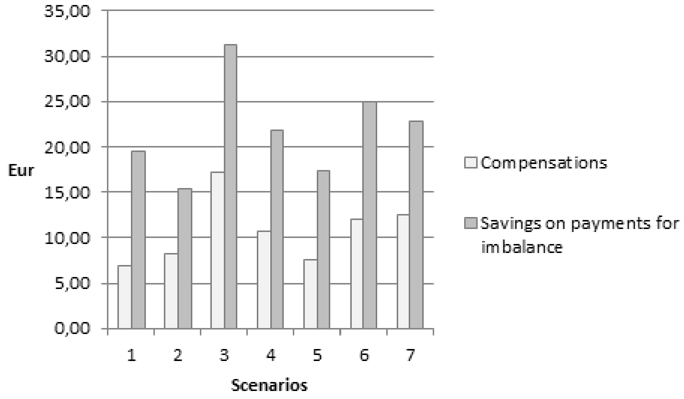


Figure 9: Compensations to consumers and savings on payments for imbalance (Case 2)

As we can see from Figure 9, compensations to consumers for provided flexibility also differ depending on a scenario (see Appendix B Figure B.2 for Case 1). The highest compensations are paid for flexibility of small home appliances (€17,10), the lowest – to EVs' owners (€6,91). Even though the expenses for flexibility in Scenario 3 are largest, the amount of shifted consumption is smallest (see Table 6). However, the value of this shifted consumption is highest. This means that the consumption pattern of small home appliances allows to use their flexibility when the differences in regulating energy, as well as spot prices, are the largest. Thus, the most expensive type of flexibility is the most effective one too. On average, for every megawatt hour of small home appliances' flexibility the aggregator pays €4,04 (see Table 6) and this saves €7,37 in imbalance payments, so it gains €3,33. The gain of shifting one megawatt hour of HPs' consumption is only €1,42 and corresponds to the lowest savings among all scenarios.

However, with the current disutility function, consumers' profit is too low to incentivise them to provide flexibility. Table 7 shows that for one week in winter all consumers together could earn from €0,02 to €0,26. During one year, i.e. in Case 1, 18 owners of electric vehicles share €4,61 and 170 people, who have one of the small home appliances, gain only €8,41. Even if the aggregator would agree to double the compensations and reduce its profit to minimum, most likely the sum would be too low to attract flexibility providers. Hence, if the aggregator decides to target small consumers, in addition to financial incentives, it should consider other ways to incentivise consumers to participate, for example, additional service offers.

Table 7: Consumers' profit and a number of contracts in each portfolio (Case 1 and Case 2)

Case 1	1	2	3	4	5	6	7
Consumer profit, €	4,61	7,87	8,41	6,78	6,15	6,43	7,97
EV	*4,61*	*0,00*	*0,00*	*1,54*	*2,30*	*2,30*	*0,00*
HP	*0,00*	*7,87*	*0,00*	*2,50*	*3,85*	*0,00*	*3,85*
WM, DR, DW	*0,00*	*0,00*	*8,41*	*2,74*	*0,00*	*4,12*	*4,12*
Number of contracts	18	18	170	68	18	93	93
EV	*18*	*0*	*0*	*6*	*9*	*9*	*0*
HP	*0*	*18*	*0*	*6*	*9*	*0*	*9*
WM, DR, DW	*0*	*0*	*170*	*56*	*0*	*84*	*84*
Case 2	1	2	3	4	5	6	7
Consumer profit, €	0,02	0,12	0,26	0,13	0,07	0,14	0,19
EV	*0,02*	*0,00*	*0,00*	*0,01*	*0,01*	*0,01*	*0,00*
HP	*0,00*	*0,12*	*0,00*	*0,04*	*0,06*	*0,00*	*0,06*
WM, DR, DW	*0,00*	*0,00*	*0,26*	*0,09*	*0,00*	*0,13*	*0,13*
Number of contracts	214	68	1769	684	141	991	918
EV	*214*	*0*	*0*	*71*	*107*	*107*	*0*
HP	*0*	*68*	*0*	*23*	*34*	*0*	*34*
WM, DR, DW	*0*	*0*	*1769*	*590*	*0*	*884*	*884*

5.3 The effects of consumption patterns

The length of the time interval for consumption shifting is a very important factor in optimising consumption schedules. Differences in prices increase significantly in longer periods and this makes it possible to use flexibility more effectively. Table 8 illustrates that the longer the period for possible consumption shifting, the higher the standard deviation of spot and imbalance prices for consumption. In this aspect, HPs and clothes dryers are less attractive flexibility sources, while EVs' performance seems to be the best.

Table 8: The average moving standard deviations of spot prices and imbalance prices for consumption during the year for three time periods

	3 hours	6 hours	10 hours
Average moving standard deviation of spot prices	2,01	3,32	4,48
Average moving standard deviation of imbalance prices for consumption	4,57	6,79	8,48

However, the value of flexibility also depends on the time of the day, when it is offered. The standard deviations of regulating energy prices are significantly higher during the day (on average €9,81 during all days of the year) compared to 10 hours at night (on average €6,43), when consumers are charging their electric vehicles. Therefore, from this perspective, EVs is a less attractive flexibility source comparing to small home appliances, often used during the day time, or HPs, available at all times during the heating season.

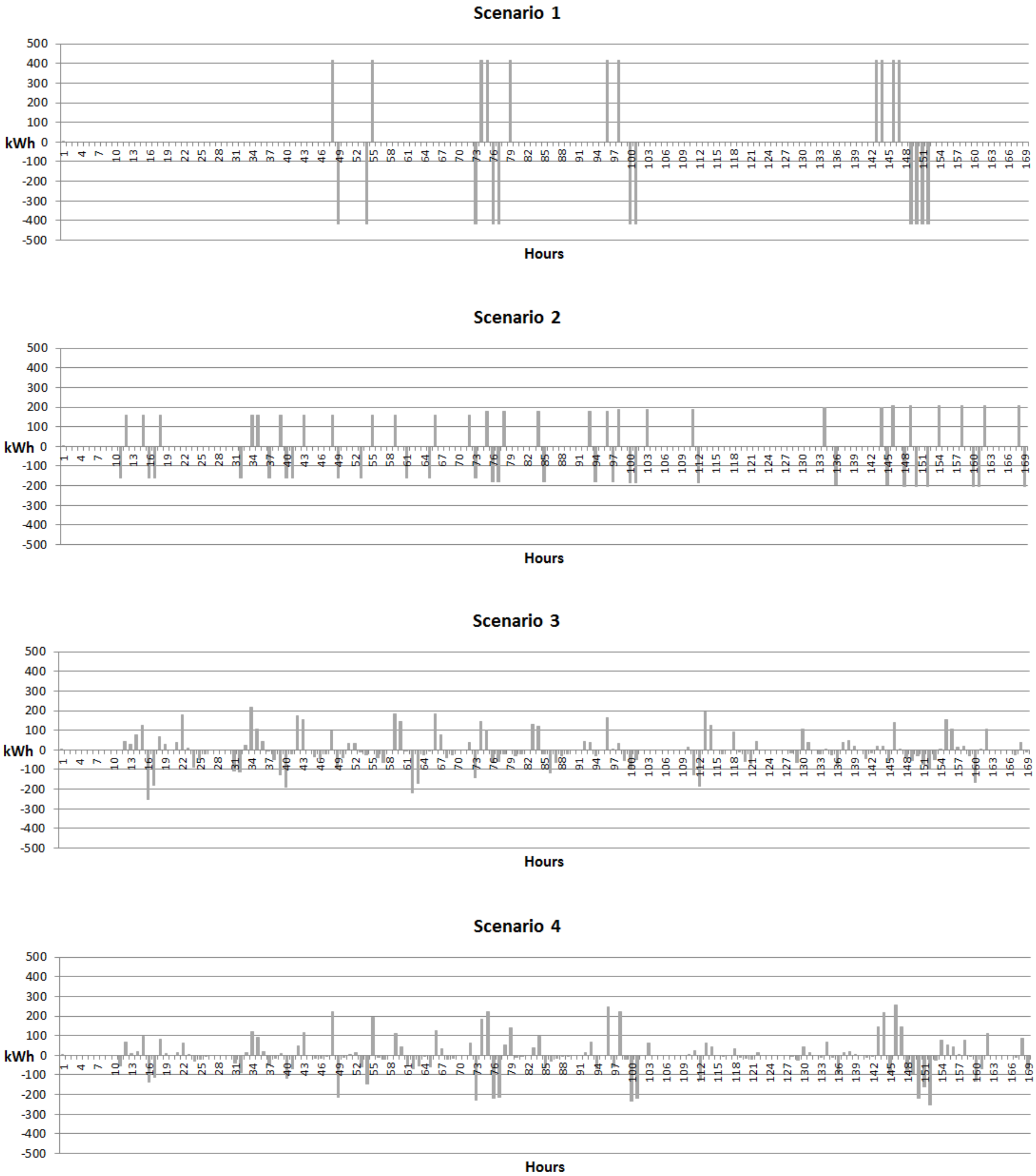


Figure 10: Shifted consumption patterns during one week in winter (Case 2)

Consumption shifting patterns for one week in winter are illustrated in Figure 10. It is easy to distinguish the first three scenarios of EVs, HPs and small home appliances. In Scenario 1, consumers are optimising the charging schedules for their EVs according to the spot prices for the next day. Charging can be interrupted, therefore, consumers choose four hours when the spot price is lowest. This means that all owners of EVs charge their cars at the same four hours during the ten-hour interval at night, when their electric vehicles must be plugged-in. After receiving consumers' schedules, the aggregator checks forecasted regulating energy prices in the ten-hour interval and decides in which hours the consumption should be shifted. Consequently, if the change in regulating energy prices is larger than the change in spot prices plus the compensation to consumers, all available flexibility in those hours is used.

Thus, the maximum number of hours when the demand curve is adjusted during the night is eight. The graph for Scenario 1 shows that charging was shifted only four nights during the week. Negative values indicate consumption reduction: for example, all the consumption in hour 48 (417 kWh) is moved to hour 47. Consequently, because of the identical schedules of all consumers we can see only huge and very fragmented shifts in EVs' power usage. There are only 22 hours during this week, when the demand curve was adjusted for balancing purposes (see Table 6).

In Scenario 2, we can also observe similar amounts of energy being shifted during the week. These amounts are not identical, as in Scenario 1, because the consumption of heat pumps depends on the outside temperature. However, the pattern is quite similar. Consumers are optimising heating schedules for three-hour intervals during the week. Thus, their schedules become identical when they choose the cheapest hours to consume. As a result, in this scenario, due to more often and shorter available flexibility intervals, i.e. three hours eight times per day instead of one interval of ten hours, the aggregator changes the demand curve maximum 16 hours per day. In this particular winter week the aggregator changes the consumption in 56 hours.

Scenario 3 shows more dispersed consumption shifting. This is mainly due to stochastic needs to use small home appliances. In this portfolio, there are many consumers who offer smaller flexibility amounts and their consumption schedules differ, in contrast to the first two scenarios. Also, when the aggregator is moving the consumption of washing machines or dish washers, it has to move a block of two hours of flexibility, as those appliances cannot be interrupted once started. As a result, we can see smaller adjustments of consumption (up to 200 kWh) that are more frequent and take place in 122 hours during the week.

In Scenario 4, where the aggregator has all types of flexibility sources in its portfolio, we can distinguish features of consumption schedule adjustments from the other three scenarios. There are still a few larger shifts of demand, but changes in consumption are dispersed the most (126 hours). However, the results show that this better distribution of flexibility offers does not compensate for the lower effectiveness of EVs and HPs in terms of the total imbalance payments reduction.

The shifted consumption graphs for scenarios 5, 6 and 7 are provided in Appendix B Figure B.1 and illustrate combinations of the first three portfolios. Once again, we cannot distinguish any advantage of having a better diversified portfolio in terms of various flexibility sources.

5.4 The effects of forecasting errors

The aggregator does not have complete information about the market. Hence, another factor influencing payments for imbalance is the ability to forecast regulating prices, the direction of regulating energy for the whole system and the aggregator's imbalance amounts. Even though the aggregator's forecast has high accuracy, the difference in forecasted and actual imbalance payments without optimisation is off by 9%. After the optimisation, the difference depends on the flexibility source.

Table 9: The amount of shifted consumption during the hours with incorrect direction prediction (Case 2)

	1	2	3	4	5	6	7
The amount of shifted consumption, kWh	1253	1312	921	1048	1080	1124	1074

Table 9 shows that the aggregator is shifting HPs' consumption the most, but this brings only moderate savings on imbalance payments. This could mean two things. First, the differences in regulating energy prices are not so big during flexible demand shifting periods. Second, the consumption is shifted more often than in other scenarios and forecasting errors are reducing gains in those hours where the consumption is moved.

When we look at the aggregator's expected and actual reductions in total imbalance pay-

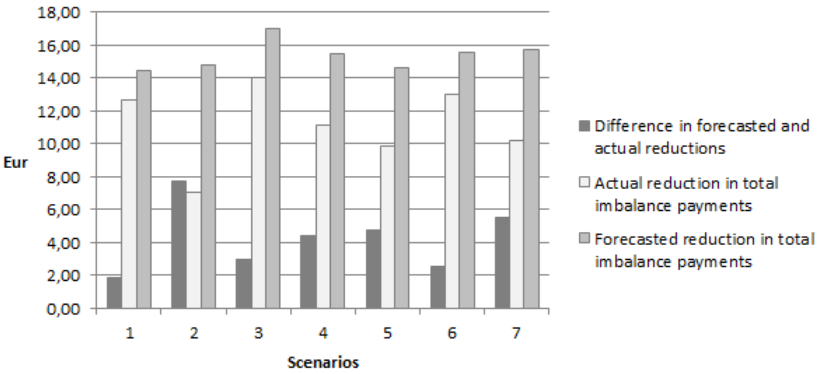


Figure 11: Differences in forecasted and actual reductions in total imbalance payments after optimisation (Case 2)

ments, we see that the largest gap between those values is for HPs scenario (see Figure 11). Thus, the second argument seems more applicable in this case. Results shows that in the hours when the aggregator's forecast fails to predict the direction of regulating energy needs the flexibility from HPs is used the most (1,312 MWh) comparing to other scenarios (1,253 MWh in Scenario 1 and 0,921 MWh in Scenario 3, see Table 9). This in part explains why the gap between forecasted and actual savings in the portfolio with HPs is biggest. However, we should also look at the value of not optimally shifted consumption. Even though the amount of shifted energy during the hours with incorrect direction prediction is smallest for small home appliances scenario, the difference in monetary terms is lowest in EVs scenario (see Figure 11). This is related to the consumption pattern of each type of flexibility source and the fact that, on average, the flexibility of small home appliances is offered when the differences in regulating energy prices are larger. Therefore, shifting the consumption of these appliances in the opposite direction than it is optimal causes larger negative effect to imbalance payments reduction.

However, not only errors in the forecasted dominating direction, but also errors in forecasted regulating energy prices diminish possible savings on imbalance payments. These discrepancies might lead to shifting the consumption in the opposite direction than it is optimal or the actual imbalance savings might not outweigh the compensation for changing the demand curve.

In terms of the forecasting errors' influence on the optimisation, the results are consistent for a longer period too (see Appendix B Figure B.3). In Case 2, the differences in differences between actual and forecasted total imbalance payments before and after optimisation show, that the aggregator is too optimistic about imbalance savings in all scenarios. The mildest effect of forecasting errors can be noticed in Scenario 1, only €1,83 in Case 2 and €14,68 in Case 1, the strongest – in Scenario 2, €7,73 in Case 2 and €27,38 in Case 1.

5.5 Trading at the regulating energy market

A one-price balance settlement system allows the aggregator to make a profit when it has an imbalance in the opposite direction than the dominating direction of the system's total imbalance. Thus, in this case, the aggregator does not have to participate in the regulating energy market in order to benefit from excess demand flexibility. However, we still can see how much energy it would offer at the regulating energy market, in case of two-price balance settlement system (see Table 10).

Table 10: Potential energy offers at the regulating energy market (Case 2)

	Orig. imb.	1	2	3	4	5	6	7
Potential offers at the regulating energy market, kWh	410	5558	4326	3699	3747	4421	4141	3457
Number of hours with offers placed	9	22	34	45	44	39	44	43

In the model, the aggregator's imbalance before the optimisation is allowed to be in the opposite direction than the whole system 5% of the time. In Table 10 we see, that this happens in nine hours during the week. Thus, the aggregator is able to sell 410 kWh of flexible demand at the regulating energy market even before accepting flexibility offers from the consumers. After the optimisation, the amount of offered energy at the market depends on the scenario and hence on shifted flexible consumption patterns.

The largest hourly shifts in demand appear in Scenario 1. Very fragmented and large offers of EVs flexibility mean that the main part of the shifted energy is used for trading in the market, but not to reduce the aggregator's imbalances. In 22 hours during the week, the aggregator can sell around 5,6 MWh of energy at the regulating market. In contrast, the portfolio with small home appliances in Scenario 3 is more suitable for imbalance reduction, as flexibility offers are smaller but occur more frequently. The aggregator can place bids accounting for a total of 3,7 MWh in 45 hours during the week.

According to current regulations, bids that are smaller than 10 MWh are not accepted at the regulating energy market. This means, that it would be easier for the aggregator to place a bid if it would have a portfolio of EVs instead of small home appliances.

5.6 Impact of fixed contract cost

Fixed contract cost has a considerable influence on the aggregator's profitability and can change its preferences with regard to portfolio composition. For example, due to a large number of contracts in Scenario 3, where the aggregator uses small home appliances' flexibility, the level of fixed contract cost, naturally, has the biggest impact (see Figure 12 and Figure 13). When the cost level reaches €0,482 per year in Case 1 and €0,009 per week in Case 2, the savings in imbalance payments are outweighed by the fixed contract cost and the aggregator should revise it's portfolio: the composition or the number of contracts (see Table 11).

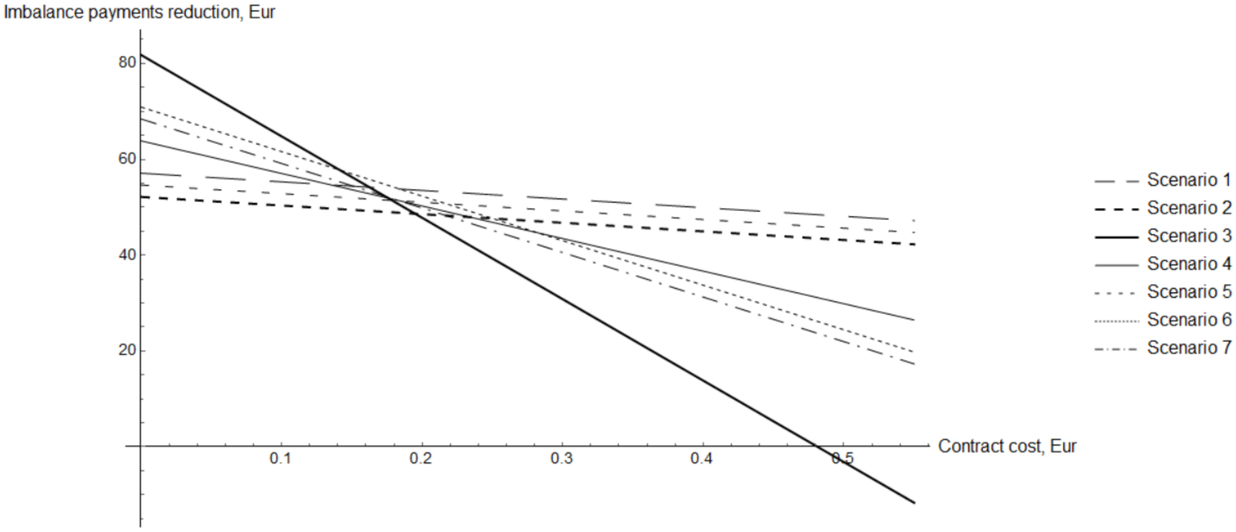


Figure 12: The impact of fixed contract cost on imbalance payments reduction, Case 1

Figure 12 shows that in the longer run (Case 1 representing the whole year), when the fixed contract cost becomes relatively high, a portfolio of EVs (Scenario 1) provides the largest net benefit of using flexibility. Meanwhile, portfolios that include small home appliances

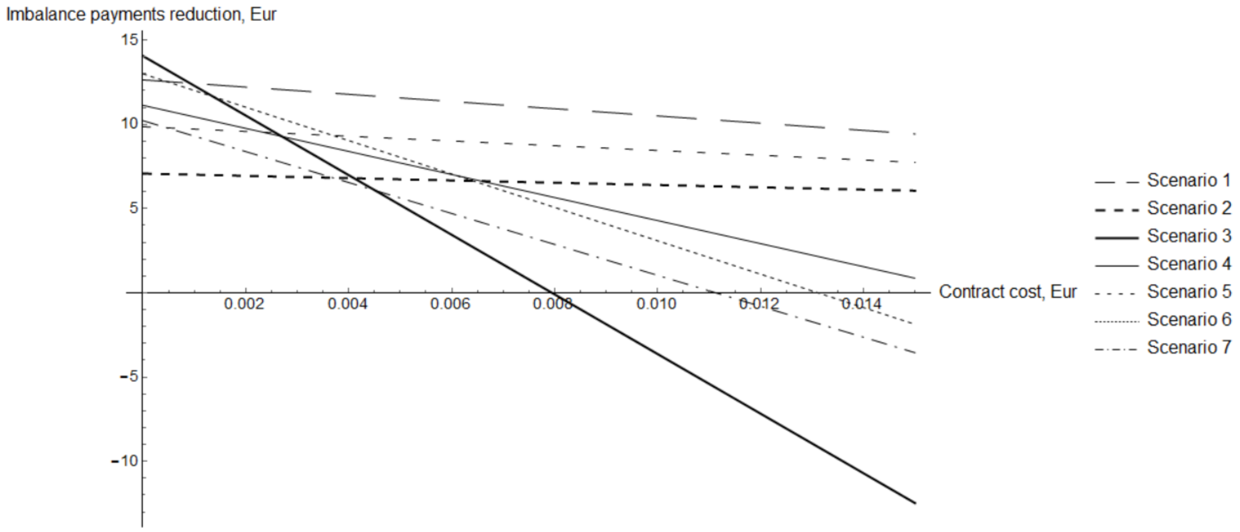


Figure 13: The impact of fixed contract cost on imbalance payments reduction, Case 2

(Scenario 3, 4, 6 and 7) are the least attractive, since the number of contracts and the total contract cost is large. In the short period (see Figure 13), situation is similar: with relatively high fixed contract cost the benefit of small home appliances' flexibility cease to outweigh fixed contract cost sooner that in other portfolios that does not include this source. However, in the analysed winter week, the number of heat pumps is the lowest comparing to other sources of flexibility, leading to lower total fixed contract cost and the highest net benefit of using their flexible load. In this case, fixed contract cost can be the highest among all portfolios, €0,104, and still sustain a non-negative profit from shifting the consumption of heat pumps (see Table 11).

In Figure 12 and Figure 13 we can distinguish contract cost intervals indicating the best portfolio choice for the aggregator. In Case 1, when the cost is relatively low, $c_c \in [0; 0,141)$, the aggregator would choose a portfolio with small home appliances' flexibility. When the cost is in the interval $c_c \in (0,141; 0,184)$, the aggregator prefers a portfolio of mixed flexibility sources: small home appliances and EVs. And finally, when the cost gets relatively high, $c_c \in (0,184; 3,172)$, the portfolio of EVs is the most attractive. If the contract cost rises even higher, then aggregator should reduce the number of contracts in its portfolio and look for the most profitable option to shift flexible consumption. In Case 2, when the cost is in the interval $c_c \in [0; 0,001)$, the aggregator prefers a portfolio of small home appliances, when $c_c \in (0,001; 0,038)$ – a portfolio of EVs, and when $c_c \in (0,038; 0,104)$ – a portfolio of

HPs.

The analysis suggests that under certain fixed contract cost levels a portfolio with mixed types of flexibility sources can be superior to the one with a single type of flexibility source. However, in both investigated cases, most of the time the aggregator chooses a single type of flexibility source in which it would specialise depending on the fixed contract cost level.

Table 11: Maximum fixed contract cost to keep non-negative profit from shifting the consumption depending on a scenario and case, €

	1	2	3	4	5	6	7
Case 1	3,172	2,897	0,481	0,939	3,035	0,762	0,736
Case 2	0,059	0,104	0,008	0,016	0,070	0,013	0,011

6 Conclusions and discussion

This paper focuses on the role of flexible demand aggregators and the effects of their portfolio choice on imbalance payments and compensations to flexibility providers. A game theoretical model has been used to simulate optimal flexible load schedules yielding the highest savings on imbalance payments. The model has five stages in which the consumer schedules his or her flexible load based on day-ahead prices, and the aggregator decides what flexibility prices would incentivise the consumer to shift flexible load and reduce payments for imbalance. The effects of different portfolio compositions are reflected in seven scenarios. Nordic power market data for Denmark's DK2 price area, as well as specific technical data for appliances and typical usage of appliances in Danish households allow to achieve realistic outcomes of demand-side flexibility employment for balancing purposes.

Results show that different compositions of flexibility sources (EVs, HPs, washing machines, clothes dryers and dish washers) influence the aggregator's imbalance payments and compensations to consumers for provided flexibility. A portfolio of small home appliances seems to be the most attractive option for the aggregator. Moreover, it also yields the highest payoffs for the consumers. However, in all scenarios the compensation for the shifted load is too low to incentivise consumers to participate in flexibility trading. Consequently, aggregators might have to find other ways to encourage consumers to offer their flexibility, for example, promote additional services.

An important factor in optimising consumption schedules is the length of the time interval for the flexible load shifting. Differences in regulating energy prices increase significantly in longer periods and higher volatility enables to yield higher savings on imbalance payments. However, this is not a sufficient characteristic for the flexibility source to be the most effective. The effectiveness also depends on time when the flexibility is offered. Results indicate that flexibility offers during the day time are more valuable than at night. This is also related to the fact that price differences are larger during the day time.

With no fixed contract cost, there is no indication that portfolio diversification, in terms of different flexibility sources, could bring additional value in reducing imbalance payments. Therefore, the aggregators might choose to specialise in certain types of flexibility sources that have a potential for maximum savings. However, if the aggregator incurs fixed contract cost, under certain cost level, the mix of different flexibility sources can be beneficial. Also, with increasing fixed contract cost, the aggregator might switch from one type of flexibility to another.

The difference between the forecasted and the actual reductions in imbalance payments is also affected by the portfolio composition. Portfolio of EVs allows to predict the reductions in imbalance payments with the smallest error, while the forecasted outcomes of HPs portfolio are the least accurate. In the latter scenario, frequent changes in consumption schedules lead to lower actual savings due to an increase in forecasting errors.

In a one-price balance settlement system the aggregator does not have to participate in the regulating energy market in order to benefit from excess demand flexibility. However, this model allows to determine potential flexibility trades in case of two-price balance settlement system. Due to the largest hourly shifts in load schedules, EVs' flexibility can be traded the most. Furthermore, high value of minimum bid size, determined by current regulations, causes more difficulties for the aggregator to place bids of dispersed small home appliances flexibility than that of more fragmented but larger in size EVs' flexibility. Thus, since diversification results in more dispersed flexibility offers, they are more likely to be used for imbalance payments reductions than excess flexibility trading.

There are several directions for future extensions of this research. In the future, increased renewable energy integration will change electricity prices and therefore potential value of demand-side flexibility. Modelling possible future scenarios would allow the aggregators to choose the best investment strategy and evaluate related risks. Aggregators could also be BRPs responsible not only for the consumption but also for the production side. Moreover, different portfolio compositions and introduction of penalties for not delivered flexibility could lead to different bidding strategies in the balancing market. This model is applied for the Nordic power market, thus, different geographical areas and peculiarities of other power markets could generate different outcomes. Also, the aggregator's decisions could be influenced by its behaviour in the day-ahead and intraday markets. From the consumer's point of view, different disutility functions or other contracts for changing flexible consumption schedule could also be investigated.

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Appendix A Additional information about data

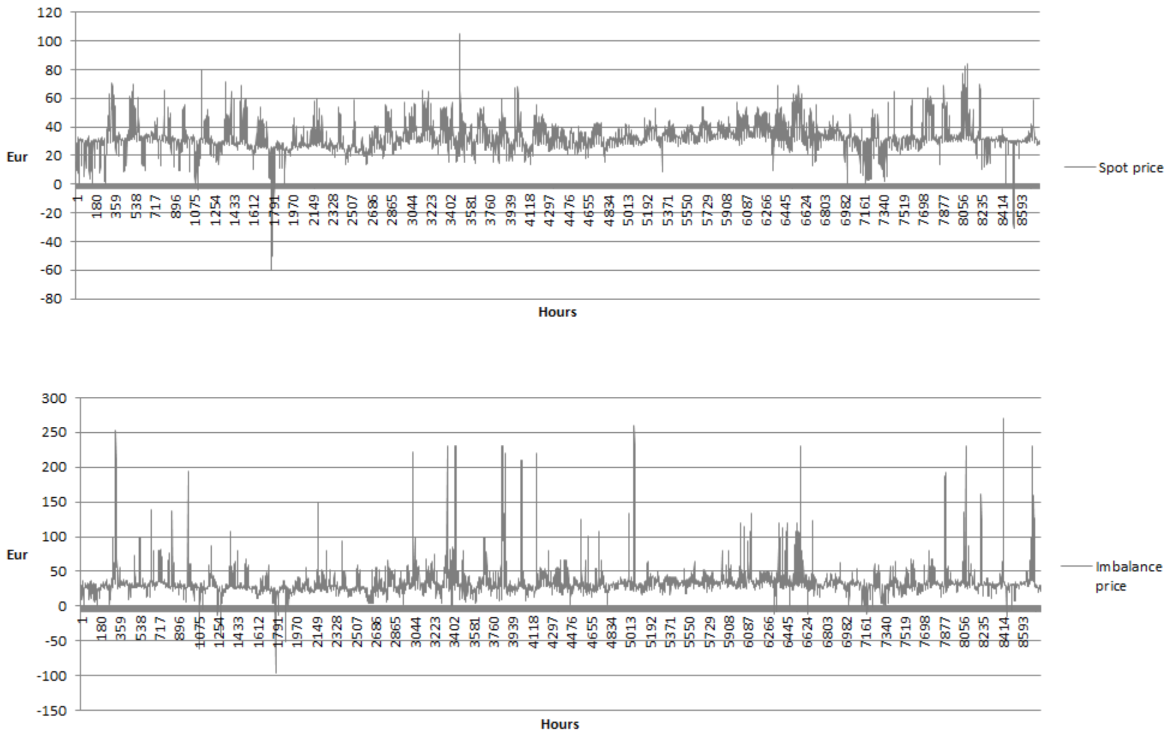

Figure A.1: Compensations to consumers and savings on payments for imbalance (Case 1)

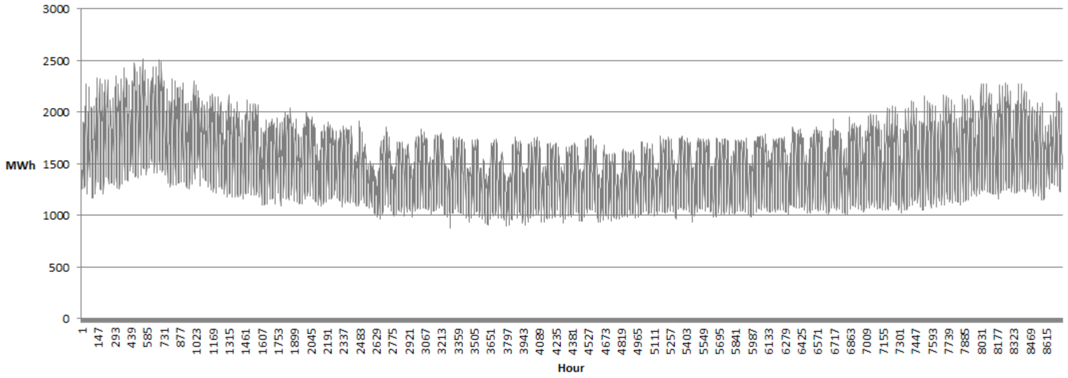

Figure A.2: DK2 area hourly consumption in 2014

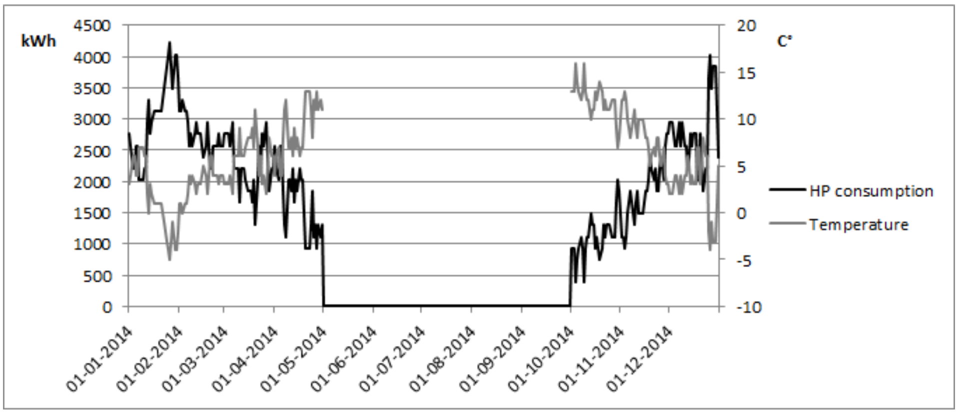

Figure A.3: Modelled HP load and actual outside temperature in 2014

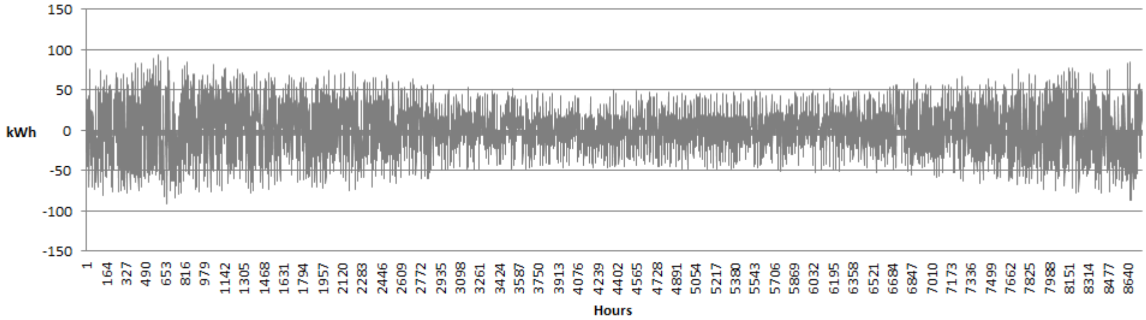

Figure A.4: Modelled aggregator's hourly imbalances

Appendix B Additional results

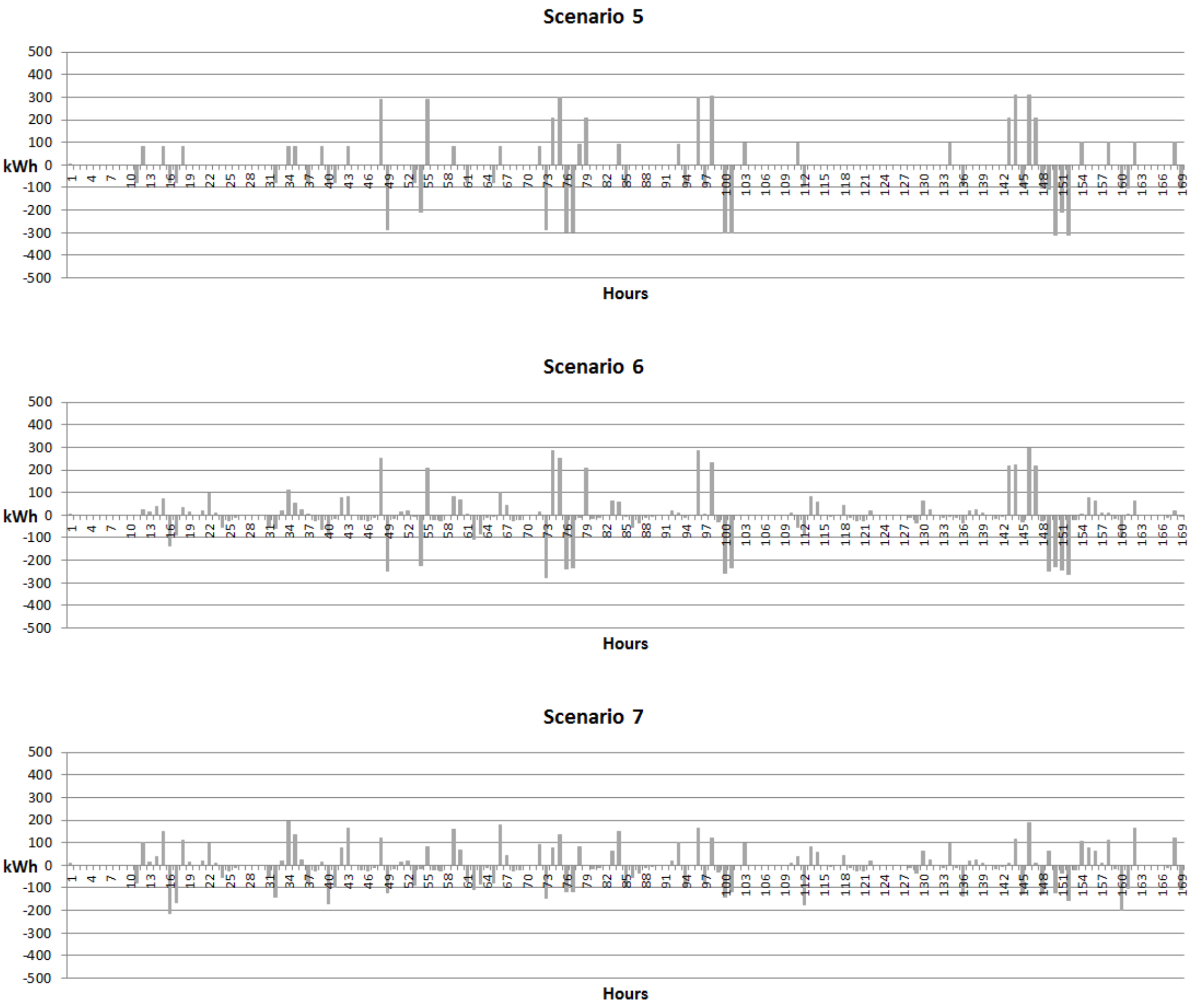

Figure B.1: Shifted consumption patterns during one week in winter (Case 2), Scenarios 5, 6 and 7

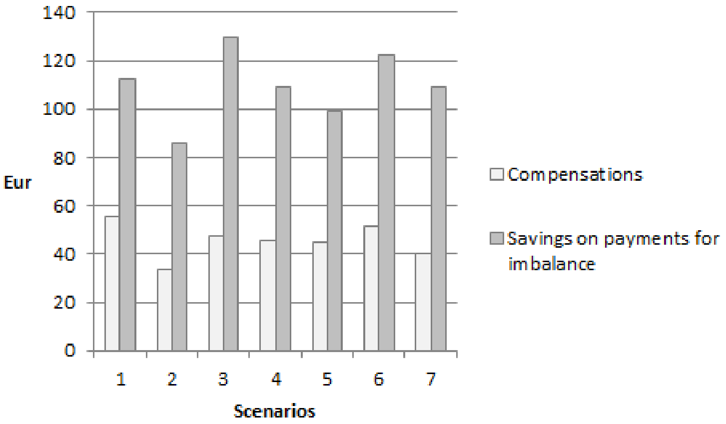

Figure B.2: Compensations to consumers and savings on payments for imbalance (Case 1)

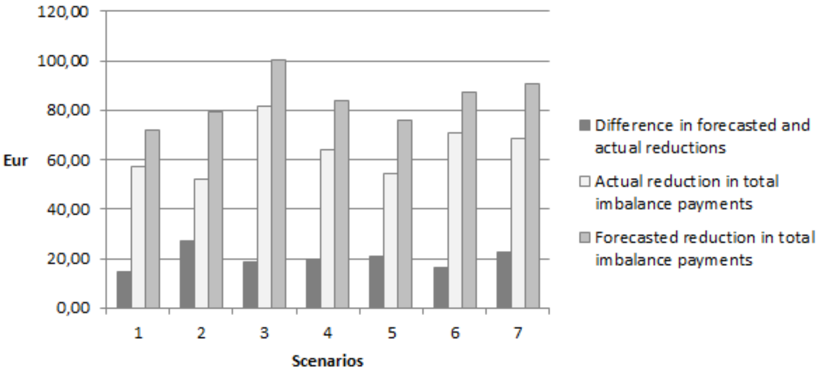

Figure B.3: Differences in forecasted and actual reductions in total imbalance payments after optimisation (Case 1)

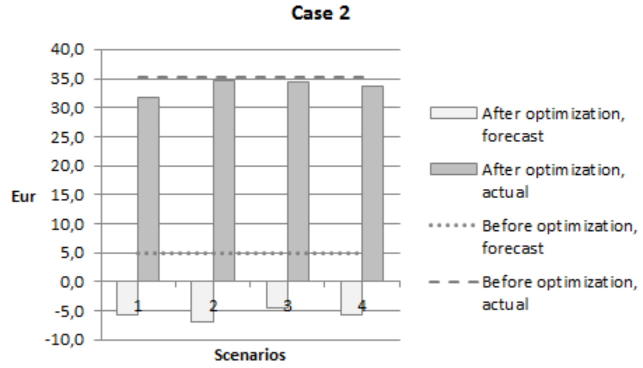

Figure B.4: Total imbalance cost before and after optimisation (Case 2) with a maximum of 20% error in the imbalance price forecast

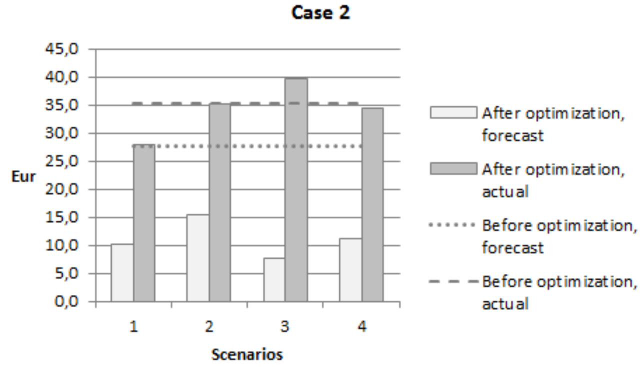

Figure B.5: Total imbalance cost before and after optimisation (Case 2) when the aggregator takes the previous hour data for the imbalance price forecast

Chapter 2

Cooperative governance structures in flexible electricity demand aggregation

Cooperative Governance Structures in Flexible Electricity Demand Aggregation

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September 9, 2018

Abstract

With an increasing share of renewable energy sources, the need for demand flexibility is growing. Large consumers have a potential to provide this flexibility to the market, however, in order to do that, they need right incentives and a favourable environment. This paper examines whether the cooperative governance structures in flexible electricity demand aggregation and trading could bring value to the market participants and final power consumers comparing to situations, where demand flexibility is traded individually or via the investor owned aggregator. We provided numerical estimation using Nord Pool intraday market data for DK2 price area in Denmark. We found that the cooperative of large consumers would offer the lowest price and the largest quantity of flexible demand in the long run. Moreover, sharing the fixed flexible demand coordination and market access cost would result in the highest profit for large consumers, giving the necessary incentives to stay in the market.

Keywords: demand-side management, flexibility, aggregation, electricity market, cooperative governance structure
JEL classification: C61, C63, C72, L94

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1 Introduction

Recent development in power systems resulting from green energy oriented policy and increasing share of renewable energy sources among power producers bring some new challenges in sustaining power system stability and efficiency. However, advancing technologies create a favourable environment for the new market participants who were not able to provide balancing services or adjust the consumption according to the system's needs and trade their flexibility in the market.

The intraday market, which is a place to trade power closer to the real time and adjust traded volumes in the spot market according to the forecast corrections, will play a more important role in the future, since the production of intermittent renewable energy sources complicate the forecasting process. Demand-side management is more suitable for providing a short-term flexibility up to hours before the actual consumption (Linkenheil et al., 2017). Thus, the intraday market has a great potential in accommodating demand flexibility of large consumers who want to trade flexibility on their own, because the reaction time for the load adjustments is relatively long, comparing to markets for regulating power.

The potential for available flexibility can be distinguished between installed capacity, theoretical, technical, economical and achievable potential (Grein and Pehnt, 2011). Theoretical potential is characterised by typical daily, weekly and annual available load variations. Technical potential takes into account technical aspects of load shifting, while economical potential reflects only the cost-effective part of load shifting. Finally, achievable potential accounts for various barriers limiting the access to the flexible load, such as market requirements, lack of knowledge and experience of the potential flexibility providers. Thus, the practically available flexible load is significantly lower compared to its installed capacity.

Demand-side flexibility providers can be divided into three groups: small consumers, such as households, large (commercial) consumers, such as supermarkets, hospitals, universities, and industrial consumers. In terms of theoretical potential, they differ in terms of their flexible load profiles. Usually, industrial consumers with energy-intensive processes are able to offer constant amounts of flexibility in each hour of the year, while households' and large consumers' flexible load varies depending on the season, weekday and hour during the day

(Grein and Pehnt, 2011). For example, residential demand-side management programmes are analysed based on active occupancy profiles by López-Rodríguez et al. (2013), and one of the factors that influence large consumers' load is their working hours. The sources of flexibility for residential consumers include electric vehicles, washing machines, tumble dryers, dish washers, heat pumps and refrigerators; for large consumers the common source is cooling and heating activities.[1] However, this paper does not consider the hourly, weekly or annual variability of flexible load and analyses a certain point in time, where the access to shiftable load is guaranteed from a technical perspective and limited only to economic incentives.

Demand-side flexibility and price elasticity of electricity demand are closely related. The elasticity of price depends on time and in a long term the demand is more elastic than in a short term. One explanation could be that in a long term consumers can adapt to price changes and change their consumption habits, appliances or use new technologies. Also, consumers' response to price changes vary between different consumers: in general, small consumers are less price elastic than large consumers. Price elasticity can also be different for different price ranges. For instance, when large industrial consumers face high prices, their price elasticity increases. Elasticity can be influenced by the type of tariff that consumers are charged. For example, when small consumers are charged using real time pricing, they tend to respond to prices less than when they are charged using a time-of-use tariff. One reason could be that consumers understand time-use-tariff better and, therefore, adjust their consumption.[2] Thus, small and large consumers may need different compensation mechanisms to ensure their willingness to provide flexibility.

Even though small consumers have a potential for offering flexibility, their individual volumes are too low to place a bid at the market. Furthermore, the gain from this activity would be moderate considering required time and effort. Therefore, the aggregation of flexible demand and trading on behalf of small consumers became a widely discussed approach to deal with market access issues for this segment. European Energy Regulators state that "there should be a requirement that all consumers have the opportunity to participate in

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[1] For further discussion on demand response potential in Europe see Grein and Pehnt (2011).

[2] For more detailed discussion about price elasticity and electricity demand response see Risø National Laboratory, Ea Energy Analyses, RAM-løse edb report on demand response in Denmark (Andersen et al., 2006).

all relevant markets <...>" and they "recognise the benefits of introducing independent aggregation[3] and propose that MSs [Member States] enable independent aggregation, unless a national implementation assessment suggests an alternative that better serves system efficiency and can be implemented effectively" (Agency for the Cooperation of Energy Regulators (ACER) and Council of European Energy Regulators (CEER), 2017). Thus, independent aggregators are seen as a first choice for aggregating flexibility.

Large consumers, on the other hand, have the potential to trade in the market on their own, since they can meet the minimum bid requirements for some hours during the day. Despite that, it is still not clear, what is the best strategy for the large consumer: to trade individually, access the market via the investor owned aggregator or form a cooperative of large consumers, where the members share part of the cost but can freely choose the volumes they want to deliver. Thus, this paper investigates whether cooperative governance structures have an advantage in aggregating and trading flexible electricity load at the intraday market comparing to cases where there is no coordination or where the coordinator is owned by investors.

The model is illustrated by providing a numerical estimation. Due to the complex expressions of the equilibrium outcomes, it is not easy to identify winners and losers in all analysed scenarios. By showing a numerical example representing the intraday market trading in one hour and market players' participation cost in Nord Pool power market, we evaluate potential benefits and losses for different market players depending on the chosen governance structure. The input data is chosen carefully to reflect a real world trading in Nord Pool power market.

The rest of the paper is organised as follows. Section 2 provides a literature review. Section 3 presents the model, i.e. the coordination game and the players. Equilibrium analysis in every scenario is provided in section 4. In section 5, we show the numerical estimates of our model, also include the sensitivity analysis of the main input variables. Finally, in section 6, we make the conclusion and suggest possible directions for future research.

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[3] According to the European Energy Regulators, "independent aggregator" is "an aggregator that is not affiliated to a supplier or any other market participant". (Agency for the Cooperation of Energy Regulators (ACER) and Council of European Energy Regulators (CEER), 2017)

2 Literature review

Intermediation and cooperation are concepts worth focusing on while analysing the emerging changes in energy markets. Intermediary can be defined as an entity, which is a link between different actors, such as producers and end-users (Grandclément et al., 2015). However, the concept of intermediation has evolved with time. According to Saglietto (2017), commercial intermediation started with the commercial travellers in the Middle ages, then mafia intermediation emerged in the 1900, followed by financial intermediaries (banks) in 1970, logistic intermediaries (brokers) in 1980, economic (intermediary agents) in 1990, electronic (e-intermediary) in 2000 and finally cultural and legal intermediation in 2010. All these types of intermediation, however, have the same function – they all coordinate and control physical, financial, informational or cultural flows, processes and activities (Saglietto, 2017).

A wide range of intermediary types result in a large number of studies on intermediation. An interested reader is referred to Appendix A for a more detailed intermediation literature review. This study focuses on intermediation in power markets, where the aggregator acts as a link between large consumers and the intraday market.

Among many services provided by intermediaries[4], the reduction of transaction cost compared to the situation where the parties interact directly, can increase social welfare. The concept of transaction cost was introduced by Coase (1937) as “a cost of using a price mechanism”. This cost includes search and information, bargaining and decision, and policing and reinforcement costs. According to Coase, transaction cost can help to explain the emergence of firms. Transaction cost analysis became a more popular topic with Williamson’s work. Williamson studied “the comparative costs of planning, adapting, and monitoring task completion under alternative governance structures” and came to a conclusion that “governance structures that have better transactional cost economizing properties will eventually displace those that have worse”(Williamson, 1981). He also claimed that there are two sides of vertical integration: on the one hand, when the transactions are organised within a firm, decision rights are centralised and this reduces bargaining cost and the risk related to bargaining impasse; on the other hand, the executives may extract rents in inefficient ways.

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[4] See Saglietto (2017)

Therefore, the choice of conducting transactions in the market or within a firm depends on the net effect of this trade-off (The Economic Sciences Prize Committee, 2010).

According to Joskow (2005), currently, there is no unified theory of vertical integration, as some theoretical works advocate the benefits of vertical integration due to increased efficiency, and others highlight the drawbacks of anticompetitive foreclosure[5]. Tirole (1988) claims that even though a vertical integration is usually efficient from the viewpoint of the integrated parties, it does not consider the interests of consumers, i.e. third parties. Although a vertical integration often brings positive externalities to consumers, for example, it can help to avoid excessive contraction of output, a public intervention might be needed to correct some negative externalities. However, it is not easy to tell when a vertical integration is anticompetitive. Hart and Tirole (1990) present a theoretical model that shows how vertical integration influences competition in upstream and downstream markets, also, they identify conditions under which market foreclosure is a consequence or a purpose, or both, of a vertical integration. This paper studies vertical integration in power consumers' flexibility trading and market outcomes for market participants and final consumers.

Intermediaries can not only reduce the transactions cost but they can also offer services that require knowledge and expertise in a particular field. Therefore, intermediation seems to have a great potential in complex energy systems where the participation of distributed energy sources is expected to increase in the future. As flexibility trading is not the main activity for the large consumers, the aggregator's services may seem as an attractive option to participate in the intraday market. Therefore, a vertical integration is a likely outcome in this situation. Nevertheless, this is not the only way to access the market.

In some hours, the requirement of a minimum bid size may prevent some consumers from bidding directly at the market. Here, cooperation of several consumers and coordination of their actions would help to overcome this obstacle. Moreover, sharing the transaction cost would bring an additional benefit to the members of a cooperative. The International Co-operative Alliance (2018) provides the following definition of a cooperative: "a co-operative

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[5] Tirole (1988) distinguishes between two kinds of market foreclosure. In the first one, the sectors (downstream or upstream) is already monopolised, and the monopolist goal is to exploit its monopoly power efficiently. In the second one, neither of sectors is monopolised. In this case, the foreclosure increases the monopolisation of one of the sectors.

is an autonomous association of persons united voluntarily to meet their common economic, social, and cultural needs and aspirations through a jointly owned and democratically-controlled enterprise." The first successful cooperative enterprise, The Rochdale Society of Equitable Pioneers, was founded in 1844 and was based on the ideas of Robert Owen (Balnave and Patmore, 2012). Also, it had a clear set of principles, that later were adopted by the International Co-operative Alliance.[6] A more detailed review of different kinds of cooperatives, such as worker, consumer, marketing, social, new generation cooperatives, etc., is provided by Altman (2009).

Aggregation, coordination and cooperation are quite popular terms among the demand-side management researchers. For example, benefits of cooperative demand response for households are estimated by Rieger et al. (2016). Lopes et al. (2016) introduce the concept of Cooperative Net Zero Energy Community, which improves load matching in the community. Zhu et al. (2016) look at the demand-side management as a control networked evolutionary game, where the actions of cooperative communities can increase common benefits even if the majority of the communities are non-cooperative.

From a more technical perspective, Sanjari and Gharehpetian (2014) analyse frequency stability in islanded microgrids and how cooperative distributed energy resources' controllers can keep the microgrid stable. Hosseinimehr et al. (2017) investigate the control of battery energy storage units within a microgrid and show that cooperative control can help to avoid power imbalance in the system. Similarly, Huang et al. (2017) are also looking at cooperative control of charging and discharging multiple energy storage units, which mitigates regulation issues in the power system. Cooperative control of storage systems is also discussed by Moradi et al. (2016), while semi-cooperative schemes for scheduling flexible load of electric vehicles are analysed by Omran and Filizadeh (2017).

Usually, the cooperation and aggregation is seen as a solution for accumulating enough flexible demand to meet the minimum bid size requirements of the market. However, strategic

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[6] The original set of principles include: open membership, democratic control, distribution of surplus in proportion to trade, payment of limited interest on capital, political and religious neutrality, cash trading, and the promotion of education (Balnave and Patmore, 2012). Later, several of them were revised and the current set of principles is: voluntary and open membership, democratic member control, member economic participation, autonomy and independence, education, training and information, cooperation among cooperatives, and concern for community (The International Co-operative Alliance, 2018).

bidding at the market is another stream of research where cooperation might be useful. For instance, Srinivasan and Woo (2008) show that in a competitive power market, individual buyers can use cooperative strategies, form groups and adjust their demand curves in this way reducing cost with minimum loss in the utility of consumption. Nevertheless, little attention has been given to the use of cooperatives in power trading.

In this paper, we focus on cooperation of large consumers offering their flexibility at the market, i.e. trading and competing with a bigger aggregator. Similarly, like in cooperative structures in the trucking industry analysed by Agrell et al. (2017), where cooperative governance is compared to integrated and Cournot-competition settings, and the analysis of cooperative organisation in supply chains when the market is an oligopoly with a competitive fringe, like in Agrell and Karantininis (2000), we propose a model to compare the cooperative governance to integrated and Stackelberg competition settings. The main contribution of this paper to the existing literature is the introduction of cooperative governance structures in power markets and a realistic estimation of potential benefits using Nord Pool intraday market data.

3 Model

Let $N \equiv \{1, 2, \dots, n\}$ be the set of large consumers and $M \equiv \{1, 2, \dots, m\}$ – the set of small consumers. The aggregator of flexible demand is denoted by A. Market participants are trading a homogeneous good, i.e. electricity, at the intraday market.

3.1 Electricity demand

After the day-ahead market closes, market participants adjust their production and consumption forecasts and trade electricity in the intraday market. It is assumed that demand for one hour is fixed and known in advance. The inverse demand function can be expressed as:

$$p(Q) = \beta_0 - \beta_1 Q, \tag{1}$$

where β_0 and β_1 are constants and Q is the total power supply for one hour.

3.2 Electricity supply

Electricity supply is determined by available flexibility of small and large consumers, which means that there is an upper limit of volume each consumer can provide in a certain hour. Each supplier has a quadratic cost function with a linear marginal cost.[7] Large consumer's cost function is:

$$c_i(q_i) = 0.5\alpha_i q_i^2, \tag{2}$$

where q_i is the amount of flexibility of the i^{th} large consumer offered to the intraday market, $\alpha_i q_i$ is a marginal cost of reducing consumption. If a large consumer places a bid at the market directly, it also incurs variable cost of placing a bid at the market ψ and a fixed cost of coordination of flexible demand, as well as fees for accessing the market ϕ_i.

3.3 Aggregator

The aggregator acts as an intermediary between small consumers and the intraday market, because there is a minimum bid size requirement preventing small consumers from participating in the market directly. So, it places bids at the market on behalf of its consumers and in addition offers coordination services. The total available flexibility for the aggregator q_a is the sum of its small consumers' flexibility $\sum_{j \in M} q_j$. The aggregator's cost function is:

$$c_a(q_a) = 0.5 w_a q_a^2 + \psi q_a + \phi_a, \tag{3}$$

where the aggregator has a marginal cost of $w_a q_a$, which is a compensation to all small consumers for reducing consumption, and ψ, variable cost of placing a bid at the market.[2] ϕ_a is a fixed cost of coordinating flexible load and fees for accessing the market.

3.4 Coordination game

Model structure is shown in Figure 1. We have considered three possible scenarios that reflect how a large consumer could participate at the intraday market. In Scenario 1,

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[7] A quadratic cost function guarantees that the flexibility is not limitless and at a certain point it becomes too expensive to change the consumption.

[2] Nord Pool is charging the variable fee of 0,11 €/MWh for trading on the intraday market. (Nord Pool, 2017*b*)

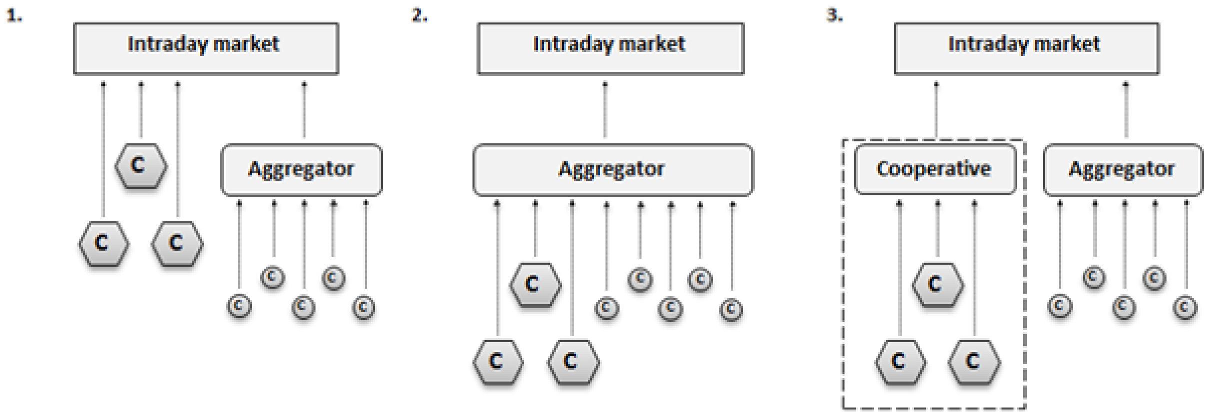


Figure 1: Three governance structures in flexible electricity demand aggregation ("C" represents large consumers, while "c" – small consumers)

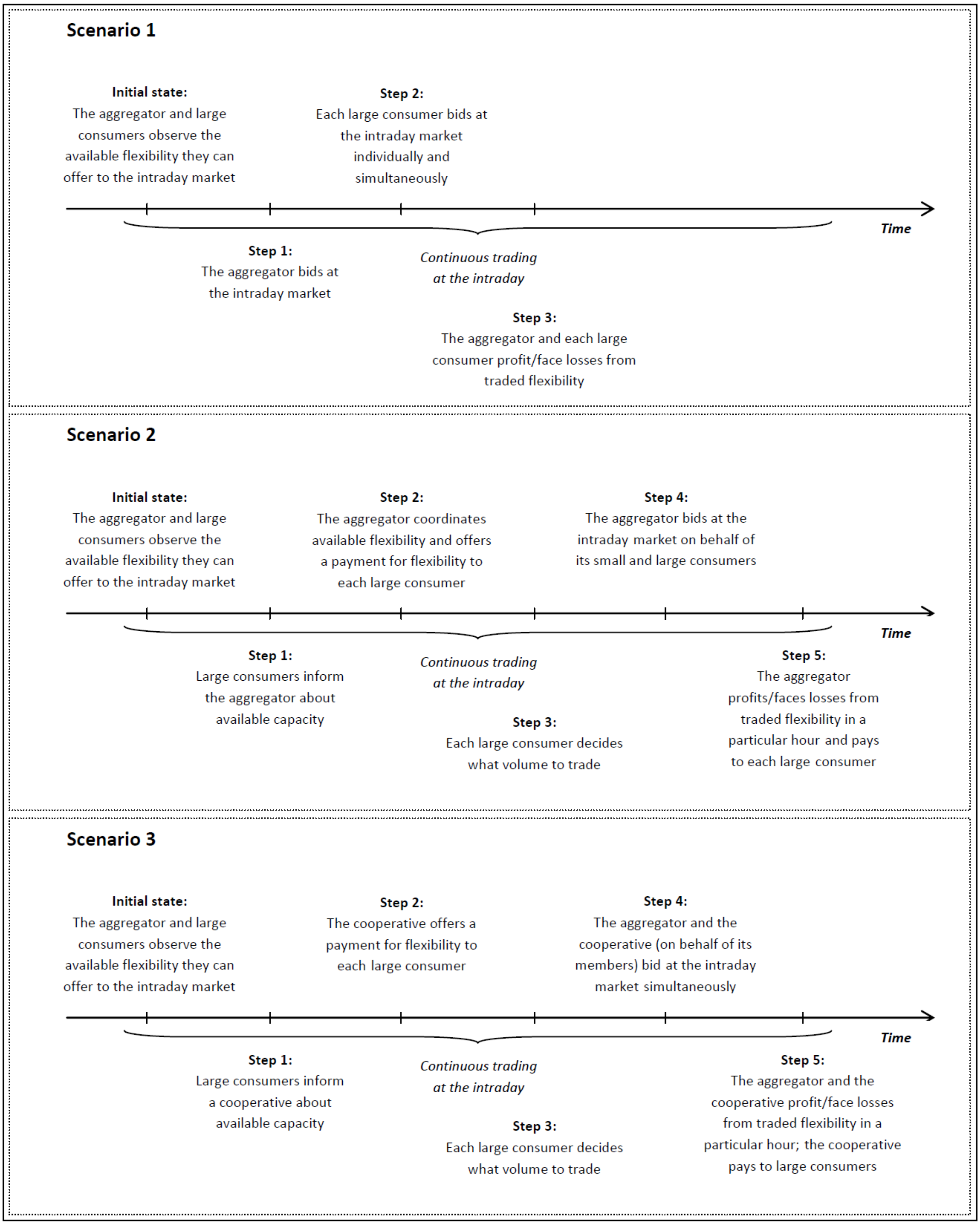
large consumers are participating at the market directly and placing bids individually with no coordination among them. The investor owned aggregator is coordinating only small consumers and bidding on their behalf. In Scenario 2, large consumers choose to participate at the market through the investor owned aggregator together with small consumers. This scenario can be seen as a common agency structure, where the aggregator acts as an agent. In Scenario 3, large consumers form a cooperative, coordinate their loads and place their bids at the market through the cooperative, while the aggregator is competing by offering small consumers' flexibility at the intraday market.

Figure 2 shows the steps of placing a bid at the market in all three scenarios. In Scenario 1, we have a one-stage game, while in Scenario 2 and Scenario 3 profits are maximised in a two-stage game. The bidding sequence, i.e. whether the aggregator bids first or second, influence the participants' profits and offered quantities. However, the main conclusion remains the same despite of the bidding sequence (see Appendix B).

4 Equilibrium analysis

4.1 Integrated system

Integrated system defines the first best solution. Here, the aggregator and all large consumers form an entity and internalise all costs and profits. The entity places a bid at the



Scenario 1

Initial state: The aggregator and large consumers observe the available flexibility they can offer to the intraday market

Step 1: The aggregator bids at the intraday market

Step 2: Each large consumer bids at the intraday market individually and simultaneously

Step 3: The aggregator and each large consumer profit/face losses from traded flexibility

Continuous trading at the intraday

Time

Scenario 2

Initial state: The aggregator and large consumers observe the available flexibility they can offer to the intraday market

Step 1: Large consumers inform the aggregator about available capacity

Step 2: The aggregator coordinates available flexibility and offers a payment for flexibility to each large consumer

Step 3: Each large consumer decides what volume to trade

Step 4: The aggregator bids at the intraday market on behalf of its small and large consumers

Step 5: The aggregator profits/faces losses from traded flexibility in a particular hour and pays to each large consumer

Continuous trading at the intraday

Time

Scenario 3

Initial state: The aggregator and large consumers observe the available flexibility they can offer to the intraday market

Step 1: Large consumers inform a cooperative about available capacity

Step 2: The cooperative offers a payment for flexibility to each large consumer

Step 3: Each large consumer decides what volume to trade

Step 4: The aggregator and the cooperative (on behalf of its members) bid at the intraday market simultaneously

Step 5: The aggregator and the cooperative profit/face losses from traded flexibility in a particular hour; the cooperative pays to large consumers

Continuous trading at the intraday

Time

Figure 2: The steps for placing a bid at the intraday market in three scenarios

intraday market on behalf of all suppliers. As it is a large market participant, its coordination and market access cost is equal to the aggregator's, i.e. ϕ_a. The market price is determined by the inverse demand function $p(q_a + \sum_{i\in N} q_i) = \beta_0 + \beta_1(q_a + \sum_{i\in N} q_i)$. In this case, the identity of large consumers does not matter, therefore, we can denote the sum of their offered volume by Q_i. Since all large consumers are identical, $Q_i = nq_i$. The profit function is concave and quadratic.

The integrated entity optimises the standard profit function:

$$\pi_{int}(q_a, q_i) = (\beta_0 - \beta_1(q_a + nq_i))(q_a + nq_i) - 0.5w_a q_a^2 - \psi q_a - \phi_a - n0.5\alpha_i q_i^2 - n\psi q_i. \quad (4)$$

Proposition 1. *A solution to the integrated problem:*

(i) The demand served by the aggregator and a large consumer is

$$q_a^* = \frac{\alpha_i(\beta_0 - \psi)}{w_a\alpha_i + 2\beta_1(nw_a + \alpha_i)}, \quad (5)$$

$$q_i^* = \frac{w_a(\beta_0 - \psi)}{w_a\alpha_i + 2\beta_1(nw_a + \alpha_i)}. \quad (6)$$

(ii) The market price is

$$p^* = \frac{w_a\alpha_i\beta_0 + \beta_1(nw_a + \alpha_i)(\beta_0 + \psi)}{w_a\alpha_i + 2\beta_1(nw_a + \alpha_i)}. \quad (7)$$

(iii) The profit is

$$\pi_{int}(q_a^*, q_i^*) = \frac{nw_a(\beta_0^2 - 4\beta_1\phi_a - 2\beta_0\psi + \psi^2) + \alpha_i(\beta_0^2 - 2\phi_a(w_a + 2\beta_1) - 2\beta_0\psi + \psi^2)}{4\alpha_i\beta_1 + 2w_a(\alpha_i + 2n\beta_1)}. \quad (8)$$

4.2 Scenario 1: Direct participation

In this scenario, large consumers bid at the market directly and compete with each other and one aggregator, which represents all small consumers. This case is modelled as a Stackelberg game, where the aggregator is a leader. The profit function for a large consumer is

$$\pi_i(q_a, q_i, Q_{-i}) = (\beta_0 - \beta_1(q_a + q_i + Q_{-i}))q_i - 0.5\alpha_i q_i^2 - \psi q_i - \phi_i. \quad (9)$$

The quantity offered by a large consumer depends on the aggregator's quantity and the total quantity of the rest of the large consumers Q_{-i}. The decision problem for the i^{th} large consumer is

$$\pi_i^*(q_a, q_i, Q_{-i}) = \max_{q_i} \pi_i(q_a, q_i, Q_{-i}). \tag{10}$$

The aggregator anticipates the reaction functions of the followers, i.e. the large consumers. The reaction functions are found by solving the following set of equations:

$$\left.\frac{\partial \pi(q_i)}{\partial q_i}\right|_{q_i=q_i^*} = \beta_0 - \beta_1(q_a + 2q_i + Q_{-i}) - q_i\alpha_i - \psi = 0, \tag{11}$$

where $2q_i + Q_{-i}$ is $q_i(n+1)$ since all large consumers have symmetrical costs, which result in identical solutions and $Q_i = nq_i$. Thus, the reaction function for a large consumer is

$$q_i^*(q_a) = \frac{\beta_0 - q_a\beta_1 - \psi}{\alpha_i + \beta_1 + n\beta_1}. \tag{12}$$

The aggregator's profit function is

$$\pi_a(q_a, Q_i(q_a)) = (\beta_0 - \beta_1(q_a + Q_i(q_a)))q_a - 0.5w_a q_a^2 - \psi q_a - \phi_a, \tag{13}$$

where $Q_i(q_a)$ is the followers', i.e. large consumers', quantity as a function of the aggregator's quantity and is equal to $nq_i^*(q_a)$. The aggregator is maximizing its profit given the reaction function of a large consumer $q_i^*(q_a)$.

Proposition 2. *A solution to the one-stage Stackelberg game is:*

(i) The demand served by the aggregator and a large consumer is

$$q_a^* = \frac{(\alpha_1 + \beta_1)(\beta_0 - \psi)}{2\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1)} \tag{14}$$

$$q_i^* = \frac{\beta_0 - \psi - \frac{\beta_1(\alpha_i+\beta_1)(\beta_0-\psi)}{2\beta_1(\alpha_i+\beta_1)+w_a(\alpha_i+\beta_1+n\beta_1)}}{\alpha_i + \beta_1 + n\beta_1} \tag{15}$$

(ii) The market price is

$$p^* = \frac{w_a(\alpha_i + \beta_1 + n\beta_1)(\beta_0(\alpha_i + \beta_1) + n\beta_1\psi) + \beta_1(\alpha_i + \beta_1)((\beta_0 + \psi)(\alpha_i + \beta_1) + \beta_1 2n\psi)}{(\alpha_i + \beta_1 + n\beta_1)(2\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1))} \tag{16}$$

(iii) The profits for the aggregator and a large consumer are

$$\begin{aligned}\pi_a^* = -\frac{(\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1))(\beta_0 - \psi)^2}{2(\alpha_i + \beta_1 + n\beta_1)^2(2\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1))^2}\big(w_a^2(\alpha_i + \beta_1 + n\beta_1) - \\ 2\beta_1(\alpha_i + \beta_1)(2\alpha_i + \beta_1 + n\beta_1) + w_a(\beta_1^2 - 2\alpha_i^2 - \alpha_i(\beta_1 + 2n\beta_1))\big) - \phi_a\end{aligned} \tag{17}$$

$$\pi_i^* = -\phi_i + \frac{(\alpha_i + 2\beta_1)(\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1))^2(\beta_0 - \psi)^2}{2(\alpha_i + \beta_1 + n\beta_1)^2(2\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1))^2} \tag{18}$$

4.3 Scenario 2: Aggregator's coordination

In this scenario, large consumers trade their flexibility via an investor owned aggregator. Here, there is a two-stage game, where the aggregator offers a contract (w_{ai}, Q_i) based on the available flexibility. The aggregator has to set such a price w_{ai} so that the participation of large consumers would be guaranteed. We have analysed three sub-scenarios representing different strategies of payments to large consumers:

- Scenario 2a: The aggregator offers a payment guaranteeing that a large consumer would yield a non-negative profit.
- Scenario 2b: The aggregator offers a payment guaranteeing that a large consumer would yield a profit that is not less than in Scenario 1, where a large consumer is bidding at the market directly.
- Scenario 2c: The aggregator offers a payment guaranteeing that a large consumer would yield a profit that is not less than in Scenario 3b, where large consumers form a cooperative.

In Scenario 2, a large consumer does not incur variable cost of placing a bid at the market ψ and a fixed cost of coordination and market access fees ϕ_i since the aggregator takes the responsibility to coordinate flexible demand and place bids at the market on behalf of small and large consumers. Thus, the profit function for a large consumer is

$$\pi_i(q_i) = w_{ai}q_i - 0.5\alpha_i q_i^2. \tag{19}$$

The aggregator offers prices w_a and w_{ai} to its small and large consumers respectively, while ϕ_a is a common coordination and market access cost for the aggregator. We formulate the aggregator's profit function as

$$\pi_a(q_a, q_i, w_{ai}) = (\beta_0 - \beta_1(q_a + nq_i))(q_a + nq_i) - 0.5w_a q_a^2 - \psi q_a - \phi_a - nq_i(w_{ai} + \psi). \tag{20}$$

Here, the aggregator has to decide about the offer price for a large consumer and the quantities of small and large consumers' flexibility it wants to trade. The offer price for small consumers is not the focus of this study, therefore, it is assumed to be known in advance.

The decision problem of the aggregator depends on a sub-scenario:

$$\begin{aligned}
&\pi_a^* = \max_{q_a, q_i, w_{ai}} \pi_a(q_a, q_i, w_{ai}) \\
&\text{s.t.} \\
&\qquad \begin{array}{lll}
\pi_i(q_i) & \geq & 0 \qquad\qquad\quad \text{(Scenario 2a)} \\
\pi_i(q_i) & \geq & \pi_i^{*Sc1}(q_i) \qquad \text{(Scenario 2b)} \\
\pi_i(q_i) & \geq & \pi_i^{*Sc3b}(q_i) \qquad \text{(Scenario 2c),}
\end{array}
\end{aligned} \tag{21}$$

where π_i^{*Sc1} and π_i^{*Sc3b} are the maximised profits for a large consumer in Scenario 1 and Scenario 3b respectively.

To solve this two-stage game we haved used multiplier λ and a Lagrange function L. In Scenario 2a, a Lagrange function is

$$\begin{aligned}
L(w_{ai}) = (\beta_0 - \beta_1(q_a + nq_i))(q_a + nq_i) - nq_i(w_{ai} + \psi) \\
- 0.5w_a q_a^2 - \psi q_a - \phi_a - \lambda(w_{ai}q_i - 0.5\alpha_i q_i^2).
\end{aligned} \tag{22}$$

In Scenario 2b, it becomes

$$L(w_{ai}) = (\beta_0 - \beta_1(q_a + nq_i))(q_a + nq_i) - nq_i(w_{ai} + \psi) \\ - 0.5w_a q_a^2 - \psi q_a - \phi_a - \lambda(w_{ai}q_i - 0.5\alpha_i q_i^2 - \pi_i^{*Sc1}(q_i)) \quad (23)$$

and, in Scenario 2c, it is

$$L(w_{ai}) = (\beta_0 - \beta_1(q_a + nq_i))(q_a + nq_i) - nq_i(w_{ai} + \psi) \\ - 0.5w_a q_a^2 - \psi q_a - \phi_a - \lambda(w_{ai}q_i - 0.5\alpha_i q_i^2 - \pi_i^{*Sc3b}(q_i)). \quad (24)$$

In Scenario 2a, a large consumer will not gain a profit because only the aggregator has an access to the market. That creates a monopsony where the aggregator has complete information and can reduce a large consumer's profit to zero, allowing to cover only the average cost. The outcome of this game is identical to the integrated system case with the aggregator acting as an entity internalising all costs and profits.

Corollary 1. *In Scenario 2a, the solution for the two-stage game is*

- *(i) The demand served by the aggregator and a large consumer is identical to the integrated system's solution* q_a^*, q_i^*, p^**,*
- *(ii) The integrated system's profit is absorbed the aggregator* $\pi_a^* = \pi_{int}^*$*,*
- *(iii) The profits of a large consumer is equal to zero* $\pi_i^* = 0$*,*
- *(iv) The aggregator's compensation to a large consumer is*

$$w_{ai} = \frac{w_a\alpha_i(\beta_0 - \psi)}{2(2\alpha_i\beta_1 + w_a(\alpha_i + 2n\beta_1))}. \quad (25)$$

Proposition 3. *In Scenario 2b, the optimal solution is:*

- *(i) The demand served by the aggregator and a large consumer and the price are identical to the integrated system's solution* q_a^*, q_i^*, p^**,*
- *(ii) The profit for the aggregator and a large consumer is*

$$\pi_a^* = -\phi_a - \frac{w_a\alpha_i^2(\beta_0 - \psi)^2}{2(w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1)^2} + \frac{\alpha_1\psi(-\beta_0 + \psi)}{w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1} - \\ \frac{nw_a(\beta_0 - \psi)}{w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1}\Big(- \frac{w_a\alpha_i + 2(nw_a + \alpha_i)\beta_i}{w_a(\beta_0 - \psi)}\big(\phi_i - \frac{w_a^2\alpha_i(\beta_0 - \psi)^2}{2(w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1)^2} - \\ \frac{(\alpha_i + 2\beta_1)(\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1))^2(\beta_0 - \psi)^2}{2(\alpha_i + \beta_1 + n\beta_1)^2(2\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1))^2}\big) + \psi\Big) + \\ \frac{(nw_a + \alpha_i)(\beta_0 - \psi)(\alpha_i\beta_1(\beta_0 + \psi) + w_a(\alpha_i\beta_0 + n\beta_1(\beta_0 + \psi)))}{(w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1)^2}, \quad (26)$$

$$\pi_i^* = \pi_i^{*Sc1}, \quad (27)$$

(iii) the aggregator's compensation to a large consumer is

$$\begin{aligned} w_{ai}^* = -\frac{2\alpha_i\beta_1 + w_a(\alpha_i + 2n\beta_1)}{w_a(\beta_0 - \psi)}(\phi_i - \\ \frac{(\alpha_i + 2\beta_1)(\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1))^2(\beta_0 - \psi)^2}{2(\alpha_i + \beta_1 + n\beta_1)^2(2\beta_1(\alpha_i + \beta_1) + w_a(\alpha_i + \beta_1 + n\beta_1))^2} - \\ \frac{w_a^2\alpha_i(\beta_0 - \psi)^2}{2(2\alpha_i\beta_1 + w_a(\alpha_i + 2n\beta_1))^2}). \end{aligned} \tag{28}$$

Proposition 4. *In Scenario 2c, the optimal solution is:*

(i) The demand served by the aggregator and a large consumer is identical to the integrated system's solution q_a^*, q_i^*, p^*,

(ii) The profit for the aggregator and a large consumer is

$$\begin{aligned} \pi_a^* = -\phi_a - \frac{w_a\alpha_i^2(\beta_0 - \psi)^2}{2(w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1)^2} + \frac{\alpha_i\psi(\psi - \beta_0)}{w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1} - \\ \frac{nw_a(\beta_0 - \psi)}{w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1}(-\frac{w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1}{w_a(\beta_0 - \psi)} \\ (-\frac{1}{4n^2(\alpha_i + \beta_1 + n\beta_1)^2}(-2\alpha_i^2\phi_c - 2n(\alpha_i^2 + 6\alpha_i\beta_1 + 4\beta_1^2)\phi_c + \\ n^2(2\beta_1(-4\beta_1\phi_c + (\beta_0 - \psi)^2) + \\ \alpha_i(-2\beta_1\phi_c + (\beta_1 - \psi)^2)) - \alpha_i 2\beta_1\phi_c + \\ \sqrt{n^2(-4n\alpha_i\phi_c + 4(\alpha_i + \beta_1)\phi_c + n^2(-4\beta_1\phi_c + (\beta_0 - \psi)^2))}(\beta_0 - \psi)(\alpha_i + 2\beta_1)) - \\ \frac{w_a^2\alpha_i(\beta_0 - \psi)^2}{2(w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1)^2}) + \psi) + \\ \frac{(nw_a + \alpha_i)(\beta_0 - \psi)(\alpha_i\beta_1(\beta_0 + \psi) + w_a(\alpha_i\beta_0 + n\beta_1(\beta_0 + \psi)))}{(w_a\alpha_i + 2(nw_a + \alpha_i)\beta_1)^2}, \end{aligned} \tag{29}$$

$$\pi_i^* = \pi_i^{*Sc3b}, \tag{30}$$

(iii) the aggregator's compensation to a large consumer is

$$\begin{aligned} w_{ai}^* = -\frac{2\alpha_i\beta_1 + w_a(\alpha_i + 2n\beta_1)}{w_a(\beta_0 - \psi)}(-\frac{1}{4n^2(\alpha_i + \beta_1 + n\beta_1)^2} \\ (-2\alpha_i^2\phi_c - 2n(\alpha_i^2 + 6\alpha_i\beta_1 + 4\beta_1^2)\phi_c + \\ n^2(2\beta_1(-4\beta_1\phi_c + (\beta_0 - \psi)^2) + \alpha_i(-2\beta_1\phi_c + (\beta_0 - \psi)^2)) - \alpha_i 2\beta_1\phi_c + \\ \sqrt{n^2(-4n\alpha_i\phi_c + 4(\alpha_i + \beta_1)\phi_c + n^2(-4\beta_1\phi_c + (\beta_0 - \psi)^2))}(\beta_0 - \psi)(\alpha_i + 2\beta_1)) - \\ \frac{w_a^2\alpha_i(\beta_0 - \psi)^2}{2(2\alpha_i\beta_1 + w_a(\alpha_i + 2n\beta_1))^2}). \end{aligned} \tag{31}$$

As long as the aggregator stays in the market, the small consumers providing flexibility to the aggregator are indifferent between Scenario 2a, 2b, and 2c, because they get the same payment for their flexibility in all three sub-scenarios. Thus, the profit for traded energy is distributed between the aggregator and the large consumers depending on a scenario. Scenario 2a is a medium scenario for the aggregator and the large consumers, Scenario 2b is the best for the aggregator and the worst for the large consumers, as the large consumers face losses equal to those when trading at the market individually. Scenario 2c is the best for large consumers, because they get a highest compensation, which should guarantee that they use the aggregator's services instead of forming a cooperative. Accordingly, for the aggregator, this scenario is the worst of all sub-scenarios, because the aggregator pays the largest compensations to the large consumers. This means that by having an opportunity to form a cooperative, large consumers can negotiate with the aggregator and receive a higher profit. For the analysis of winners and losers in all scenarios see section 5.2 Results.

4.4 Scenario 3: Cooperative's coordination

The third option for large consumers to trade at the intraday market is to form a cooperative. Here, we introduce two sub-scenarios. In scenario 3a, the cooperative competes with the aggregator. The aggregator and the cooperative are seen as equal players, therefore, they move simultaneously. In scenario 3b, the aggregator becomes not competitive and is forced out of the market by a more efficient cooperative.

Large consumers share the profit of the cooperative based on their contribution, which means that the cooperative does not retain any profit for itself and only covers its coordination cost and market access fees ϕ_c and variable bidding cost ψ. Here, we have a two-stage game, where the cooperative offers a contract $(w_{ci}(q_i), q_i)$ to its members. The cooperative's offered price is formulated as

$$w_{ci}(q_i) = \frac{\pi_c(q_a, q_i + Q_{-i})}{q_i + Q_{-i}}, \tag{32}$$

where the cooperative's profit function (excluding the payments to its members) is

$$\pi_c(q_a, q_i + Q_{-i}) = (\beta_0 - \beta_1(q_a + q_i + Q_{-i}))(q_i + Q_{-i}) - \phi_c - (q_i + Q_{-i})\psi_c. \tag{33}$$

Since the cooperative's payments to large consumers depend on its members' decisions about the flexibility quantities, this two-stage game can be solved by focusing on a large consumer's profit function

$$\pi_i(q_i) = \frac{q_i}{q_i + Q_{-i}}((\beta_0 - \beta_1(q_a + q_i + Q_{-i}))(q_i + Q_{-i}) - \phi_c - (q_i + Q_{-i})\psi) - 0.5\alpha_i q_i^2. \quad (34)$$

The decision problem for the i^{th} large consumer is

$$\pi_i^* = \max_{q_i} \pi_i(q_a, q_i, Q_{-i}). \quad (35)$$

The reaction functions of large consumers are found by solving the following set of equations:

$$\left.\frac{\partial \pi(q_i)}{\partial q_i}\right|_{q_i = q_i^*} = -\frac{1}{(q_i + Q_{-i})^2}(q_i^3(\alpha_i + 2\beta_1) + q_i^2(2Q_{-i}\alpha_i - \beta_0 + q_a\beta_1 + 5Q_{-i}\beta_i + \psi) +$$
$$q_i Q_{-i}(Q_{-i}(\alpha_i + 4\beta_1) + 2(q_a\beta_1 - \beta_0 + \psi)) + Q_{-i}(\phi_c + Q_{-i}((q_a + Q_{-i})\beta_1 - \beta_0 + \psi))) = 0, \quad (36)$$

where $Q_i = nq_i$. The reaction function for a large consumer is

$$q_i^*(q_a) = \frac{n^2(\beta_0 - q_a\beta_1 - \psi) + \sqrt{-4(n-1)n^2(\alpha_i + \beta_1 + n\beta_1)\phi_c + n^4(q_a\beta_1 - \beta_0 + \psi)^2}}{2n^2(\alpha_i + \beta_1 + n\beta_1)}. \quad (37)$$

The aggregator maximises its profit

$$\pi_a(q_a, Q_i) = (\beta_0 - \beta_1(q_a + Q_i))q_a - 0.5w_a q_a^2 - \psi q_a - \phi_a \quad (38)$$

and its reaction function is

$$q_a^*(q_i) = \frac{\beta_0 - nq_i\beta_1 - \psi}{w_a + 2\beta_1}. \quad (39)$$

The solution for this game is found by solving the reaction functions equations simultaneously and is characterised below.

Proposition 5. *The optimal solution in the game where the cooperative of large consumers is competing with the aggregator is:*

(i) The demand served by the aggregator and a large consumer is

$$q_a^* = \frac{-A + (2w_a\alpha_i + (2+n)w_a\beta_1 + \beta_1(4\alpha_i + (4+n)\beta_1))(\beta_0 - \psi)}{2(w_a + 2\beta_1)(w_a(\alpha_i + \beta_1 + n\beta_1) + \beta_1(2\alpha_i + (2+n)\beta_1))}, \quad (40)$$

where A is

$$A = (\beta_1^2(4(\alpha_i+\beta_1)(w_a+2\beta_1)^2\phi_c - 4n(w_a+2\beta_1)(w_a\alpha_i+\beta_1(2\alpha_i+\beta_1))\phi_c + n^2(w_a+\beta_1)(\beta_1(-8\beta_1\phi_c+(\beta_0-\psi)^2)+w_a(-4\beta_1\phi_c+(\beta_0-\psi)^2))))^{\frac{1}{2}}, \tag{41}$$

$$q_i^* = \frac{A+n\beta_1(w_a+\beta_1)(\beta_0-\psi)}{2n\beta_1(w_a(\alpha_i+\beta_1+n\beta_1)+\beta_1(2\alpha_i+(2+n)\beta_1))}. \tag{42}$$

(ii) The market price is

$$p^* = \beta_0 - \beta_1\left(\frac{A}{\beta_1} - \frac{A}{w_a+2\beta_1} + 2(\beta_0-\psi)(\alpha_i+\beta_1) + \frac{n(w_a+\beta_1)(w_a+3\beta_1)(\beta_0-\psi)}{w_a+2\beta_1}\right) \frac{1}{2(w_a(\alpha_i+\beta_1+n\beta_1)+\beta_1(2\alpha_i+(2+n)\beta_1))} \tag{43}$$

(iii) The profit for the aggregator and a large consumer is

$$\pi_a^* \;=\; -\phi_a \;+\; \frac{(A-(2w_a\alpha_i+(2+n)w_a\beta_1+\beta_1(4\alpha_i+(4+n)\beta_1))(\beta_0-\psi))^2}{8(w_a+2\beta_1)(w_a(\alpha_i+\beta_1+n\beta_1)+\beta_1(2\alpha_i+(2+n)\beta_1))^2}, \tag{44}$$

$$\pi_i^* = (\beta_1(-2\alpha_i(\alpha_i+\beta_1)(w_a+2\beta_1)^2\phi_c - 2n(w_a+2\beta_1)(w_a\alpha_i^2+2\alpha_i(3w_a+\alpha_i)\beta_1 + (4w_a+9\alpha_i)\beta_1^2+6\beta_1^3)\phi_c + n^2(w_a+\beta_1)(\beta_1(2\beta_1(-6\beta_1\phi_c+(\beta_0-\psi)^2)+\alpha_i(-4\beta_1\phi_c+(\beta_0-\psi)^2)) + w_a(2\beta_1(-4\beta_1\phi_c+(\beta_0-\psi)^2)+\alpha_i(-2\beta_1\phi_c+(\beta_0-\psi)^2)))) + An(w_a+\beta_1)(\alpha_i+2\beta_1)(\beta_0-\psi))/(4n^2\beta_1(w_a(\alpha_i+\beta_1+n\beta_1)+\beta_1(2\alpha_i+(2+n)\beta_1))^2). \tag{45}$$

In scenario 3b, the profit function for a large consumer is

$$\pi_i(q_i) = \frac{q_i}{q_i+Q_{-i}}((\beta_0-\beta_0(q_i+Q_{-i}))(q_i+Q_{-i}) - \phi_c - (q_i+Q_{-i})\psi) - 0.5\alpha_i q_i^2. \tag{46}$$

The decision problem for a large consumer no longer depends on the aggregator's quantity, since the aggregator exits the market due to high average cost:

$$\pi_i^* = \max_{q_i} \pi_i(q_i, Q_{-i}). \tag{47}$$

The solution is found by solving the following set of equations:

$$\left.\frac{\partial\pi(q_i)}{\partial q_i}\right|_{q_i=q_i^*} = -\frac{1}{(q_i+Q_{-i})^2}(q_i^3(\alpha_i+2\beta_1)+q_i^2(2Q_{-i}\alpha_i-\beta_0+5Q_{-i}\beta_1+\psi) + q_iQ_{-i}(-2\beta_0+Q_{-i}(\alpha_i+4\beta_1)+2\psi)+Q_{-i}(\phi_c+Q_{-i}(Q_{-i}\beta_1-\beta_0+\psi))=0, \tag{48}$$

where $Q_i = nq_i$.

Proposition 6. *The optimal solution in the two-stage game where the cooperative is the only player in the market is:*

(i) The demand served by a large consumer is

$$q_i^* = \frac{\sqrt{n^2(4\phi_c(\beta_1 + \alpha_i - n\alpha_i) + n^2((\beta_0 - \psi)^2 - 4\beta_1\phi_c))} + n^2(\beta_0 - \psi)}{2n^2(\alpha_i + \beta_1 + n\beta_1)}, \tag{49}$$

(ii) The market price is

$$p^* = \beta_0 - \frac{\beta_1(\sqrt{n^2(4\phi_c(\beta_1 + \alpha_i - n\alpha_i) + n^2((\beta_0 - \psi)^2 - 4\beta_1\phi_c))} + n^2(\beta_0 - \psi))}{2n^2(\alpha_i + \beta_1 + n\beta_1)}, \tag{50}$$

(iii) The profit for a large consumer is

$$\begin{aligned} \pi_i^* = {} & \frac{1}{4n^2(\alpha_i + \beta_1 + n\beta_1)^2}(-2\alpha_i^2\phi_c - 2n(\alpha_i^2 + 6\alpha_i\beta_1 + 4\beta_1^2)\phi_c + \\ & n^2(2\beta_1((\beta_0 - \psi)^2 - 4\beta_1\phi_c) + \alpha_1((\beta_0 - \psi)^2 - 2\beta_1\phi_c)) - \alpha_i 2\beta_1\phi_c + \\ & \sqrt{n^2(4\phi_c(\beta_1 + \alpha_i - n\alpha_i) + n^2((\beta_0 - \psi)^2 - 4\beta_1\phi_c))}(\beta_0 - \psi)(\alpha_i + 2\beta_1)). \end{aligned} \tag{51}$$

Since in this scenario the aggregator is forced out of the market, the flexible load of small consumers is not used and and the consumers follow their initial consumption schedule. Their capacity is too small to bid at the market directly, therefore, they will no longer participate in flexibility trading.

4.5 Equilibrium quantities and prices

The expressions of equilibrium prices and quantities offered to the market seem rather complicated to interpret. Nevertheless, the expressions give some insights into the aggregator's and the large consumers' game. In addition, the sensitivity analysis provided in section 5.3 and Appendix D helps to determine some relations between the variables of the model and equilibrium outcomes. The equilibrium prices and quantities in Scenario 2 are equal to those of the integrated system. Therefore, in this subsection we are only comparing the outcomes of the integrated system, Scenario 1 and Scenario 3.

The first insight is that the equilibrium prices and quantities do not depend on the fixed intraday market access and flexible demand coordination cost ϕ in the integrated system and Scenario 1. This fixed cost does not influence the chosen quantity and price, but it affects the market participants' profit, i.e. the profit is reduced by the amount of the fixed cost. This is not the case in Scenario 3, though, where the members of the cooperative share the fixed intraday market access and flexible demand coordination cost ϕ depending on their traded quantity. This means that their and the aggregator's (in Scenario 3a) offered quantities, as well as the market price, depend on the cooperative's fixed cost ϕ_c.

The second insight is that larger variable cost of placing a bid at the intraday market ψ reduces the quantity offered by the aggregator and the large consumers and the price increases in all scenarios. The profit of all players becomes lower and the consumer surplus diminishes too.

The third insight is that larger number of large consumers n reduces individually offered quantities by the aggregator and large consumers, even though the total quantity at the market increases. The price falls due to increased competition and consumer surplus increases in all scenarios.

The fourth insight reveals that larger large consumer's cost of shifting the first MW of electricity α_i reduces the quantity offered to the market. Even though the aggregator is increasing the quantity, the total amount in the market is lower and the price goes up. This leads to a lower consumer surplus. An interesting observation here is that, up to a certain point, the profit of the large consumers increases with increasing α_i due to a higher market price. Thus, increasing large consumers' cost does not harm the large consumers. On the contrary, it increases the profit on the expense of the final consumers. However, when α_i becomes even higher, then the profit starts shrinking. Similarly, the aggregator's payment to small consumers for shifting the first MW of electricity w_a reduces its offered quantity, increases the quantities offered by the large consumers, the total quantity in the market decreases and the market price goes up. This harms the final consumers, as the consumer surplus shrinks. However, in this situation, the aggregator does not yield a larger profit. Its profit is lower because of the smaller quantity traded in the market, and the large consumers increase their profits on the expense of final consumers.

Finally, the aggregator could leave the market and stop trading small consumers' flexibility in Scenario 1 and Scenario 3. When the aggregator's profit becomes negative, the aggregator would exit the market in the long run. The only variable that does not affect the aggregator's profit in both scenarios is the large consumer's fixed intraday market access and flexible demand coordination cost ϕ_i. All other variables influence the aggregator's profit at a different rate. From the sensitivity analysis one can see that a few variables have a higher impact to the aggregator's decision to leave the market, i.e. larger number of large consumers n, higher aggregator's payment to small consumers for shifting the first MW of electricity w_a, higher aggregator's fixed intraday market access and flexible demand coordination cost ϕ_a, higher slope of the inverse demand function β_1, and lower large consumer's cost of shifting the first MW of electricity α_i, as well as lower intercept of the inverse demand curve β_0 would lead to a situation where the aggregator leaves the market in the long run. Naturally, higher competition, increasing cost, decreasing competitors' cost and lower consumers' willingness to pay negatively affects the aggregator's profit and may lead to exiting the market. With decreasing β_0, α_i, and increasing β_1, n, w_a, ϕ_a the aggregator exits the market sooner in Scenario 1, where it has to compete with large consumers bidding at the market individually. A more detailed analysis of different scenarios is provided in sections 5.2 Results and 5.3 Sensitivity analysis.

The equilibrium outcomes of all scenarios also depend on the market size. For example, a larger market could lead to the equilibrium where the large consumers would be able to cover their cost when bidding individually; or, due to increased traded quantities, the aggregator would be able to stay in the market and compete with the cooperative. However, the rating of all analysed scenarios would not change much, except the Scenario 2b, where the large consumers are compensated according to their potential profits when bidding individually. This would make the Scenario 2b more attractive to the large consumers than the Scenario 2a, where the large consumers profit is equal to zero. Furthermore, Scenario 2c might become less attractive to the large consumers, if the aggregator does not need to leave the market in Scenario 3, as their compensations would be equal to those where the aggregator competes with the cooperative.

4.6 Consumer surplus

The total expected consumer utility can be written as $\int_0^Q(\beta_0 - \beta_1 u)du$, where Q is the total flexibility offered at the market. Since the consumers pay $(\beta_0 - \beta_1 Q)Q$, in equilibrium, the expected consumer surplus is $CS(Q^*) = \frac{\beta_1}{2}(Q^*)^2$. Thus, the consumer surplus for each scenario depends on the amount of provided flexibility to the market. As, in the long run, the largest quantity of flexibility is provided by a cooperative, the consumers prefer the cooperative's presence at the market, which increases their surplus. The least attractive option for the consumers is to have only the aggregator, which uses its market power and limits the amount of provided flexibility in order to receive a higher profit.

4.7 Profit distribution

Profit distribution among market players depends on the chosen governance structure. The market power of the aggregator is reduced by the entry of large consumers directly to the market or by forming a cooperative. The aggregator's profit is reduced by the increased competition. Therefore, the aggregator has an incentive to offer compensations to the large consumers and trade flexibility on their behalf. If the large consumers face too high market access cost and cannot trade flexibility on their own, also, if they do not have an option to form a cooperative, all the profit would be absorbed by the aggregator and would go to its owners. In this case the aggregator can be seen as a winner, because its profit is the highest, the large consumers receive zero profits and the consumer surplus is the lowest. Situation changes when the large consumers face lower market access and flexibility coordination cost, which allows them to trade flexibility on their own. This leads to a different profit distribution between the aggregator and the large consumers. Even though the total profit in the system remains the same, the large consumers receive their share, equal to the potential profit of trading flexibility directly in the market. Their share can increase even more, when they have an option to leave the aggregator and form a cooperative, which reduces their individual market access and flexibility coordination cost and guarantees higher profits than bidding individually. Thus, an integrated system means the lowest consumer surplus and highest total profits for the flexibility sellers, but the distribution of profits among the market players depend on the large consumers' ability to leave the aggregator.

The profit is distributed more evenly when the market players face competition. In Scenario 1, where the large consumers are bidding directly at the market, the total system profit is reduced compared to the integrated system and the consumer surplus increases. When the large consumers can form a cooperative and share the market access and flexibility coordination cost, their individual profit increases. If the market is small, the aggregator may be forced to leave the market due to a more efficient competitor. Even though the cooperative is the only one trading flexibility at the market, its members are still competing in terms of their individual quantities, which does not allow the price to rise up to the integrated system's level. This means that the consumer surplus is much higher than in the integrated system's case.

5 Numerical estimates

To compare the performance under different governance structures, we have used numerical data representing intraday market trading and players' participation costs. Since the analysis is focused on trading outcomes for one hour, we have also provided a sensitivity analysis accounting for any changes in cost parameters, demand elasticity and the number of large consumers in the market.

5.1 Input data

The need for demand flexibility increases during peak consumption periods when power prices jump up due to more expensive generators being dispatched to cover the demand and when the grid is used heavily resulting in possible congestions in certain areas. Thus, our analysis is based on one peak load hour in Nord Pool intraday market.

European synchronous peak load in winter is calculated for Wednesdays 19:00 CET [3] (ENTSO-E, 2016). Market data is publicly available and is retrieved from the Nord Pool database accessed via Nord Pool website (Nord Pool, 2017*a*). Our analysis focuses on 19:00

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[3] From 18:00 CET to 19:00 CET.

CET of January 4, 2017. Since market data is provided on price area level, we investigated Denmark's DK2 price area.

During this hour at the intraday market in DK2 price area, market participants traded 259 MWh at the weighted average price of 37,95 €/MWh. The lowest price was 32,0 €/MWh and the highest – 42,7 €/MWh. The day-ahead price for this hour was lower – 35,55 €/MWh (36,81 €/MWh and 34,5 €/MWh one hour before and after respectively), which means that market participants underestimated the load in their day-ahead forecasts. In DK2 price area, the consumption was 2127 MWh, while production reached only 1651 MWh, of which wind power accounted for 543 MWh. This resulted in import of 476 MWh.

Table 1: Parameter values

Parameter	β_0	β_1	n	w_a	α_i	ψ	ϕ_a	ϕ_i	ϕ_c
Value	42,7	0,0413	50	1,27	1,16	35,66	6,13	6,91	7,63

The values of all input parameters are summarised in Table 1. The intercept β_0 and the slope β_1 of the inverse demand function are found using the intraday market data, i.e. the minimum and maximum bid prices and the total traded quantity during one hour (see Appendix C). In the base case, the number of large consumers participating in the DK2 price area is 50.

The aggregator's payment to small consumers for shifting the first MW of electricity w_a and the i^{th} large consumer's cost of shifting the first MW of electricity α_i are calculated using average differences in day-ahead prices one hour before and after the initial consumption. The logic behind that is that the consumer has an option to postpone the consumption or consume one hour earlier and in this way reduce the consumption (or sell energy) at the initial consumption hour. The cost of reducing this consumption is related to the increase in the day-ahead price in the hour where the consumption is shifted. Here, we make an assumption that the consumer is charged according to a day-ahead price for every unit of electricity on hourly basis. A necessary condition for demand response is smart metering, which allows the day-ahead prices to be a substantial incentive for demand response (Katz, 2014). Thus, with advanced technology and smart meters consumers would be facing real-time pricing, where day-ahead prices can be used as a baseline.[4] In addition, we assume that small consumers are less flexible and require 10% higher compensations than a large consumer. Since for a small consumer the return from providing flexibility accounts for a smaller share of total budget than for a large consumer, a small consumer needs a higher compensation per unit of provided flexibility to encourage the shift in consumption.

Variable cost of placing a bid at the intraday market ψ consists of Nord Pool fee of 0,11 €/MWh and the day-ahead electricity price for a particular hour, which in our case is 35,55 €/MWh. The latter cost should be included too, as the aggregator or a large consumer has already paid for the initially planned consumption by buying electricity at the day-ahead market. In aggregator's case, a small consumer pays a day-ahead price for his or her consumption and since the consumption is moved from that hour, the consumer wants his or her money back. In addition, a consumer will ask to compensate for a day-ahead price increase due to shifting the consumption and some payment for inconvenience, which is denoted by w_a (α_i in case of a large consumer).

Finally, the fixed cost of accessing the intraday market and coordinating the flexible demand ϕ varies between the aggregator, a large consumer and the cooperative. This variable accounts for the annual market access fees by the Nord Pool which differs for large and small market participants. Annual payment for a large participant is €12.300, while a small participants pays only €6.000. Other fees related to intraday trading include electronic transmission of intraday data – €1.000 (Nord Pool, 2017*b*). The annual fixed cost also accounts for the salary, paid to a professional who is trading the flexible demand at the intraday market (€25,6 hourly rate), as well as the cost of renting an office space (€64,1 per month). Here we assume that the aggregator has an advantage comparing to a large consumer or a cooperative, since it already has employees trading at the the intraday market and an office space. Thus, the increase in its fixed cost of salary and office space is 25% lower than for a large consumer or the cooperative. After adjusting the annual fixed cost for one trading hour [5], ϕ_a, ϕ_i and ϕ_c are €6,13, €6,91 and €7,63 respectively.

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[4] The Danish Government is planning to make hourly sampled electricity meters available to all consumers by 2020. This will make it possible to introduce a settlement method where the consumption is metered hourly but data is read and provided to consumers only once a month. (Biegel et al., 2014)

[5] In total there are 8760 trading hours during the year.

5.2 Results

Table 2 shows the main results of all analysed scenarios. It provides the aggregator's traded quantity q_a, the large consumers' individual quantity q_i, the total quantity offered to the market Q, the aggregator's profit π_a, the large consumers' individual profit π_i, the total profit in the system Π, the market price p and the consumer surplus CS.

The total traded quantity by the aggregator and large consumers Q is lowest in the integrated system, as well as Scenario 2, 66,8 MWh, and results in the highest price for the final consumer, 39,94 €/MWh. In contrast, in Scenario 1, where the aggregator and all large consumers compete with each other, we see the largest quantity traded and the lowest price – 108,50 MWh and 38,22 €/MWh respectively. However, one can see that this is not a stable situation in the market, since all intraday market participants are facing losses and would exit the market in the longer run. The reason is relatively high fixed cost necessary to access the market. Perfect competition lowers the price to the level, where it is no longer profitable to trade the flexible demand.

Table 2: Equilibrium quantities, profits, prices and consumer surpluses (MWh, €, €/MWh)

	q_a	q_i	Q	π_a	π_i	Π	p	CS
Integrated system	1,20	1,31	66,80	-	-	229,02	39,94	92.15
Scenario 1	1,99	2,13	108,50	-3,57	-4,09	-208,11	38,22	243.10
Scenario 2a	1,20	1,31	66,80	229,02	0,00	229,02	39,94	92.15
Scenario 2b	1,20	1,31	66,80	433,56	-4,09	229,02	39,94	92.15
Scenario 2c	1,20	1,31	66,80	87,72	2,83	229,02	39,94	92.15
Scenario 3a	1,99	2,11	107,41	-3,46	2,76	134,50	38,26	238.25
Scenario 3b	-	2,13	106,69	-	2,83	141,30	38,29	235.07

Scenario 2 corresponds to the integrated system, where the aggregator acts as an entity internalising all costs and profits. Thus, the total traded quantity and the market price for the final consumer is the same as in the integrated system. Unlike in the integrated system case, here we can see the profit distribution between the aggregator and large consumers. In Scenario 2a, only the aggregator has the market access, therefore, large consumers' profits are reduced to minimum, just to keep them offering flexibility. In our case, large consumers shall receive a non-negative profit, which would incentivise them to stay in the game. Consequently, the aggregator absorbs all the profits [8], which is equal to the integrated system's

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[8] This illustrates Tirole's and Williamson's insights of vertical integration and the use of market power.

profits, i.e. €229,02. In Scenario 2b, the aggregator's profit jumps to €433,56. Here, large consumers are offered a price that is equal to Scenario 1, where each large consumer is bidding at the market directly. As we already know, large consumers would have a negative profit and would stop offering flexibility to the aggregator in a longer run. This market situation is not stable, so, to gain from large consumers' flexibility, the aggregator would be forced to raise the payment at least to the same level as in Scenario 2a. In Scenario 2c, the aggregator is assuming that large consumers have an option to form a cooperative, thus, to keep them offering flexibility to the aggregator, they must be paid at least as much as in Scenario 3b (we will see later that Scenario 3a is not a stable market situation either). This leaves the aggregator with only €87,72 profit and each large consumer receives €2,83.

In Scenario 3, large consumers form a cooperative and share fixed market access and coordination cost. This allows to increase individual profit from €-4,09 in the direct bidding case to €2,76 in Scenario 3a, where the cooperative competes with the aggregator. From Table 2 we see that this is not a stable market situation, since the aggregator is receiving a negative profit. This means that in the long run we would have a situation, that is similar to Scenario 3b, where the less efficient aggregator is pushed out of the market and there is only the cooperative that offers flexibility to the intraday market without competition. Naturally, the individual profit for a large consumer increases to €2,83 and is the largest among all analysed scenarios.

From Table 2 we can conclude, that if the aggregator is able/allowed to aggregate the flexibility of large consumers who have an option to form a cooperative, it would choose to pay the compensation equal to the profits of large consumers in Scenario 3b.

Consumer surplus is determined by the total traded quantity at the intraday market. Table 2 shows that the largest quantity and, accordingly, the lowest price for the final consumer is in Scenario 1. Here, the consumer surplus reaches €243,10. Unfortunately, in this scenario all market participants are facing losses and would stop offering flexibility in the long run. Second largest consumer surplus is in Scenario 3a – €238,25. However, this is not a stable market situation either, because the aggregator cannot cover its average cost and would leave the market. Finally, in Scenario 3b, the consumer surplus is slightly lower, €235,07, but it can be sustained in the long run. This means, that the cooperative of large consumers is able to offer the largest amount of flexibility at the lowest price. However, if the aggregator is able/allowed to aggregate the flexible load of large consumers, in the long run the consumer surplus would be the lowest, €92,15.

Table 3: The worst and the best scenarios for different market players in the long run

	Scenario 1	Scenario 2a	Scenario 2b	Scenario 2c	Scenario 3a	Scenario 3b
Large consumers	x*	worst	x	best	x	best
The aggregator	x	best	x	medium	x	worst
Small consumers	x	best	x	best	x	worst
Final consumers	x	worst	x	worst	x	best

* "x" means that the equilibrium is not stable in the long run

Table 3 is a summary table showing the best and the worst scenarios for large consumers, the aggregator, small consumer providing flexibility to the aggregator and final consumers buying power at the intraday market in the long run. As Scenario 1, Scenario 2b and Scenario 3a are not stable in the long run due to negative profits for some of the market participants, only Scenario 2a, Scenario 2c and Scenario 3b are analysed further. One can see that none of these scenarios is the best for all market participants. There is always a trade-off and each scenario has its winners and losers. For example, Scenario 2a, where the aggregator is trading flexibility on behalf of small and large consumers, is the best for the aggregator and its small consumers and the worst for the large consumers and final consumers. Meanwhile, Scenario 3b, where the cooperative is the only seller in the market, is the best for large consumers and the final consumers. Some scenarios are equally good or equally bad to some market participants. For instance, Scenario 2c and Scenario 3b are equally good to the large consumers because they get the same profit in both of them. Small consumers are indifferent between Scenario 2a and 2c, as the amount and compensation for the provided flexibility are the same. Similarly, final consumers find Scenario 2a and Scenario 2c equally bad due to the aggregator's market power and lower quantity of flexibility in the intraday market. It is a likely outcome, that in the long run the aggregator would agree to pay the large consumers a compensation, equal to their profits in a cooperative in Scenario 3b. However, this should raise the awareness of the regulatory authorities, as in this case the final consumers would end up with the lowest consumer surplus. Moreover, the highest welfare, i.e. the sum of the system's profit and the consumer surplus, is reached in Scenario

3b (€376,37).[9]

5.3 Sensitivity analysis

The numerical example represents one hour trading in the Nord Pool intraday market. The conditions in other intraday markets might differ from those in Nord Pool. Also, the input data for other hours during a year might vary from those provided in the example. Therefore, to show the effect of changes in input variables, we have provided a sensitivity analysis. We focus on the number of large consumers participating in the market n and the coordination and other related fixed cost for the aggregator, a large consumer and the cooperative ϕ_a, ϕ_i and ϕ_c (see Figures in Appendix D). We also analyse the impact of changes in the variable cost ψ, the aggregator's payment to small consumers for shifting the first MW of electricity w_a, the i^{th} large consumer's cost of shifting the first MW of electricity α_i, as well as the slope of the inverse demand function β_1 and its intercept β_0.

The analysis shows that the rating of scenarios for the aggregator, the large consumers and final consumers does not depend on different values of input variables, except the new relevant scenarios (where the market participants do not have to leave the market in the long run) would take their place in the ranking. Small consumers, providing the flexibility to the aggregator, however, change their preference from Scenario 3a to Scenario 1 when the number of large consumers participating in the market n becomes larger than five.

5.3.1 The number of large consumers n

Figure D.1 shows that in all scenarios[6] the total quantity and, therefore, consumer surplus is increasing with the number of large consumers participating in the intraday market. Thus, the final consumers would gain more if more large consumers would be incentivised to trade at the intraday market. Their willingness to participate is reflected by the generated profit that is shown in Figure D.2.

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[9] Here we assume that the small consumers' compensation paid by the aggregator covers only their cost of providing flexibility.

[6] The total traded quantities in Scenario 2 and Integrated system are the same, since the aggregator internalises all cost and profits like in the integrated system case.

In Scenario 1, the aggregator's and large consumer's profits are the lowest and decrease with the increasing number of large consumers in the market, i.e. increasing competition. In all cases of Scenario 2, the aggregator has more power and bids at the intraday market on large consumers' behalf. In this way, the increasing number of it's clients results in higher profits. However, the steep curve in Scenario 2b is not likely to be sustainable in the long run, because large consumers face losses and, eventually, would refuse to pay to the aggregator and cease to offer flexibility at all. In Scenario 2a, large consumes receive zero profits, while in Scenario 2b and 2c their profit reduces with increased competition among each other[7]. From the graph we see that for a large consumer it is not profitable to enter the market and place bids directly at the intraday market, if the number of its competitors reaches 20. This means that only the concentrated market would guarantee the sufficient revenues to cover the average cost of flexible demand in a direct bidding case. Also, the individual trading quantities should be relatively large. When large consumers have an option to form a cooperative, they can generate positive profits even when the number of members reaches 100.

Sensitivity analysis shows that the variation in input data can slightly change the market participants' preference to some scenarios. For example, the number of large consumers n can change the ranking of scenarios for the small consumers depending on their provided amount of flexibility.[10] Also, when the value of n is low enough ($n < 21$), all market participants receive a non-negative profit in all scenarios and none of them leaves the market, which means that scenario 3b becomes not relevant. Here we distinguish two intervals resulting in a slightly different scenario ranking: $n < 6$ and $6 \leq n < 21$. When $n \geq 21$, the market participants preferences remain the same as in Table 4.

Table 4 presents the best and the worst scenarios for different market players when the number of large consumers n is low enough ($n < 21$) to keep non-negative profits for all market participants and stay in the market and when $n < 6$ (values are shown in brackets)

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[7] Large consumer's profit is the same in Scenario 1 and 2b, as well as Scenario 2c and 3a due to the aggregator's compensation policy.

[10] We assume that the small consumers are better off when they can offer larger amounts of flexibility and get compensation from the aggregator, even though the compensation only covers the consumption shifting cots.

Table 4: The worst and the best scenarios for different market players in the long run when $6 \leq n < 21$ (when $n < 6$, if different)

	Scenario 1	Scenario 2a	Scenario 2b	Scenario 2c	Scenario 3a	Scenario 3b
Large consumers	medium	worst	medium	best	best	x
The aggregator	worst	best	2nd best	medium	2dn worst	x
Small consumers	best (medium)	worst	worst	worst	medium (best)	x
Final consumers	best	worst	worst	worst	medium	x

and the small consumers' preferences are slightly different.[11]

The best option for the large consumers is still to form a cooperative and share fixed cost with other cooperative members or provide their flexibility to the aggregator and be compensated based on the profit in a cooperative. As large consumers receive a positive profit bidding in the market individually, it is their second best option. It is also equally good to provide their flexibility to the aggregator and be compensated based on their profit when bidding individually. When the large consumers cannot choose any of these options, they can offer their flexibility to the aggregator which absorbs all the profit. Obviously, this is the least attractive option for the large consumer and the best for the aggregator. The aggregator's profit is the lowest when it has to compete with the individually bidding large consumers. Thus, the aggregator prefers to compete with the cooperative. Or, if it is possible, to trade flexibility on behalf of the large consumers, pay compensations and receive an even higher profit. The aggregator's small consumers prefer when the aggregator is in a competition with individually bidding large consumers (when $6 \leq n < 21$) or the cooperative (when $n < 6$). The smallest amount of small consumers' flexibility is used when the aggregator has market power and is the only one offering flexibility in the market. This scenario is the worst for the final consumers too, as they prefer competition in the market and receive the highest consumer surplus in Scenario 1. All in all, when the number of large consumers n is low, none of the scenarios is the best for all market participants, as before. If the large consumers have an option to form a cooperative, the most likely scenario is Scenario 2c, which brings the highest overall welfare, but is the worst option for the small and final consumers.

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[11] The aggregator leaves the market when n reaches 22 in Scenario 1 and when n reaches 23 in Scenario 3a.

5.3.2 The fixed cost ϕ and variable cost ψ

The lower fixed cost of accessing the intraday market and coordinating the flexible demand ϕ may help market participants to stay in the market. For the aggregator, the increase of efficiency in coordination activities would bring relatively low benefits in Scenario 2, where it absorbs all or a large share of large consumers' profits. However, in Scenarios 1 and 3a, such cost reduction (when $\phi_a < 2{,}5$) could result in a positive profit (see Figure D.3). Naturally, for large consumers, the largest fixed coordination and related cost influence on profits is seen in Scenario 1, where large consumers are bidding at the market directly and paying coordination and market access cost individually (see Figure D.4). If $\phi_i < 2{,}8$, a large consumer's profit becomes positive and they can bid in the market individually in the long run. When these costs are shared in the cooperative, the effect of changes in ϕ_c is very mild. Nevertheless, higher ϕ_c reduces consumer surplus due to the lower quantities offered by the large consumers (see Figure D.5). The changes in ϕ do not change the market participants' preferences regarding scenarios except those cases, when the participants do not need to exit the market due to high fixed cost. For example, the final consumers prefer Scenario 1 to Scenario 3b, when the large consumers are able to bid individually with a non-negative profit. However, this scenario is the second worst for the large consumers.

Even though the increasing variable cost of placing a bid at the intraday market ψ reduces the market participants' profits and the consumer surplus, it does not change the ranking of the analysed scenarios (see Figure D.6 and Figure D.7).

5.3.3 The aggregator's and a large consumer's cost of shifting the load w_a and α_i

The increasing aggregator's payment to small consumers for shifting the first MW of electricity w_a and the i^{th} large consumer's cost of shifting the first MW of electricity α_i both reduce consumer surplus (see Figure D.9 and Figure D.10). Also, a higher cost for the aggregator diminishes its profit and increases the competitors' profit. For the large consumers the situation is different: their higher cost increases their profit up to a certain point (approx. $\alpha_i = 1,6$) and then starts to decrease it. The reason is that the large consumers offer smaller quantities, but at a higher price. However, rising cost eventually lowers their quantities even more and the higher price cannot compensate the increase in cost. Here, the aggregator receives a higher profit due to increased prices and quantities in Scenario 1 and Scenario 3a, but its profits are diminishing in Scenario 2a and Scenario 2c due to increased compensations to the consumers per MW of flexibility and the lower quantities they offer (see Figure D.8 and Figure D.11b). Nevertheless, the rating of the analysed scenarios does not change due to different w_a and α_i values.

5.3.4 The slope of the inverse demand curve β_1 and its intercept β_0

The more price inelastic the final consumers are, the higher the profit of the market participants. Thus, lower values of β_1 can encourage the market participants to stay in the market, but the ranking of all scenarios remains unchanged (see Figure D.12 and Figure D.13).

The increasing intercept of the inverse demand curve β_0, i.e. increasing demand, can increase the market participants' profits and encourage them to stay in the market. Similarly like before, the ranking of scenarios would not change, except the new relevant scenarios (where the market participants do not have to leave the market in the long run) would take their place in the ranking (see Figure D.14 and Figure D.15).

6 Conclusions

The peculiarities of electrical power systems, in particular the need for simultaneous electricity production and consumption, create conditions for specific electricity markets. Planning and adjusting the production close to real time consumption is a usual routine for the power generators. With increasing share of less predictable production of renewable power sources, the planning becomes a bigger challenge and the need for regulating energy, as well as the flexibility of demand, is growing. To ensure the sufficient amount of cheap energy at the intraday market, consumers should be incentivised to offer their flexibility and adjust consumption according to the system's needs. Due to high market access cost and usually small offer sizes, large consumers are struggling to bid their flexibility at the intraday market. Thus, an appropriate governance structures should be put in place to help large consumers to overcome coordination and market access issues.

The model, presented in this paper, provides a few important insights to governance structures and flexible demand trading at the Nord Pool intraday market. First of all, fixed flexible demand coordination and market access cost is too high for a large consumer to bid directly at the intraday market. Therefore, the largest consumer surplus, obtained in Scenario 1, cannot be sustained in the long run, because large consumers would cease unprofitable trading of flexibility and focus on their primary activities. Second, if large consumers would access the market via the aggregator, all the profit would be absorbed by the aggregator unless it would try to keep large consumers from leaving by offering a payoff equal to the one obtained by forming a cooperative. However, in this case the final consumers would face relatively high price and their surplus would be moderate. Third, the cooperative of large consumers would offer the lowest price and the largest quantity of flexible demand in the long run. Furthermore, the cooperative structure guarantees the largest profit to large consumers. If the aggregator would not be able/allowed to aggregate the flexibility provided by large consumers, it would be forced to increase efficiency or leave the intraday market.

Sensitivity analysis shows that the variations in input variables used in the numerical example would not change the ranking of the analysed scenarios, although different values of some input variables might lead to a situation where none of the market participants exits the market. In this case, Scenario 1, where the large consumers bid directly at the market, and Scenario 3a, where the aggregator competes with the cooperative, would take place in the ranking. As before, there would be no scenario that is the best for all market participants. There is always a trade-off and there are winners and losers in each scenario. The large consumers are incentivised to form a cooperative and share high market access cost, which is one of the main obstacles to bid directly at the market, while the aggregator prefers an integrated system where it trades flexibility on its small and large consumers' behalf. Here, the regulatory authorities should be aware of the aggregator's market power growth and its harm to the final consumers. Even though the aggregator is seen as a first choice to aggregate flexible demand by the European Energy Regulators, the Member States should also look at alternative ways to enable demand-side flexibility in electricity markets. One way could be encouraging the large consumers to form cooperatives and reduce the market power of the aggregators.

The analysis could be extended by including other electricity markets with their specific demand functions. Also, the strategies of other market players, for example, wind or conventional power producers, could be investigated too. Another extension could be to include a longer optimisation period. In our model, the equilibrium is found for one hour of trading. However, if the flexibility providers shift the consumption instead of curtailing it, they would take into account prices corresponding to demand and supply in a period of at least several hours, depending on the flexibility source. Even though this would not change the main concept of benefits gained by sharing the fixed coordination and market access cost in the cooperative governance structure, it would result in different consumer surpluses and additional market risks to market participants, such as the uncertainty about traded quantities and prices in other hours, where the consumption is moved.

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Appendix A Intermediation: literature review

This appendix presents a more detailed review of intermediation literature that provides some examples of research directions. Below one can find four groups of papers based on the intermediation type: information intermediaries, electronic intermediaries, financial intermediaries and innovation intermediaries.

The first group of papers focus on information intermediaries. For example, Rose (1999) analyses the economics, concept, and design of information intermediaries and applies microeconomic theory of search to derive the optimal strategy of the information intermediary. Bhargava and Choudhary (2004) focus on infomediaries that provide matching services and examine pricing and product line design strategies. Lee and Cho (2005) distinguishes between human and nonhuman information intermediary and identifies factors determining the likelihood of using human information intermediaries in the context of financial investment decisions. Authors find that a lower level of expertise in financial management, a large amount of total financial assets, and a high opportunity cost of time increase the likelihood of using information intermediaries. Womack (2002) studies three institutional forms of information intermediaries, the for-profit firm, the nonprofit organisation and the government agency, and comes to a conclusion that in order to encourage information consumption up to socially optimal levels, one needs government agencies or nonprofit intermediaries.

The second group of papers analyses electronic intermediaries. They are discussed by Bailey and Bakos (1997) who argue that due electronic markets some of the traditional roles of intermediaries may become less important, however, markets do not necessarily become disintermediated. Bakos (1991) studies economic models of search and examines how prices, seller profits and buyer welfare are affected by lower search cost and finds that economic characteristics of electronic markets, as well as their lower search cost, create many possibilities for the strategic use of such information systems. Later Bakos (1997) examines buyer search cost in markets with differentiated products in the context of an electronic market place. Also, the author investigates the incentives of buyers, sellers and independent intermediaries to invest in electronic market places.

The third group of papers focus on financial intermediaries. Diamond (1984) presents a theory of financial intermediation which is based on minimising the cost of monitoring information. The latter helps to deal with incentive problems between borrowers and lenders. Moreover, the analysis can be applied for the portfolio and capital structures of intermediaries. Allen and Santomero (1997) highlights an interesting observation that even though transaction cost and asymmetric information have decreased, intermediation has increased. They argue that the markets for financial futures and options are more for intermediaries and not for firms or individuals. The authors discuss the role of intermediaries in the new context focusing on risk trading and participation cost. Allen and Gale (2004) analyse financial intermediaries in terms of whether they issue complete or incomplete contracts. They find that there might be a need for regulating liquidity provision if markets for aggregate risk are incomplete. Ramakrishnan and Thakor (1984) argue that in order to explain financial intermediaries the transaction cost concept is not needed. Instead, the emergence of financial intermediaries is due to their ability to lower information production cost. Adrian and Song Shin (2010) investigate whether financial intermediaries influence the real economy and whether the financial sector instead of being passive is the main driver of "boom-bust cycle". Similarly, Smith (2003) discusses how financial intermediation affects growth and how banking crises influence major business cycle.

A relatively new field that has attracted researchers' attention is intermediation in innovation, which is the fourth group of papers. Abbate et al. (2013) presents emerging research fields on innovation intermediaries. Howells (2006) develops a typology and framework of the different roles and functions of the innovation intermediaries. Hoppe and Ozdenoren (2005) present a theoretical framework for the role of intermediaries between creators and users of new inventions. Here, the intermediary helps to sort profitable inventions from unprofitable. Lichtenthaler (2013) investigates the collaboration between manufacturing firms and innovation intermediaries. The author finds that manufacturing firms may reduce their transaction cost in technology markets if they collaborate with intermediaries. Inkinen and Suorsa (2010) investigate the role intermediaries in high-technology product development in Finland and, based on a survey of high-technology enterprises, find that funding services are seen as the most important activity of intermediaries. Gassmann et al. (2011) focus on the intermediary's role in the cross-industry innovation process and study which capabilities of an intermediary lead to a successful initiation of a cross-industry innovation.

Appendix B The sequence of bidding and its influence to the model results

This appendix provides a discussion and a numerical illustration of the bidding sequence of market participants. In the Stackelberg game, there is a first-mover advantage, therefore, the profit of participants depends on who moves first.

B.1 Alternative Scenarios 1

Table B.1 shows the model results using the same input data as before. In Scenario 1, the aggregator acts as a leader. In the alternative Scenario 1, where the large consumers bid first (simultaneously) and the aggregator bids second, the offered quantity and the profit of the aggregator is reduced from 1,99 MWh and €-3,57 in Scenario 1 to 1,89 MWh and €-3,78. In this situation, the aggregator is worse off because it looses the first-mover advantage. The large consumers, on the other hand, increase their individually offered quantity from 2,13 MWh to 2,17 MWh. Nevertheless, their individual profit decreases from €-4,09 to €-4,27 compared to Scenario 1. Even though they are bidding first, they are still competing with each other and tend to offer larger quantities. As a result, a total quantity in the market increases by 2,06 MWh and drives the price down by 9 cents to €38,13. With lower price a consumer surplus grows by €9,31. However, like in Scenario 1, in the long run, the large consumers would exit the market due to a negative profit.

Table B.1: Equilibrium quantities, profits, prices and consumer surpluses in Scenario 1 and its alternative scenarios (MWh, €, €/MWh)

	q_a	q_i	Q	π_a	π_i	Π	p	CS
Scenario 1	1,99	2,13	108,50	-3,57	-4,09	-208,11	38,22	243,10
Alt. Scenario 1 (consumers bid first)	1,89	2,17	110,56	-3,78	-4,27	-217,42	38,13	252,41
Alt. Scenario 1 (simultaneous bidding)	1,95	2,13	108,49	-3,57	-4,09	-208,05	38,22	243,03

The second alternative Scenario 1 presents the situation when all market participants place their bids simultaneously. Table B.1 shows that the results of this alternative scenario are very close to those of Scenario 1. Thus, apart from slightly lower quantity offered by the aggregator due to a lost position as the first-mover, the influence to the market outcomes is minimal.

B.2 Alternative Scenarios 3a

In Scenario 3a, the aggregator and the large consumers bid at the market simultaneously. The alternative Scenarios 3a present situations where market participants have the first-mover advantage (see Table B.2). The alternative Scenario 3a where the cooperative bids first is closely related to the alternative Scenario 1 where the large consumers bid first, only in this case they bid as a cooperative. Similarly, the aggregator's offered quantity decreases by 0,07 MWh and each large consumer increases the offered quantity by 0,04 MWh compared to Scenario 3a. Like before, the total offered quantity increases, the profits of all participants drop, the price becomes 8 cents lower and consumers enjoy higher surplus (€247,53 vs. €238,25).

Table B.2: Equilibrium quantities, profits, prices and consumer surpluses in Scenario 3a and its alternative scenarios (MWh, €, €/MWh)

	q_a	q_i	Q	π_a	π_i	Π	p	CS
Scenario 3a	1,99	2,11	107,41	-3,46	2,76	134,50	38,26	238,25
Alt. Scenario 3a (cooperative bids first)	1,92	2,15	109,49	-3,64	2,58	125,39	38,18	247,53
Alt. Scenario 3a (aggregator bids first)	2,03	2,11	107,43	-3,46	2,76	134,43	38,26	238,31

The alternative Scenario 3a where the aggregator has the first-mover advantage does not differ much from the Scenario 3a apart from a slightly larger quantity offered by the aggregator and slightly larger consumer surplus. The alternative Scenarios 3a do not reflect the market situation in the long run because the aggregator would leave the market due to a negative profit.

B.3 Alternative Scenarios 2b and 2c

Scenarios 2b and 2c are affected by the changes in large consumers' profits in the alternative Scenarios 1 and 3a. In Scenario 2b, the aggregator pays a compensation to large consumers for the provided flexibility equal to their profit that could be obtained by bidding directly at the market (i.e. Scenario 1) to prevent them from leaving the aggregator. As the consumers' profit in the alternative Scenarios 1 remains negative, alternative Scenarios 2b will not reflect large consumers' behaviour in the long run, which means that large consumers would stop offering their flexibility. Thus, the outcome would be the same as in Scenario 2b.

In Scenario 2c, the aggregator pays a compensation to large consumers, which is equal to their profit that could be obtained by forming a cooperative. As in the alternative Scenarios 3a the aggregator receives a negative profit, it would leave the market in the long run. Thus, in order to stay in the market it would have to offer a compensation equal to the profit that could be obtained by forming a cooperative without competition (i.e. Scenario 3b). As a result, the outcome would remain the same as in Scenario 2c.

Appendix C Estimation of β_0 and β_1

The inverse demand function at the intraday market is expressed as $p(Q) = \beta_0 - \beta_1 Q$. To find the intercept β_0 and the slope β_1, we need two points indicating quantities and respective prices for a particular hour, since the demand function differs for each hour of a day.

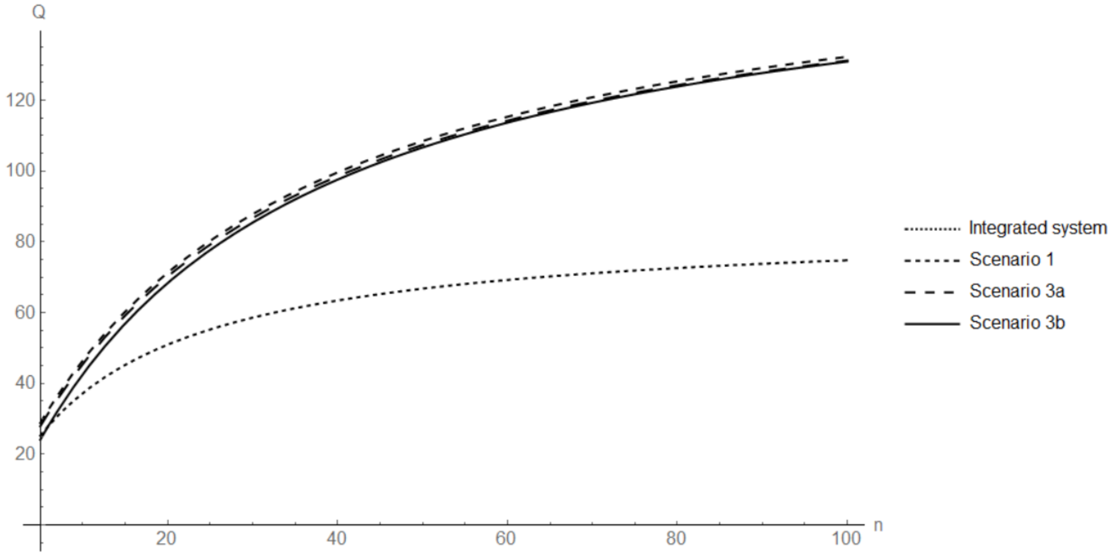
From Nord Pool data we know, that the total amount of traded energy during the analyzed hour was 259 MWh and the lowest accepted bid was 32,0 €/MWh, which determines the first point. The second point is indicated by the highest accepted bid, i.e. 42,7 €/MWh, and zero quantity. Thus, we are solving a simple system of two equations with two unknowns:

$$\begin{cases} 32,0 = \beta_0 - 259\beta_1 \\ 42,7 = \beta_0 - 0\beta_1 \end{cases}, \tag{52}$$

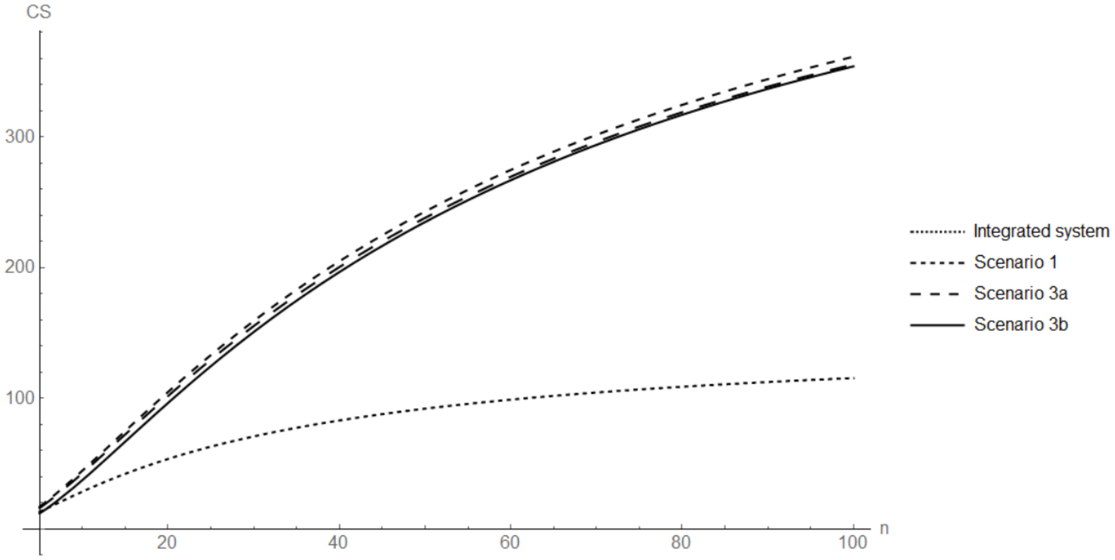
which gives $\beta_0 = 42,7$ and $\beta_1 = 0,0413$.

Appendix D Figures for Sensitivity analysis section

D.1 The number of large consumers n

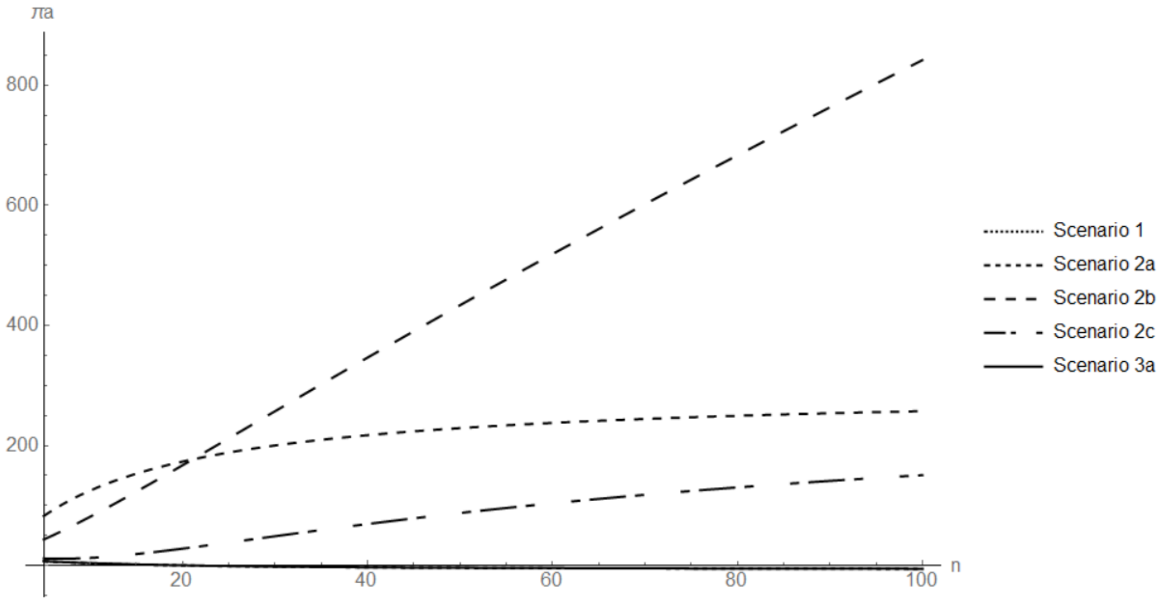


(a) Total quantity

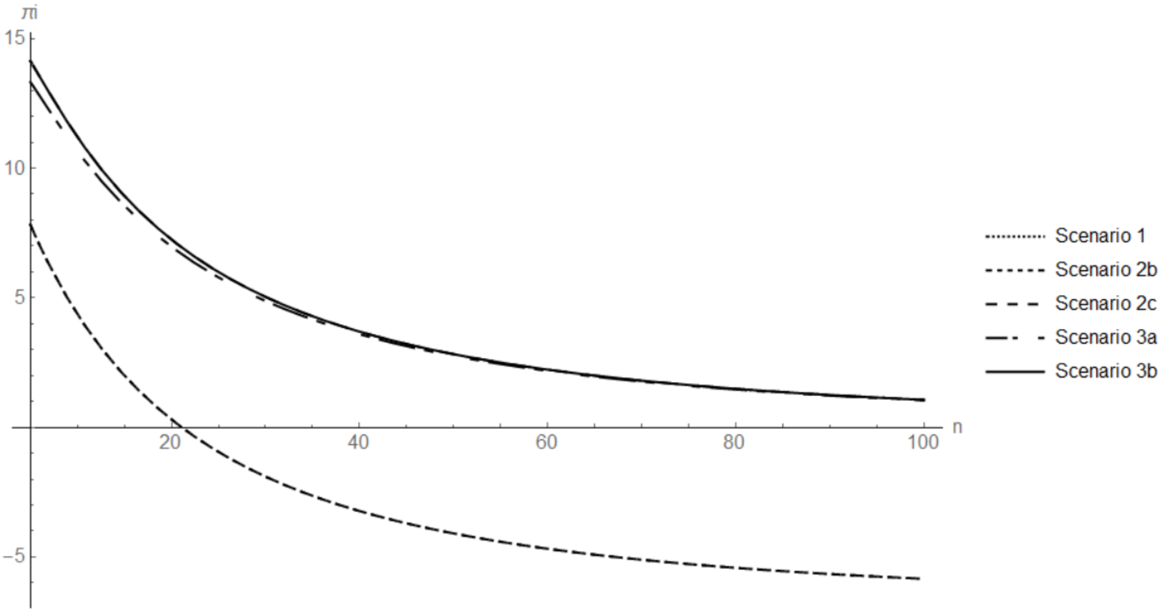


(b) Consumer surplus

Figure D.1: Total quantity and consumer surplus depending on a scenario and the number of large consumers n



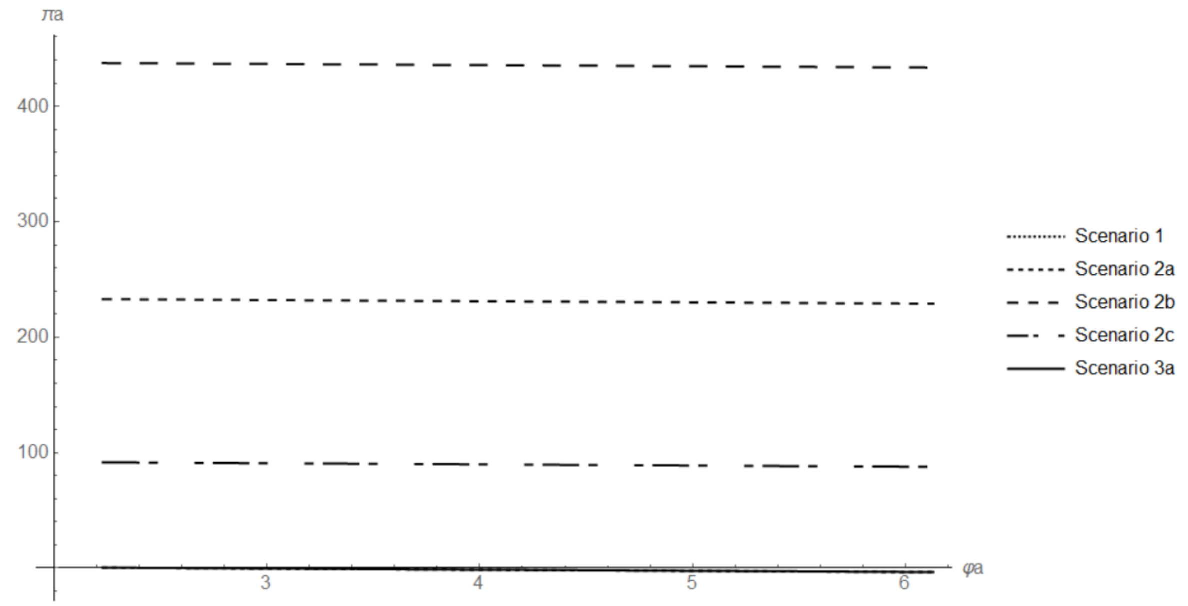
(a) Aggregator's profit



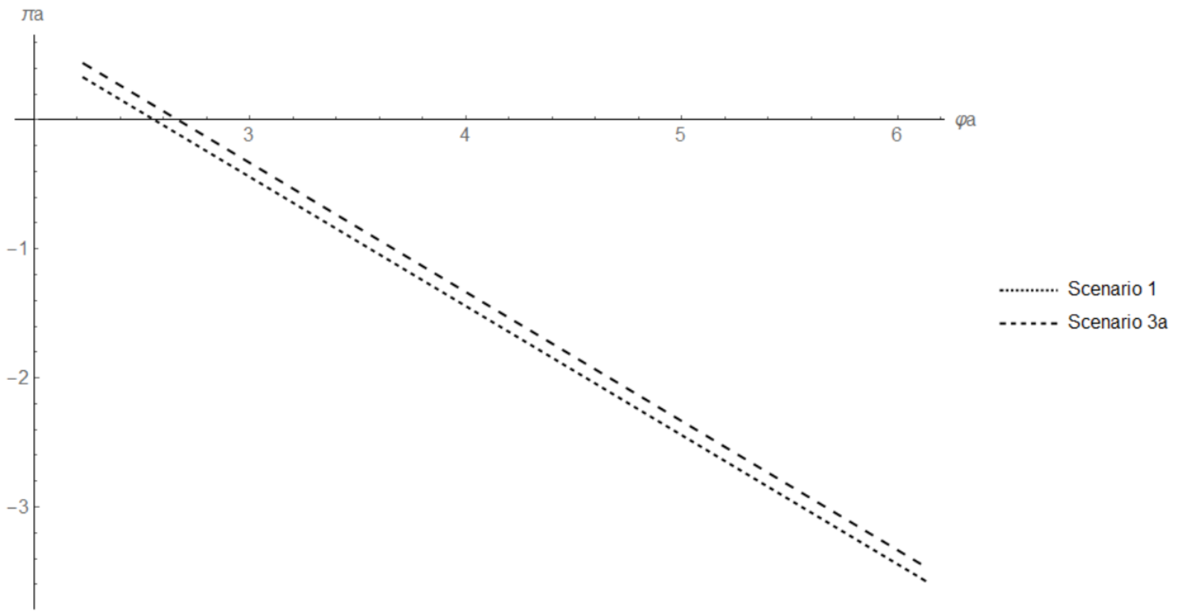
(b) Large consumer's profit

Figure D.2: The aggregator's and a large consumer's profit depending on a scenario and the number of large consumers n

D.1.1 The fixed cost ϕ and variable cost ψ

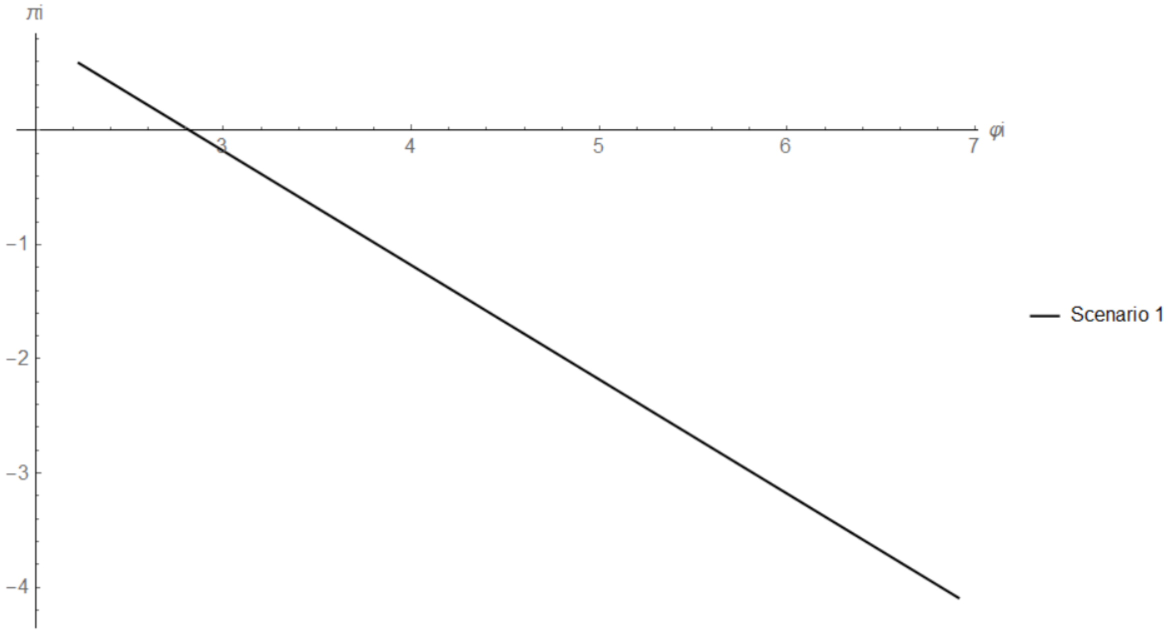


(a) All scenarios

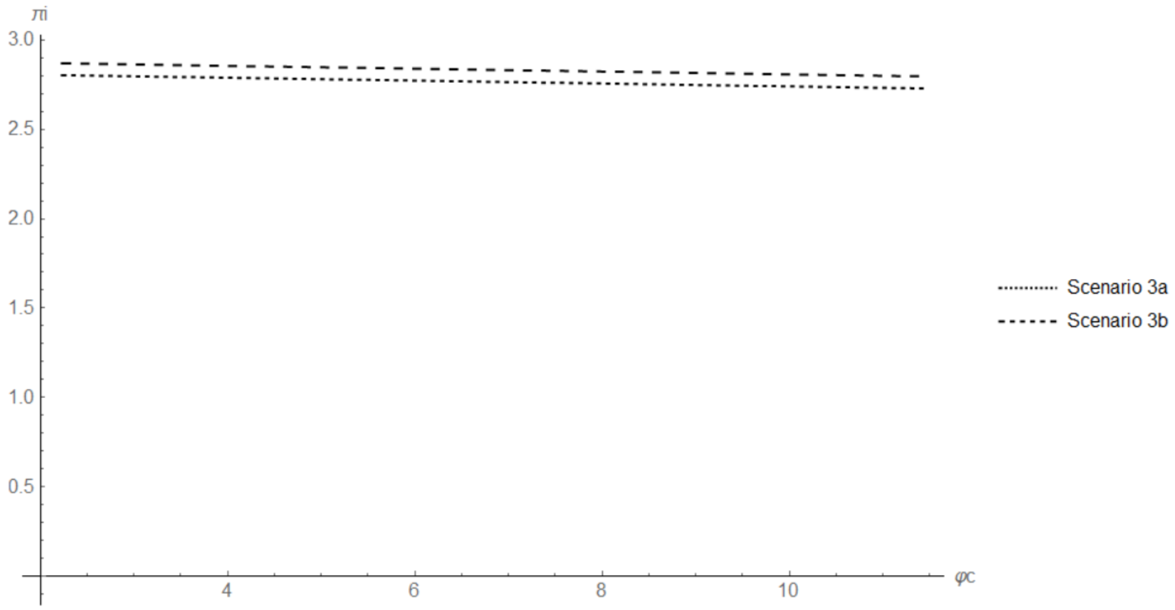


(b) Scenarios 1 and 3a

Figure D.3: The aggregator's profit depending on a scenario and fixed coordination and market access cost ϕ_a



(a) Scenario 1



(b) Scenario 3

Figure D.4: A large consumer's profit depending on a scenario and fixed coordination and market access cost ϕ_i and ϕ_c

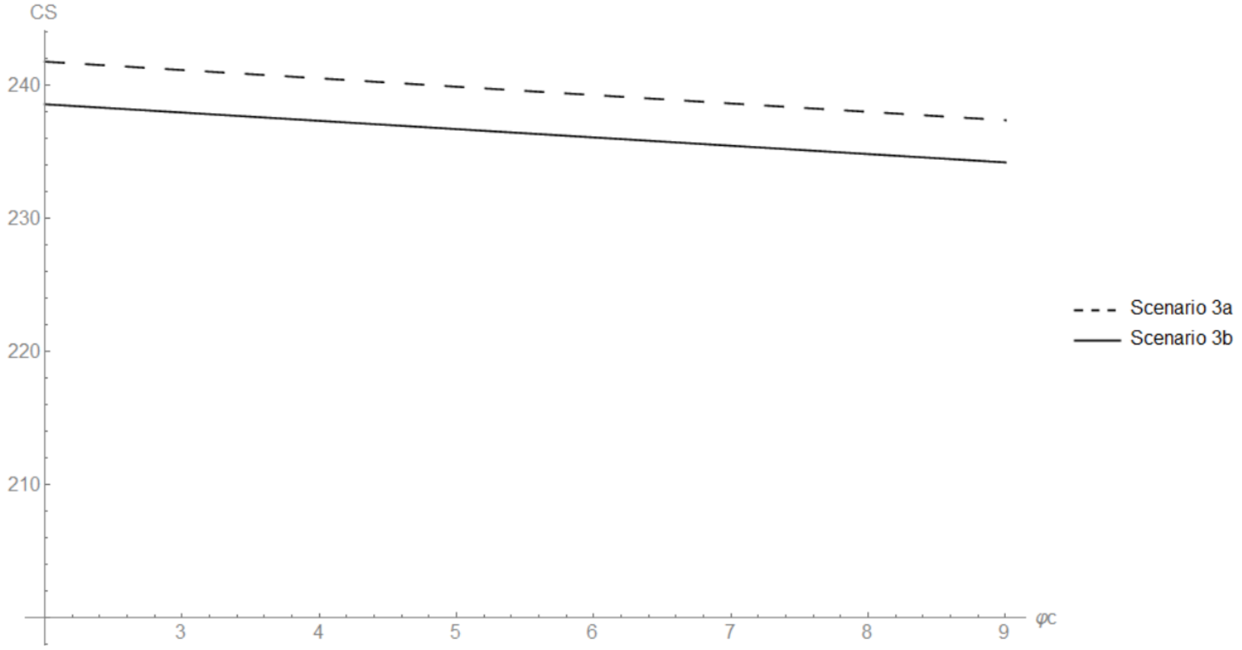


Figure D.5: Consumer surplus depending on a scenario and fixed coordination and market access cost ϕ_c

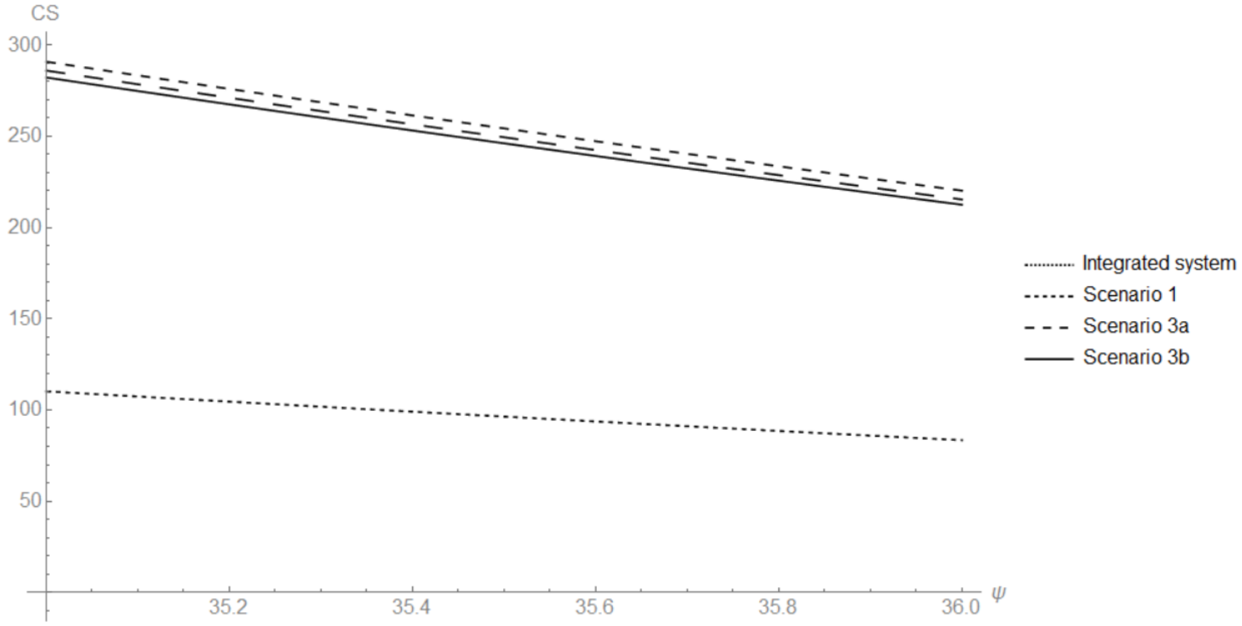
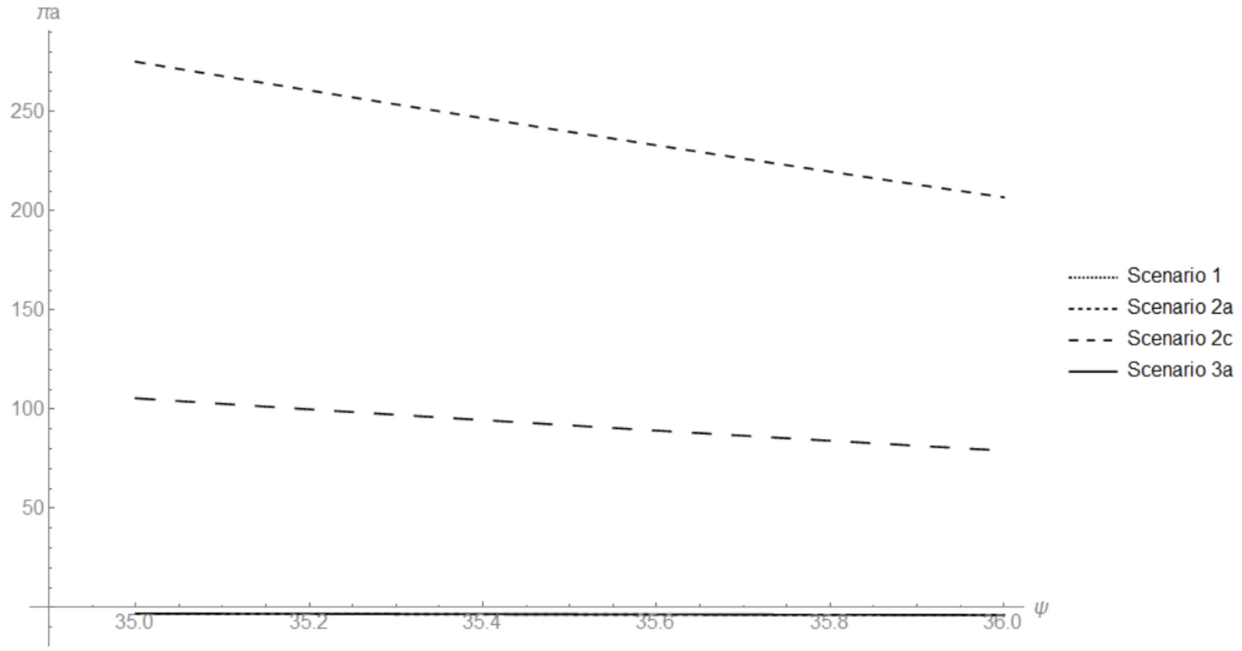
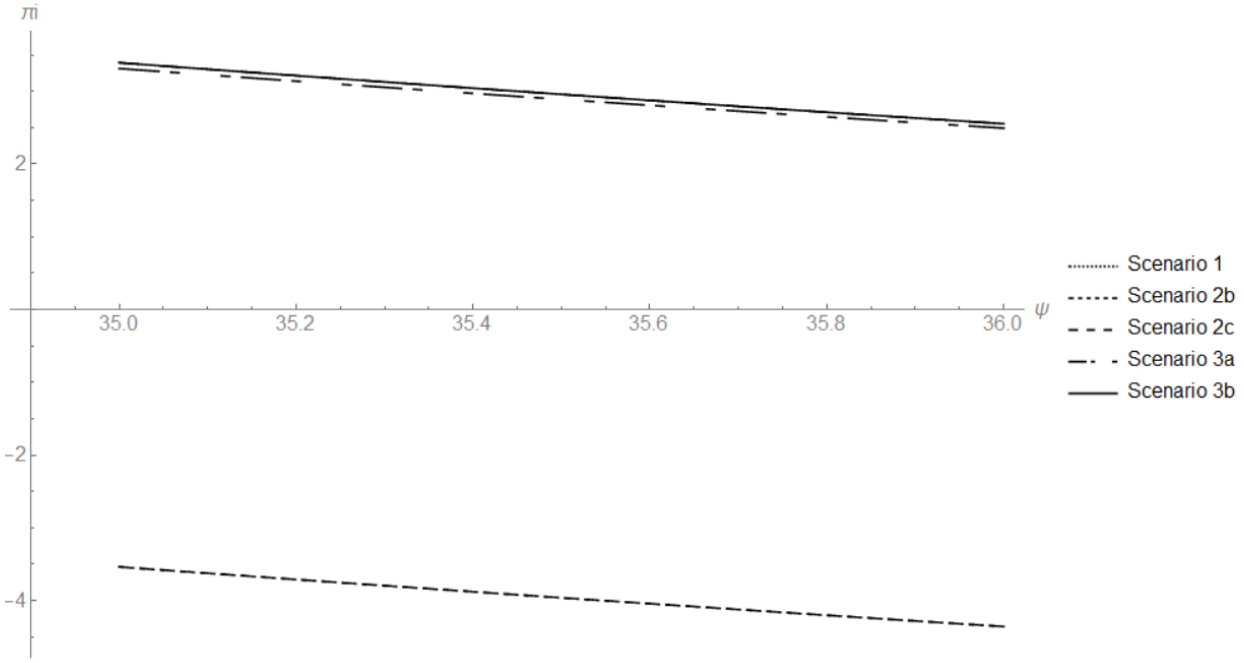


Figure D.6: Consumer surplus depending on a scenario and the variable cost of placing a bid at the intraday market ψ



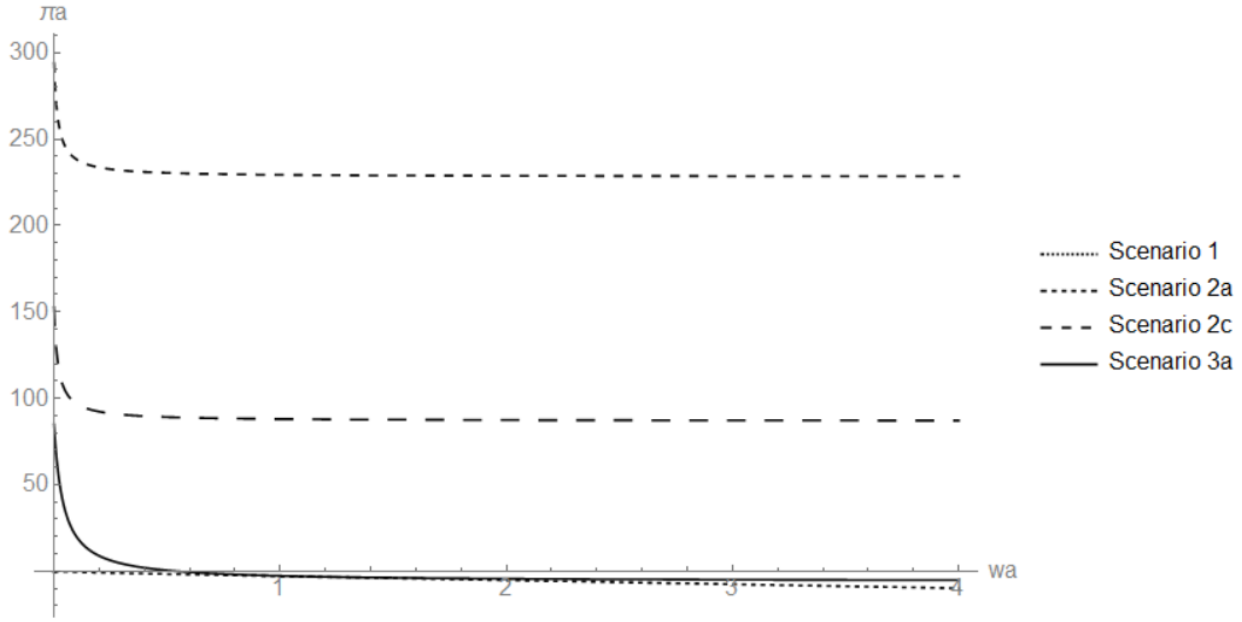
(a) The aggregator's profit



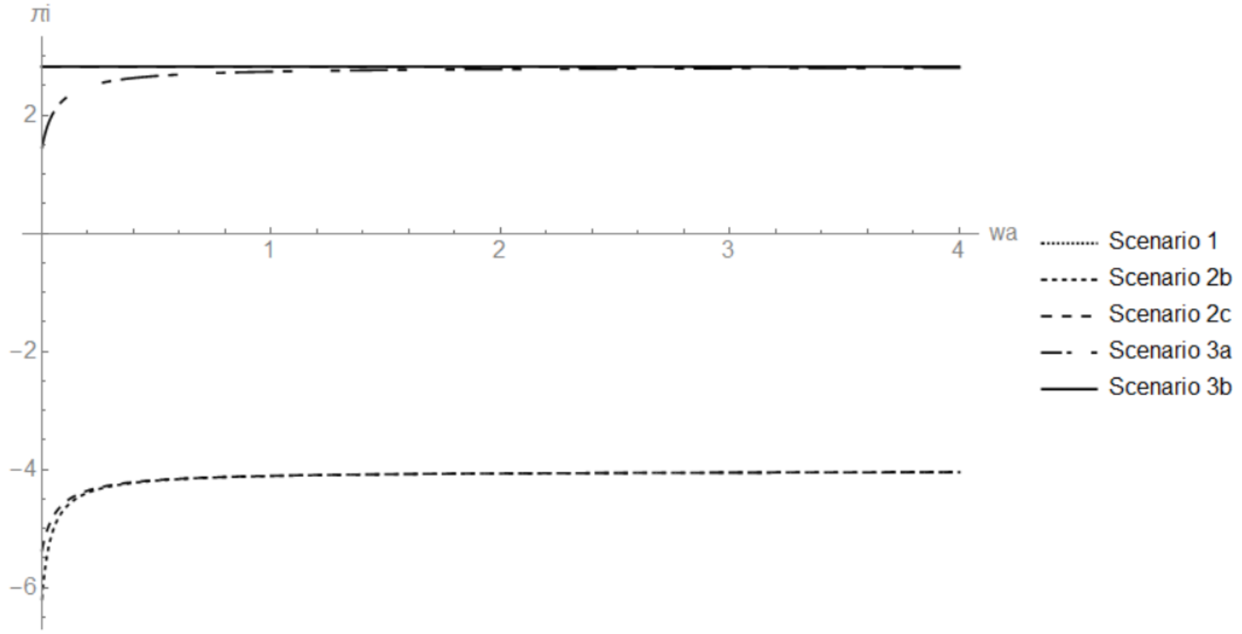
(b) A large consumer's profit

Figure D.7: The aggregator's and a large consumer's profit depending on a scenario and the variable cost of placing a bid at the intraday market ψ

D.2 The aggregator’s and a large consumer’s cost of shifting the load w_a and α_i



(a) The aggregator’s profit



(b) A large consumer’s profit

Figure D.8: The aggregator’s and a large consumer’s profit depending on a scenario and the aggregator’s payment to small consumers for shifting the first MW of electricity w_a

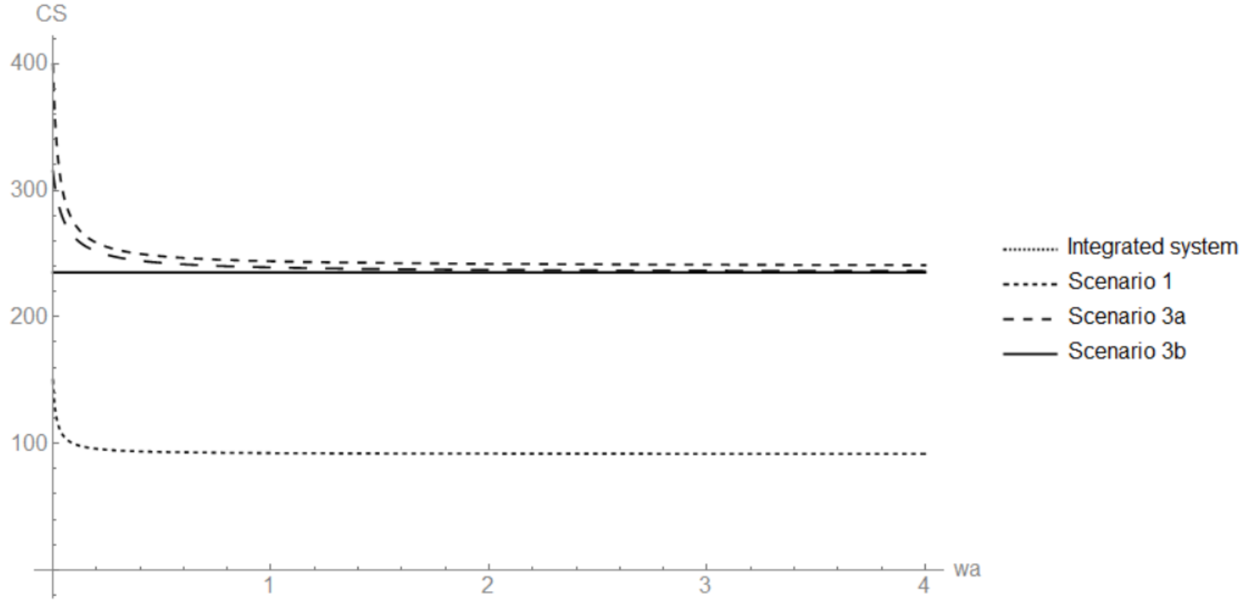


Figure D.9: Consumer surplus depending on a scenario and the aggregator's payment to small consumers for shifting the first MW of electricity w_a

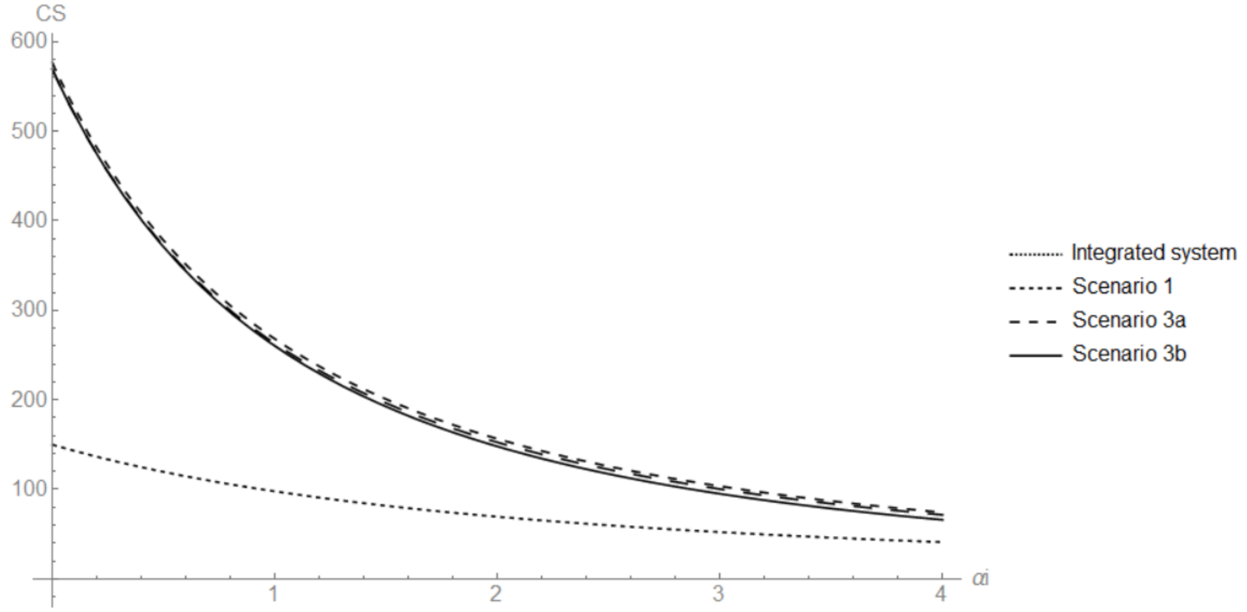
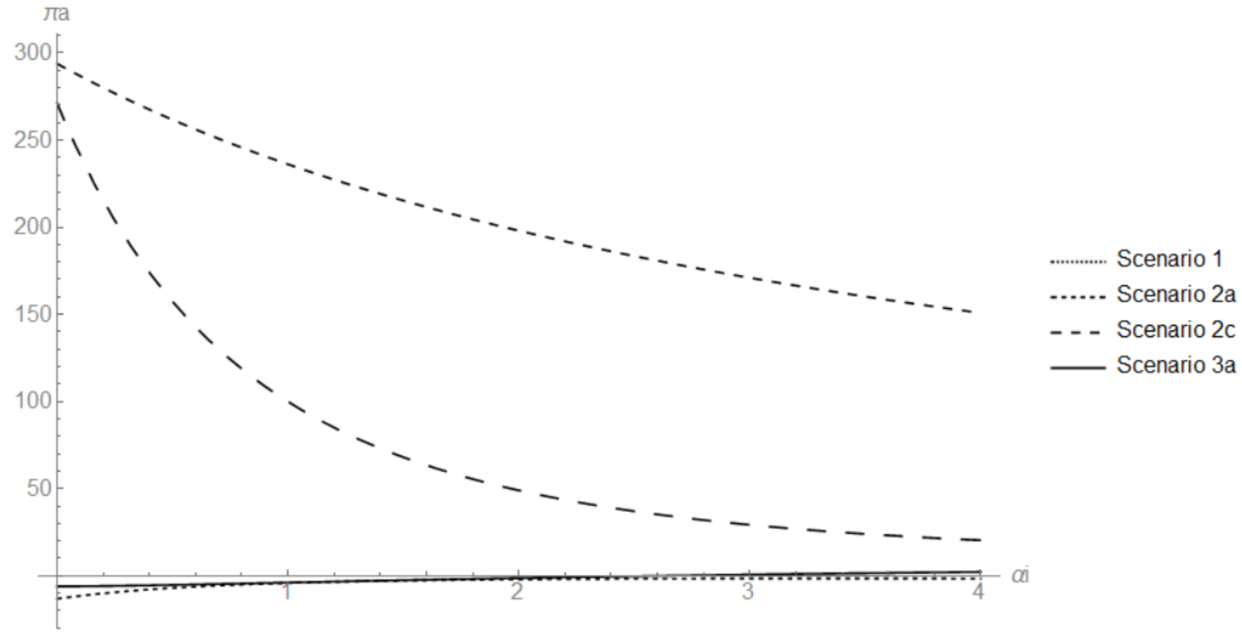
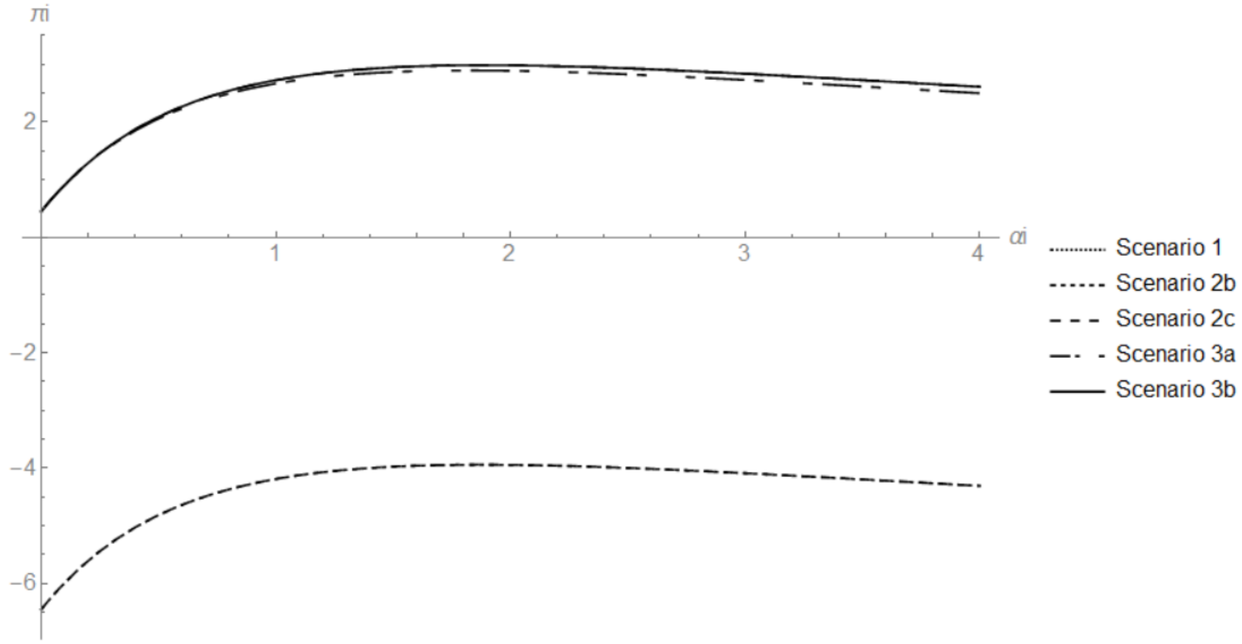


Figure D.10: Consumer surplus depending on a scenario and the i^{th} large consumer's cost of shifting the first MW of electricity α_i



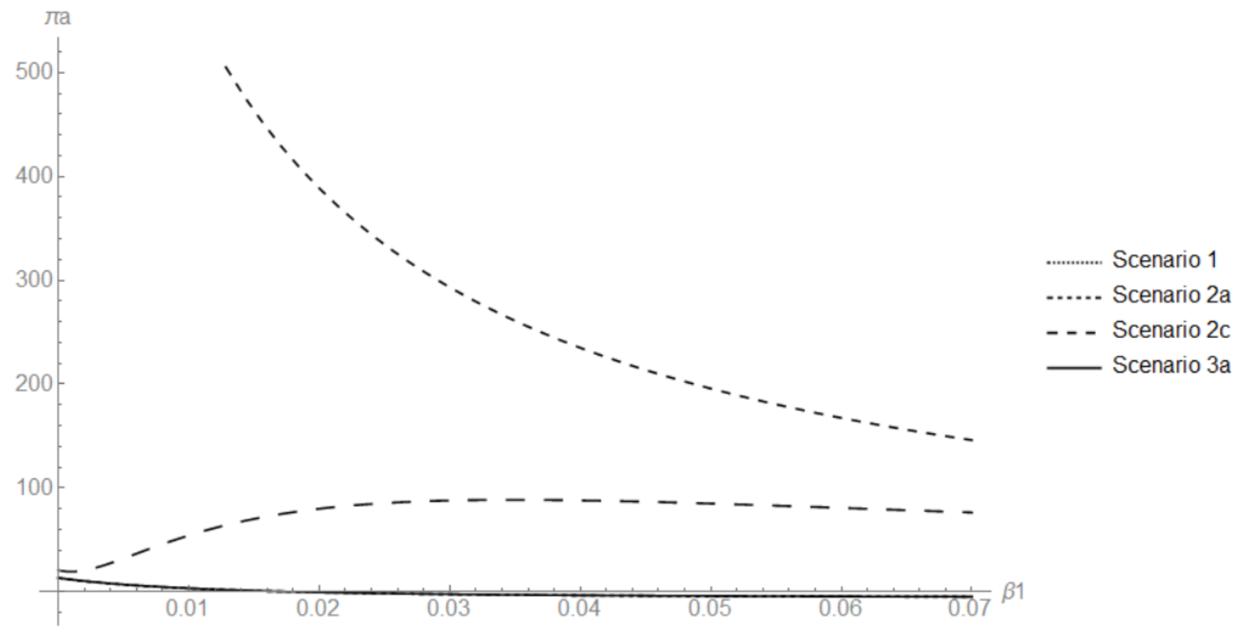
(a) The aggregator's profit



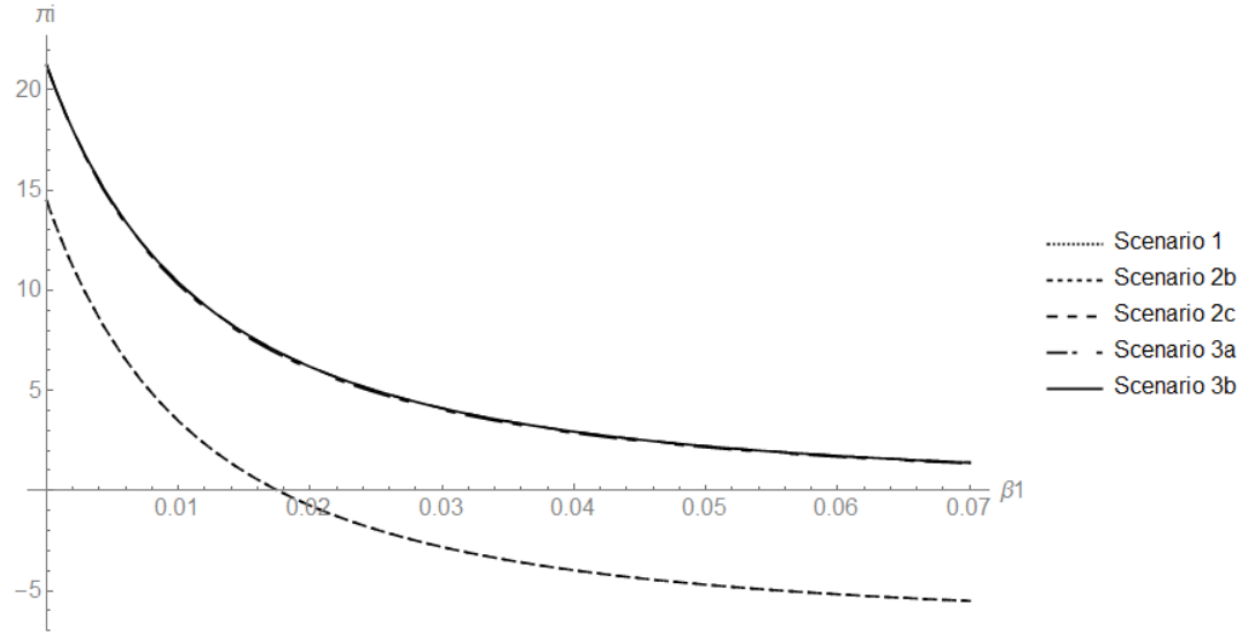
(b) A large consumer's profit

Figure D.11: The aggregator's and a large consumer's profit depending on a scenario and the i^{th} large consumer's cost of shifting the first MW of electricity α_i

D.3 The slope of the inverse demand curve β_1 and its intercept β_0

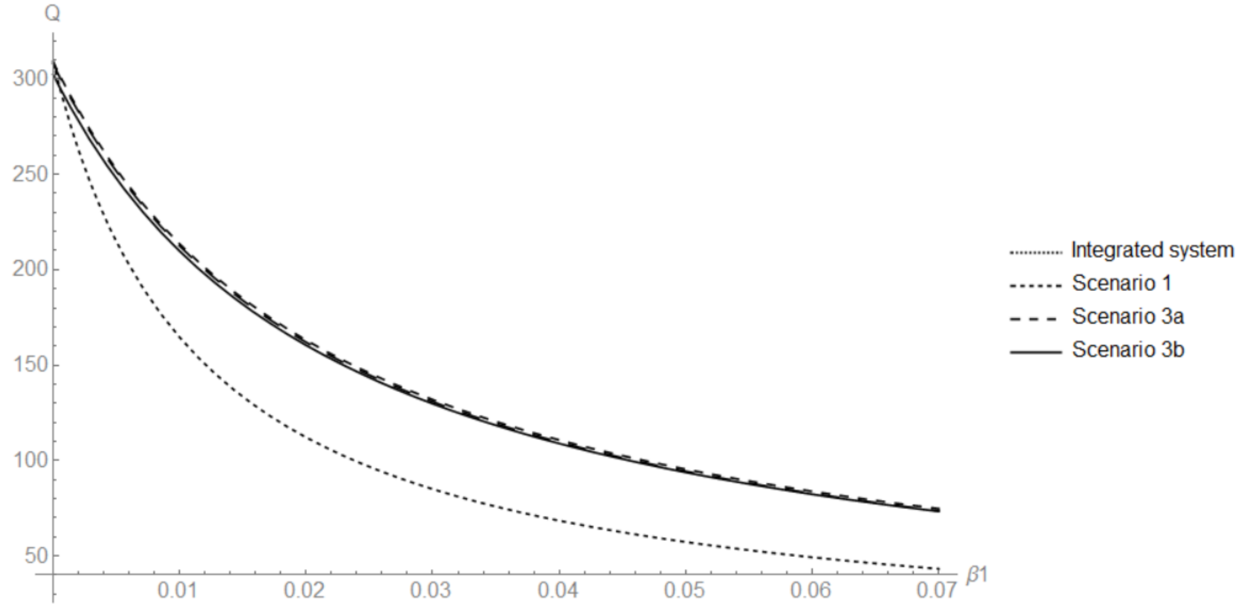


(a) The aggregator's profit

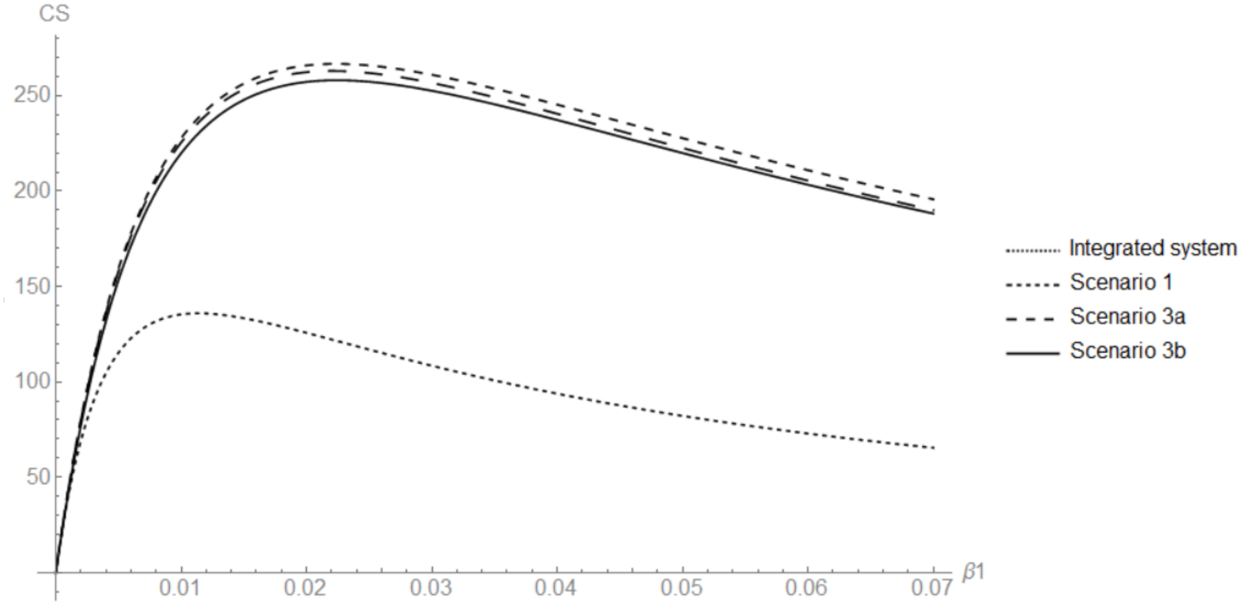


(b) A large consumer's profit

Figure D.12: The aggregator's and a large consumer's profit depending on a scenario and the slope of the inverse demand curve β_1

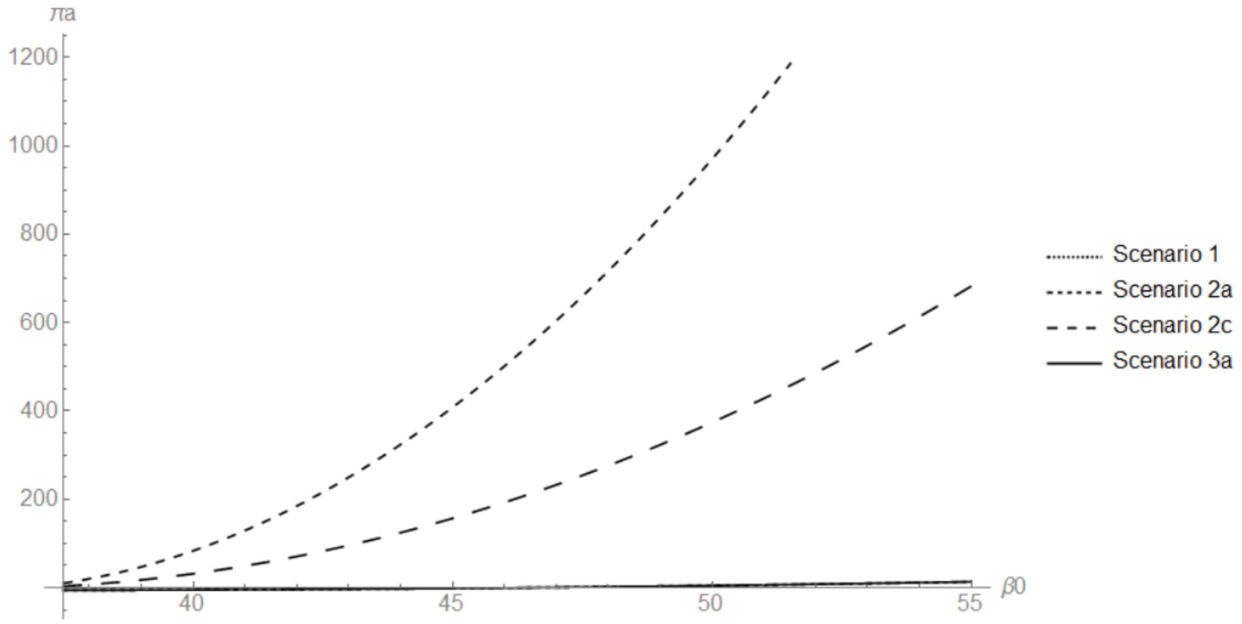


(a) Total quantity

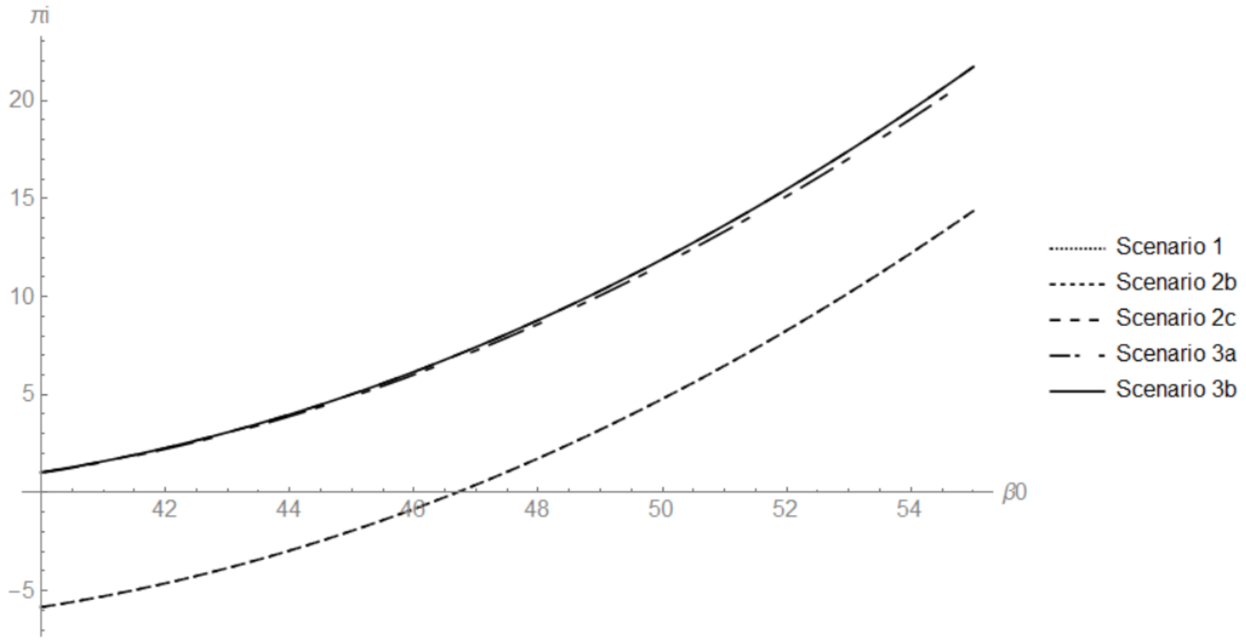


(b) Consumer surplus

Figure D.13: The total quantity and consumer surplus depending on a scenario and the slope of the inverse demand curve β_1



(a) The aggregator's profit



(b) A large consumer's profit

Figure D.14: The aggregator's and a large consumer's profit depending on a scenario and the intercept of the inverse demand curve β_0

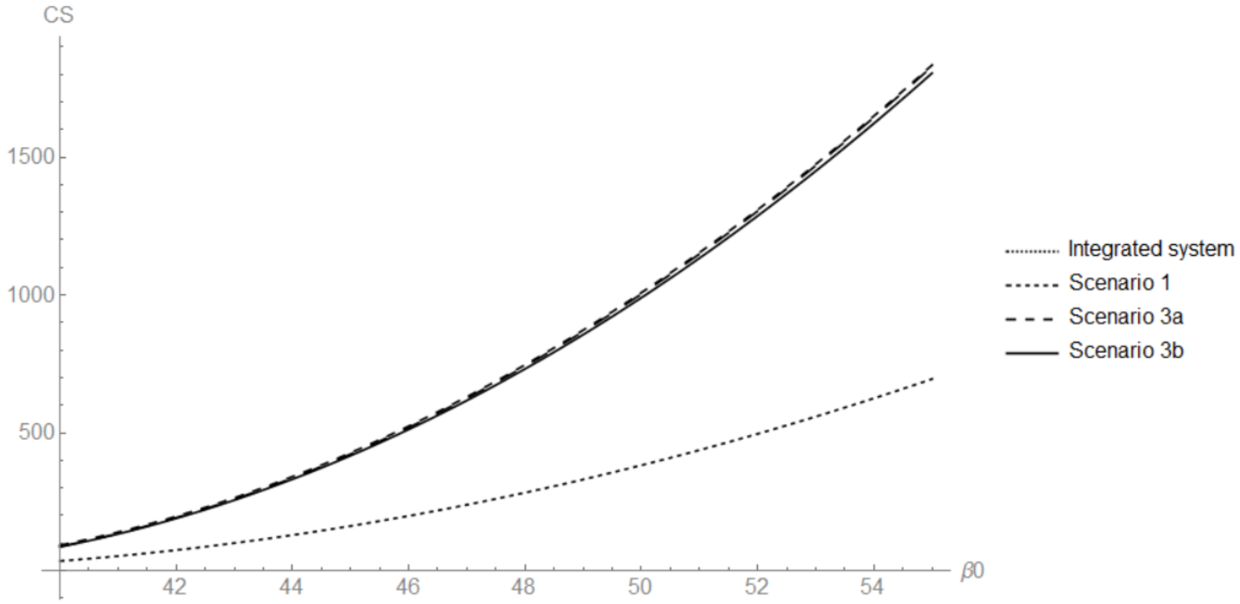


Figure D.15: Consumer surplus depending on a scenario and the intercept of the inverse demand curve β_0

Chapter 3

Flexible electricity demand aggregator in the intraday market: who gains?

Flexible Electricity Demand Aggregator in the Intraday Market: Who Gains?

Ieva Linkeviciute[*]

September 27, 2018

Abstract

Flexible electricity demand aggregators are likely to participate not only in day-ahead and balancing markets, but also in a rapidly growing intraday market. This paper examines whether the presence of a flexible demand aggregator in the intraday market can harm power buyers and increase the competing producer's profit. Equilibrium market outcomes in the Monopoly case and in the Stackelberg competition case are found using a game theoretic approach. The solutions indicate that under certain market conditions and power production cost levels, the aggregator's participation in the intraday market can increase the producer's profit and reduce the consumer surplus of power buyers. Due to the aggregator's trading patterns, in particular the increased demand in one hour and increased supply in another, the producer is able to use the change in demand and increase its profit by adjusting the amount of offered energy depending on its production cost in both hours. A numerical example is based on Nord Pool intraday market data for two trading hours in the DK2 bidding area and is complemented with a sensitivity analysis.

Keywords: demand-side management, flexibility, aggregation, intraday market
JEL classification: C61, C63, C72, L94

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1 Introduction and literature review

The importance of the intraday market is growing with the increasing share of intermittent renewable energy sources in the European power systems. Usually, the production of wind power deviates from the volumes traded day-ahead and these discrepancies must be offset after the closure of the day-ahead market. Thus, the intraday market, being a place for such contracts, is one of the key tools allowing to increase the share of renewable energy in the energy mix (Nord Pool, 2017*b*; Haas et al., 2013).

In comparison to the electricity day-ahead market, futures market and the balancing market, the intraday electricity market has received much less attention in the academic literature (Lazarczyk, 2016; Karanfil and Li, 2017). One reason could be relatively small volumes traded at this market; in 2016, the total traded volume at the Nordic and Baltic day-ahead market was 391 TWh, while the volume traded at the Nordic, Baltic and German intraday market accounted for 5 TWh, which is 1,3% of the day-ahead market volume (Nord Pool, 2016*a*). However, during the last decade the intraday market expanded five times and is expected to grow further.[1]

The intraday market will grow not only in terms of traded volumes, but it will also include new market participants – the aggregators of flexible electricity demand. The behaviour of these new players differs from the one of the usual market participants. Unlike others, the aggregator can act as both buyer and seller (Shafie-khah et al., 2016). In order to use its consumers' flexibility and sell power in one hour, the aggregator must buy the same (or larger, if, for example, heating or cooling processes require more energy to restore the temperature) amount of power in the next hours to compensate for the delayed consumption.

Demand-side management is seen as a way to reduce power consumption during peak times and lower power prices, contributing to the system's stability. It is considered, that it is beneficial for both sides, since the aggregator of flexible demand gains from offering its consumers' flexibility to the market and generates profit. For example, Ayón et al. (2017*a*) focus on the flexibility of aggregated demands of buildings with different characteristics. In the model an aggregator participates directly in the day-ahead market and optimises

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[1] The interested reader is referred to Appendix A for further discussion on the intraday markets.

the load schedule taking into account the building occupant comfort. Their results show the potential of demand aggregation in order to increase flexibility and the aggregator's profits in the day-ahead market. Moreover, the aggregator can participate not only in the intraday but also in other markets, such as reserves markets, and, for example, for the plug-in electric vehicles' flexibility aggregator reserves market is the main source of its income. Heleno et al. (2016) study a bottom-up aggregation of residential demand-side flexibility associated with thermostatically controlled loads. This flexibility is aggregated into reserve bids and is traded at the day-ahead tertiary reserve markets. Meanwhile, Shafie-khah et al. (2016) show that the participation in the intraday market can increase the aggregator's profit and improve its strategy in energy and reserves markets.

Recently, several studies have analysed the aggregator's behaviour in multiple markets: day-ahead, intraday and/or balancing markets. For example, Ottesen et al. (2018) investigates the optimal bidding for a flexibility aggregator participating in three sequential markets: flexibility reservation, a spot market and a flexibility market for near real-time dispatch. The authors present the decision models as multi-stage stochastic programs and include scenarios for the possible realisations of prices. They calculated the value of flexibility, showed a positive net profit and analysed how the different markets generate profits. Shafie-khah et al. (2016) propose a multi-stage stochastic model of a plug-in electric vehicles aggregation agent that participates in both day-ahead and intraday markets. Their model captures several uncertainties like the behaviour of plug-in electric vehicles owners, electricity market prices, and activated quantity of reserve by the system operator. MacDougall et al. (2017) also studies the flexibility of electric vehicles and its trading on the German day-ahead and intraday markets. The authors investigate the impact of applying a predictive control trading strategy, which actively offers aggregated flexibility to the markets, from a monetary and network stability perspectives. They use an artificial neural network to forecast the available ramp up and down capacity of a virtual power plant of electric vehicles. Heydarian-Forushani et al. (2014*a*) focus on the day-ahead and intraday market too. They present a framework to optimise the participation of a demand response aggregator in both markets, where it optimises its participation schedule and bidding strategy according to its consumers' behaviour. The authors use a Supply Function Equilibrium (SFE) model for the customers' participation. They also take into account the uncertainties of market prices and the behaviour of consumers.

Ayón et al. (2017*b*) present a probabilistic optimisation method that produces optimal bidding curves that an aggregator submits to the day-ahead and intraday markets. They also take into account uncertainties in forecasted market prices, demand and renewable energy sources. Zhou et al. (2017) assume that the trading in the day-ahead market is already settled and propose an optimal scheduling method for the aggregator to arbitrage in the intraday market using its flexible thermostatically controlled loads and renewable generation. Their two-level scheduling method has the upper level, which is a model predictive control optimisation minimising the sum of energy and capacity cost of imbalances under thermal constraints; and the lower level, which adopts the typical temperature priority list (TPL) control. In all these studies the results indicate gains for the aggregator. However, neither of them model the behaviour of other market participants and the effects to the original power buyers.

Even though some authors, for instance, Zhou et al. (2017), Ayón et al. (2017*b*) or Mathieu et al. (2015), who investigate the potential for aggregations of residential thermostatically controlled loads to arbitrage intraday wholesale electricity market prices, assume that the aggregator does not participate in market price formation since its offered quantities are too small, the entrance of a new player in the intraday market may affect all existing market players and final consumers. In contrast to the majority of studies, advocating the benefits of flexible demand aggregation this research draws attention to possible disadvantages of the aggregator's participation in the intraday market. This paper investigates whether the flexible demand aggregator's presence in the intraday market could increase the competing producer's profit and reduce the consumer surplus of power buyers.

A game-theoretic approach is used to compare market equilibrium outcomes in a situation where a flexible demand aggregator participates in the intraday market with a situation where there is no aggregator. To determine the effect of the aggregator's entry to the market a simplified model of a real world intraday market is set: in the first case, a producer is a monopolist; in the second case, the aggregator is in a Stackelberg competition with the producer that acts as a leader. The model allows to conclude whether the producer can benefit from the aggregator's presence at the intraday market and whether power buyers can be harmed when the aggregator starts selling flexibility in the intraday market. The results show that under certain market conditions the producer is able to reduce its production cost more than its reduced revenue due to the competition with the aggregator and in this way increase its profit. Unfortunately, in some cases, the consumer surplus of the original power buyers may shrink when the aggregator is trading flexibility, as the quantities of electricity available to them in each hour differ in both cases and those quantities have different weights that reflect their value.

The rest of the paper is structured as follows. Section 2 introduces the model. It starts with a description of electricity demand and supply in the intraday market and then presents two analysed cases: the Monopoly and Stackelberg cases. The equilibrium analysis is provided in Section 3. Section 4 includes numerical estimates for the general solutions obtained in the previous section. It discusses input data, which includes Nord Pool intraday market data, marginal production cost data and demand flexibility data. Also, it provides results and sensitivity analysis. Finally, Section 5 provides the conclusion.

2 Model

The aggregator of flexible demand is denoted by A, while the producer, a power generator, by P. These two market participants trade a homogeneous good, electricity, in the intraday market. They maximise their profits for one period of time, which consists of 2 hours denoted by n, $n = 1, 2$.

2.1 Electricity demand

Demand in the intraday market is formed by all traders who, due to inaccurate forecasts, purchased less power than needed in the day-ahead market. It is assumed that in the analysed period all electricity providers underestimated their consumers needs and have to buy more power in the intraday market. Sometimes, due to technical reasons, power producers cannot provide the energy sold in the day-ahead market. In such cases, producers would buy energy in the intraday market, too, or eliminate their imbalance in the regulating market.

As I have analysed the intraday market where the participants make their decisions about traded quantities for the same day, it is assumed that the demand for the coming hours is known in advance. The inverse demand function can be expressed as:

$$p(Q) = \beta_0 - \beta_1 Q, \tag{1}$$

where β_0 and β_1 are constants ($\beta_0 > 0$ and $\beta_1 > 0$) and Q is power demand for one hour. It is a standard downward sloping demand function, implying that electricity buyers react to prices and that they have an option to buy power in the regulating power market and in this way eliminate imbalance.[2]

The aggregator's traded volumes influence the demand in those hours, when the aggregator buys power to compensate the reduction in consumption made in the other hour. Thus, when the aggregator buys power in the market, the demand function shifts to the right by the aggregator's shifted consumption q_a:

$$p(Q, q_a) = \beta_0 - \beta_1 (Q - q_a). \tag{2}$$

2.2 Electricity supply

The effects of the aggregator's presence in the intraday market on market equilibrium outcomes are analysed by using a simplified model. In this model, electricity is supplied by the producer, that is the only power supplier in the Monopoly case, and the aggregator, that is shifting the available flexible demand within the analysed period and competing with the producer in the Stackelberg case. While the producer supplies power to the market in both hours of the optimisation, the aggregator sells power in one hour and buys it in another to keep the balance in its consumers' consumption.

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[2] Real world data supports the assumption about the downward sloping demand curve (see Appendix B Figure B.1 illustrating the aggregated demand for one hour in Nord Pool intraday market).

2.2.1 Producer

There is only one producer that is able to generate and offer electricity in the analysed period.[3] The producer's cost function in hour n, $n = 1, 2$ is:

$$c_{pn}(q_{pn}) = \alpha_{pn} q_{pn}, \tag{3}$$

where α_{pn} is a constant marginal cost of production ($c_{pn} > 0$). The marginal cost of production does not change with increasing quantity, since fuel cost for a particular hour remains the same. However, it can vary for different hours. For example, a gas power plant might buy gas at fluctuating hourly prices resulting in different electricity production cost for different hours.

2.2.2 Aggregator

The aggregator is an electricity provider, which has consumers that react to hourly energy prices and offer their flexibility of consumption in return to financial compensation. Thus, the aggregator uses flexibility of its consumers, compensates them for every shifted kilowatt hour of energy and trades this energy in the intraday market. It has a quadratic cost function with a linear marginal cost. The aggregator's cost function is:

$$c_a(q_a) = \alpha_a q_a^2, \tag{4}$$

where $2\alpha_a q_a$ is a marginal cost of shifting consumption ($\alpha_a > 0$). The quadratic form of the function guarantees that every additional kilowatt hour of shifted consumption is worth more than the last one. This is related to the consumer's disutility of postponing consumption to the next hour (or consuming earlier than planned). The shape of this function also implies that at some point flexibility becomes too expensive and the consumer is close to his or her inflexible[4] consumption level. In the model, consumption can be shifted by only one hour, similarly like in refrigeration systems.[5]

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[3] In order to simplify the model, it is assumed that all other producers have already traded their available capacity at the day-ahead market or need to buy power and compensate for already sold power shortage that appeared due to unexpected events, while all electricity providers are either in balance or need to purchase power at the intraday market.

[4] Inflexible consumption cannot be shifted to other hours.

[5] Grein and Pehnt (2011) claim that the maximum duration of load shifts of domestic refrigerators can vary between 30 to 80 minutes.

2.3 Monopoly and Stackelberg cases

I investigate two cases: in the first case, Monopoly, the producer is the only power seller in the intraday market; in the second case, Stackelberg, the aggregator enters the intraday market and competes with the producer in a Stackelberg competition. In the Stackelberg case, the aggregator is relatively small comparing to the producer, therefore, the producer acts a leader and the aggregator – as a follower. The bidding sequence issue, as well as the extreme scarcity issue in the main scenario, is addressed in the alternative scenarios in Appendix C.

Alternative scenarios are provided in Appendix C and Appendix D. Appendix C analyses a situation when, in the first case, there is more than one producer offering power at the intraday market and competing in Cournot competition. In the second case, I introduce the aggregator, which also competes with power producers in Cournot competition. Appendix D presents a situation, where a monopolistic producer, in addition to producing power, acts as an aggregator. I compare the market outcomes in two cases: when a monopolistic producer is also an aggregator vs. being only a monopolistic producer.

Figure 1 illustrates the intraday market structure in both cases. While on the sellers' side there is the producer and the aggregator (or only the producer), on the buyers' side there are suppliers of electricity that bought less power than needed at the day-ahead market, producers that cannot meet the day-ahead traded volumes due to some incidents in production, and traders/brokers.

Figure 2 shows how bid or ask orders are placed in the intraday market in both cases. Market participants decide about their orders in the intraday market after the gate closure of the day-ahead market. Each market participant places its orders for the analysed period. This means that it places one order for hour $n = 1$ and another for hour $n = 2$ at the same time. Buyers are bidding in the market continuously.

In the case of monopoly, the producer decides on its quantities q_{pn}, $n = 1, 2$ and places two ask orders, each for hour $n = 1$ and $n = 2$ at the same time. In the Stackelberg case, the producer is a leader and moves first and decides on its quantities q_{pn}, $n = 1, 2$. After

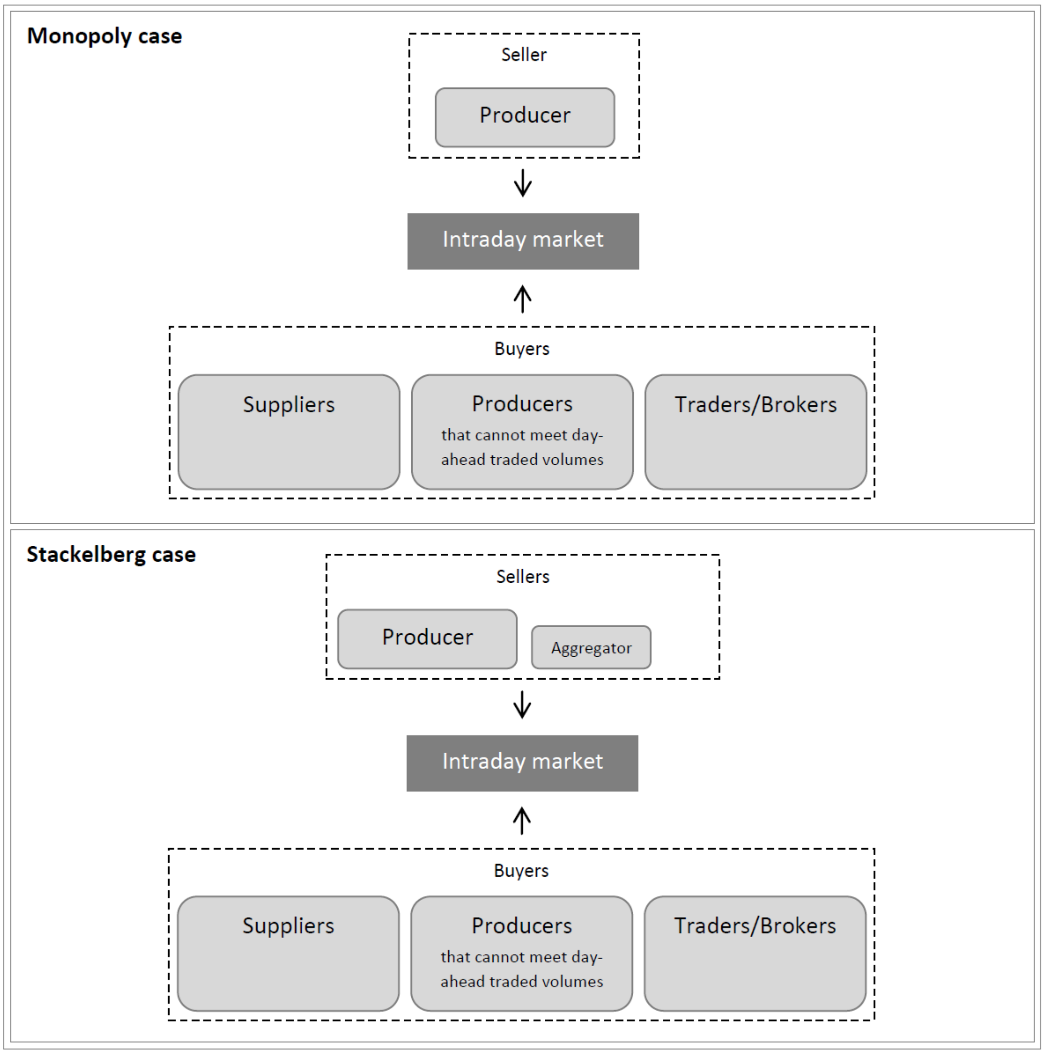

Figure 1: Intraday market structure in the Monopoly and Stackelberg cases

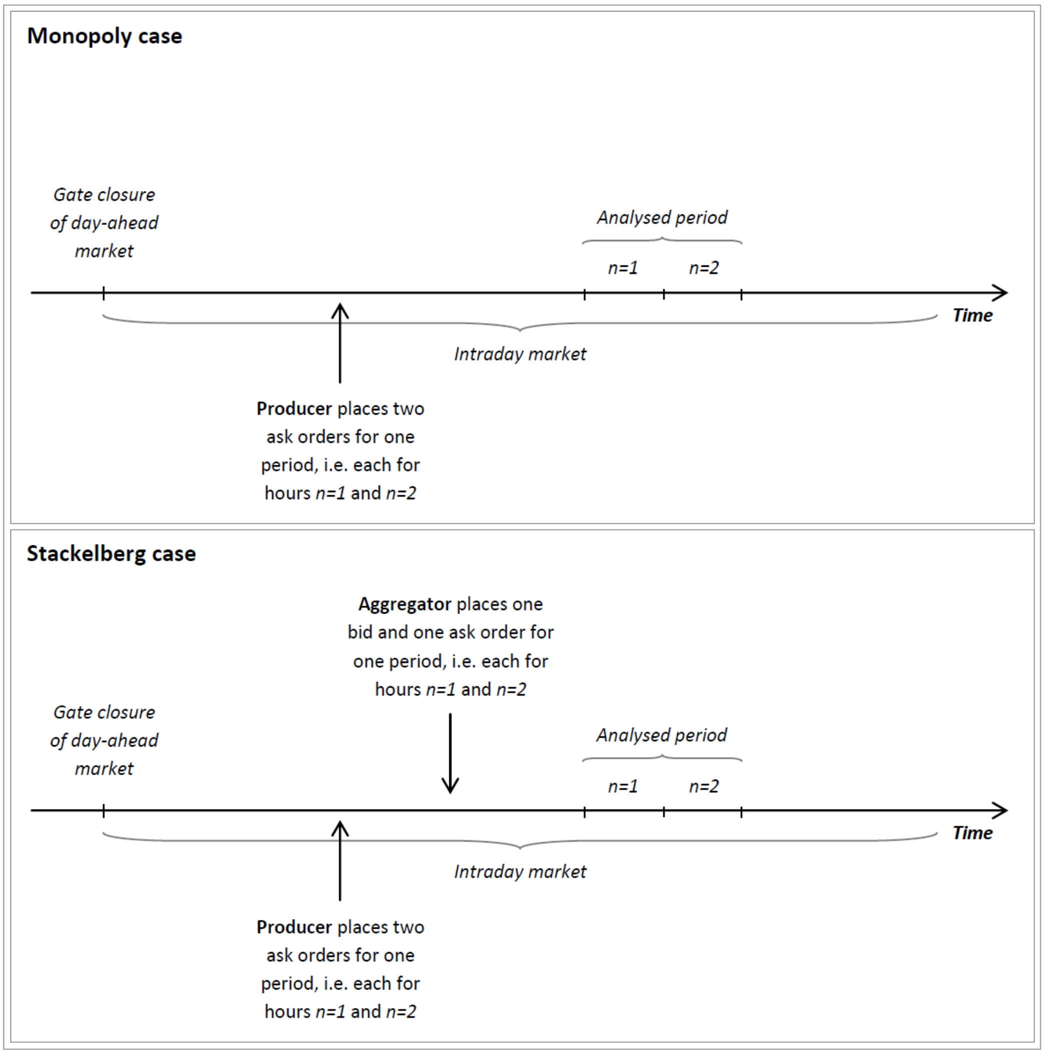

Figure 2: Timelines of trading in the intraday market in the Monopoly and Stackelberg cases

observing the producer's decision, the aggregator chooses its quantity q_a, which it sells in one hour and buys in another. The producer knows that the aggregator's bought and sold quantities in the analysed period are equal.

3 Equilibrium analysis

This section provides the equilibrium outcomes of the two previously described cases: Monopoly and Stackelberg. First, the general solutions for equilibrium quantities, prices and players' profits are shown for each case, then consumer surplus is analysed in a separate subsection.[6] Also, this section includes propositions that under certain market conditions and marginal production cost the aggregator's presence at the market can be beneficial to the producer, can harm the original power buyers, or can make all market participants better off compared to the Monopoly case.

3.1 Monopoly case

The Monopoly case defines the situation where the producer is the only supplier in the intraday market. The prices in the analysed period are determined by the inverse demand function $p_n(q_{pn}) = \beta_{0n} - \beta_{1n}(q_{pn})$, $n = 1, 2$.

The producer maximises the standard profit function for both hours in the analysed period:

$$\pi_p(q_{p1}, q_{p2}) = (\beta_{01} - \beta_{11}(q_{p1}))(q_{p1}) - \alpha_{p1}q_{p1} + (\beta_{02} - \beta_{12}(q_{p2}))(q_{p2}) - \alpha_{p2}q_{p2}, \tag{5}$$

where $(\beta_{01} - \beta_{11}(q_{p1}))(q_{p1})$ is its revenue and $\alpha_{p1}q_{p1}$ is its cost in hour $n = 1$, while $(\beta_{02} - \beta_{12}(q_{p2}))(q_{p2})$ and $\alpha_{p2}q_{p2}$ are its revenue and cost in hour $n = 2$.

Proposition 1. *A solution to the Monopoly problem:*

(i) The equilibrium quantities supplied by the producer are

$$q_{p1}^* = \frac{\beta_{01} - \alpha_{p1}}{2\beta_{11}}, \tag{6}$$

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[6] The interested reader is referred to Appendix E for a discussion on price elasticity of demand at the equilibrium outcomes.

$$q_{p2}^* = \frac{\beta_{02} - \alpha_{p2}}{2\beta_{12}}. \tag{7}$$

(ii) The market prices are

$$p_1^* = \frac{\beta_{01} + \alpha_{p1}}{2}, \tag{8}$$

$$p_2^* = \frac{\beta_{02} + \alpha_{p2}}{2}. \tag{9}$$

(iii) The producer's profit is

$$\pi_p^* = \frac{\beta_{11}(\alpha_{p2} - \beta_{02})^2 + \beta_{12}(\alpha_{p1} - \beta_{01})^2}{4\beta_{11}\beta_{12}}. \tag{10}$$

3.2 Stackelberg case

In the Stackelberg case, the producer is the leader and moves first. It anticipates the aggregator's response function and decides about its own quantities accordingly.

The profit function for the aggregator is:

$$\pi_a(q_a, q_{p1}, q_{p2}) = (\beta_{01} - \beta_{11}(q_{p1} + q_a))q_a - \alpha_a q_a^2 - (\beta_{02} - \beta_{12}(q_{p2} - q_a))q_a, \tag{11}$$

where q_a can be positive or negative. Positive value means that the aggregator is selling power in hour $n = 1$ and buying in hour $n = 2$; negative – that it is buying power in $n = 1$ and selling in $n = 2$. Hence, when q_a is positive, $(\beta_{01} - \beta_{11}(q_{p1} + q_a))q_a$ is the aggregator's revenue for sold power in hour $n = 1$ and $(\beta_{02} - \beta_{12}(q_{p2} - q_a))q_a$ is its cost of buying power in hour $n = 2$. Also, it pays compensation to its consumers for shifted load q_a, which is equal to $\alpha_a q_a^2$. When q_a is negative, $(\beta_{01} - \beta_{11}(q_{p1} + q_a))q_a$ becomes the aggregator's cost for bought power in hour $n = 1$ and $(\beta_{02} - \beta_{12}(q_{p2} - q_a))q_a$ becomes revenue for sold power in hour $n = 2$. $\alpha_a q_a^2$ remains positive and accounts for the cost of load shifting paid to its consumers.

The offered and required quantities by the aggregator depend on the producer's offered quantities in both hours. The decision problem for the aggregator is:

$$\pi_a^*(q_a, q_{p1}, q_{p2}) = \max_{q_a} \pi_a(q_a, q_{p1}, q_{p2}). \tag{12}$$

The best-response function for the aggregator is found by solving the following equation:

$$\frac{\partial \pi_a(q_a, q_{q1}, q_{p2})}{\partial q_a} = \beta_{01} - \beta_{02} - q_{p1}\beta_{11} + q_{p2}\beta_{12} - 2q_a(\alpha_a + \beta_{11} + \beta_{12}) = 0. \tag{13}$$

The best-response function for the aggregator is:

$$q_a^*(q_{p1}, q_{p2}) = \frac{\beta_{01} - \beta_{02} - q_{p1}\beta_{11} + q_{p2}\beta_{12}}{2(\alpha_a + \beta_{11} + \beta_{12})}. \tag{14}$$

The producer's profit function is:

$$\pi_p(q_a, q_{p1}, q_{p2}) = (\beta_{01} - \beta_{11}(q_{p1} + q_a))q_{p1} - \alpha_{p1}q_{p1} + (\beta_{02} - \beta_{12}(q_{p2} - q_a))q_{p2} - \alpha_{p2}q_{p2}. \tag{15}$$

Here, the producer's profit also depends on the aggregator's quantity q_a. The best-response functions for the producer are found by substituting q_a with the aggregator's best-response function q_a^* and maximising the producer's profit with respect to q_{p1} and q_{p2}, thus, solving the following equations:

$$\begin{aligned}\frac{\partial \pi_p(q_a^*, q_{q1}, q_{p2})}{\partial q_{p1}} &= \beta_{01} - \alpha_{p1} - \beta_{11}(2q_{p1} + q_{p2}) + \\ &\qquad \frac{\beta_{11}(\beta_{02} - \beta_{01} + 2q_{p1}\beta_{11} + 2q_{p2}(\alpha_a + \beta_{11}))}{2(\alpha_a + \beta_{11} + \beta_{12})} = 0,\end{aligned} \tag{16}$$

$$\begin{aligned}\frac{\partial \pi_p(q_a^*, q_{q1}, q_{p2})}{\partial q_{p2}} &= \frac{1}{2(\alpha_a + \beta_{11} + \beta_{12})}\Big(2\beta_{02}(\alpha_a + \beta_{11}) + (\beta_{01} + \beta_{02} - 2q_{p1}\beta_{11} - \\ &\qquad 4q_{p2}(\alpha_a + \beta_{11}))\beta_{12} - 2q_{p2}\beta_{12}^2 - 2\alpha_{p2}(\alpha_a + \beta_{11} + \beta_{12})\Big) = 0.\end{aligned} \tag{17}$$

Proposition 2. *A solution to the Stackelberg game is:*

(i) The equilibrium quantities supplied by the producer and by the aggregator are

$$q_{p1}^* = \frac{1}{2}\Big(\frac{\beta_{01} - \alpha_{p1}}{\beta_{11}} + \frac{\alpha_{p2} - \alpha_{p1}}{2\alpha_a + \beta_{11} + \beta_{12}}\Big), \tag{18}$$

$$q_{p2}^* = \frac{1}{2}\Big(\frac{\beta_{02} - \alpha_{p2}}{\beta_{12}} + \frac{\alpha_{p1} - \alpha_{p2}}{2\alpha_a + \beta_{11} + \beta_{12}}\Big), \tag{19}$$

$$q_a^* = \frac{1}{4}\Big(\frac{\beta_{01} - \beta_{02}}{\alpha_a + \beta_{11} + \beta_{12}} + \frac{2(\alpha_{p1} - \alpha_{p2})}{2\alpha_a + \beta_{11} + \beta_{12}}\Big). \tag{20}$$

(ii) The market prices are

$$p_1^* = \frac{\alpha_{p1} + \beta_{01}}{2} + \frac{\beta_{11}(\beta_{02} - \beta_{01})}{4(\alpha_a + \beta_{11} + \beta_{12})}, \tag{21}$$

$$p_2^* = \frac{2(\alpha_{p2} + \beta_{02})(\alpha_a + \beta_{11}) + \beta_{12}(2\alpha_{p2} + \beta_{01} + \beta_{02})}{4(\alpha_a + \beta_{11} + \beta_{12})}. \tag{22}$$

(iii) The producer's and the aggregator's profits in period t are

$$\pi_p^* = \frac{1}{8}\Big(\frac{2(\alpha_{p1} - \beta_{01})^2}{\beta_{11}} + \frac{2(\alpha_{p2} - \beta_{02})^2}{\beta_{12}} - \frac{(\beta_{01} - \beta_{02})^2}{\alpha_a + \beta_{11} + \beta_{12}} + \frac{2(\alpha_{p1} - \alpha_{p2})^2}{2\alpha_a + \beta_{11} + \beta_{12}}\Big), \tag{23}$$

$$\pi_a^* = \frac{(2(\alpha_a + \beta_{11} + \beta_{12})(\alpha_{p1} - \alpha_{p2}) + (\beta_{01} - \beta_{02})(2\alpha_a + \beta_{11} + \beta_{12}))^2}{16(\alpha_a + \beta_{11} + \beta_{12})(2\alpha_a + \beta_{11} + \beta_{12})^2}. \tag{24}$$

Further, I have focused on the producer's profit and compared equilibrium outcomes of the Monopoly and Stackelberg cases. Proposition 3 provides the conditions under which the producer is better off in a competition with the aggregator than being a monopolist.[7]

Proposition 3. *The producer is strictly better off in a Stackelberg competition with the aggregator than being a monopolist if*

$$(\alpha_{p1} - \alpha_{p2})^2 > (\beta_{01} - \beta_{02})^2 \frac{2\alpha_a + \beta_{11} + \beta_{12}}{2\alpha_a + 2(\beta_{11} + \beta_{12})}. \tag{25}$$

The producer sells the same total amount of energy in both analysed cases. However, when the aggregator is present in the market, the producer sells more in the hour when its marginal cost is lower and it sells less by the same amount of energy in the other hour compared to the Monopoly case.[8] Meanwhile the prices in two hours increase or drop by different amounts, as the aggregator is competing with the producer and lowering the market price in one hour, and increasing the demand and market price in the other hour. As long as the slopes of the inverse demand functions are not equal, the change in market prices compared to the Monopoly case differ. This means that the producer sells the same total amount of energy at different prices. Appendix G shows that the producer's total revenue in the Stackelberg case is always lower or equal to the total revenue in the Monopoly case. Nevertheless, the total producer's cost in the Stackelberg case is also lower or equal to the its total cost in the

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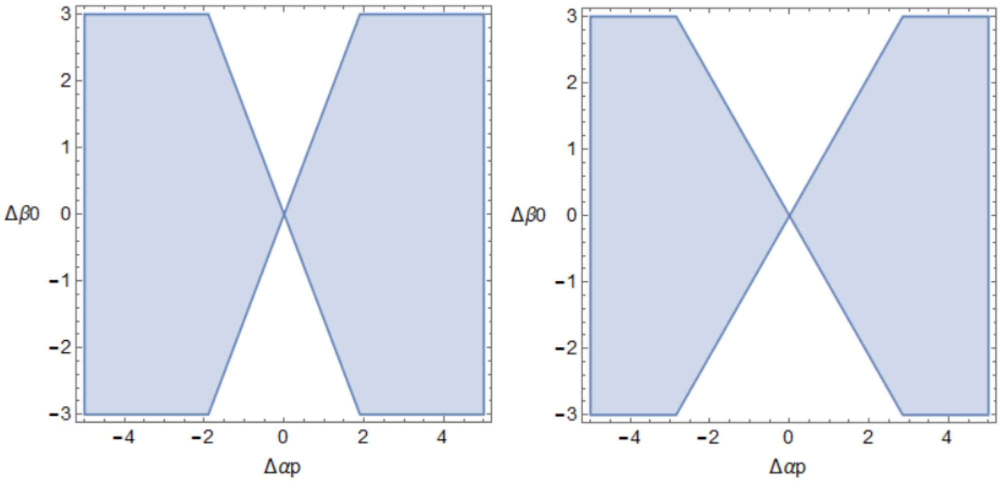
[7] The proofs of Proposition 3, Proposition 5 and Proposition 6 are provided in Appendix F.

[8] When the producer's marginal cost in both hours are equal, the producer's traded quantities do not differ in the analysed cases.

Monopoly case. Thus, the difference in profits depends on the magnitude of both effects, i.e. whether the reduction in revenue is outweighed by the reduction in cost, or not.

Figure 3 shows when the producer is better off to compete with the aggregator in one hour and sell power to the aggregator in another.[9] The likelihood of the producer to profit from the aggregator's participation in the intraday market depends on marginal cost and market conditions reflected by $\Delta\alpha_p$, $\Delta\beta_0$ and ϕ. Here, $\Delta\alpha_p = \alpha_{p1} - \alpha_{p2}$ denotes the difference between the producer's marginal costs in hours $n = 1$ and $n = 2$; $\Delta\beta_0 = \beta_{01} - \beta_{02}$ denotes the difference between the inverse demand function intercepts, or the highest bid orders in hours $n = 1$ and $n = 2$; and $\phi = \frac{2\alpha_a+\beta_{11}+\beta_{12}}{2\alpha_a+2(\beta_{11}+\beta_{12})}$ accounts for the aggregator's marginal cost factor α_a and the slopes of inverse demand functions β_1 in hours $n = 1$ and $n = 2$.

It is favourable to the producer when the difference between its marginal cost $\Delta\alpha_p$ in hours $n = 1$ and $n = 2$ is larger, the difference in the highest bid orders $\Delta\beta_0$ in those hours is smaller, and when ϕ is lower. The dependence of ϕ on the aggregator's marginal cost factor α_a and the sum of slopes of demand β_1 in $n = 1$ and $n = 2$ is shown in Appendix H Figure H.2. Thus, it is better for the producer when the aggregator's marginal cost is lower and the sum of the slopes of demand is larger.



(a) $\phi = 0,4$ (b) $\phi = 0,9$

Figure 3: Areas illustrating when the producer benefits from being in a competition with the aggregator in the intraday market depending on $\Delta\alpha_p$, $\Delta\beta_0$ and ϕ

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[9] For a 3D graph see Appendix H Figure H.1.

3.3 Consumer surplus

The total expected consumer utility, where the total volume of energy offered in the market in one hour is Q, is $\int_0^Q(\beta_0 - \beta_1 u)du$. In equilibrium, the consumers pay $(\beta_0 - \beta_1 Q^*)Q^*$. Thus, the expected consumer surplus is $CS(Q^*) = \frac{\beta_1}{2}(Q^*)^2$.

The aggregator influences demand curve in the hour when it buys power to compensate its consumers for the shifted load. Therefore, the calculation of consumer surplus also depends on the hour of the aggregators purchase of power. When the aggregator sells power in hour $n = 1$, the total consumer surplus in the analysed period is:

$$CS_{n=1}(q_{p1}^*, q_{p2}^*, q_a^*) = \frac{\beta_{11}}{2}(q_{p1}^* + q_a^*)^2 + \frac{\beta_{12}}{2}(q_{p2}^* - q_a^*)q_{p2}. \tag{26}$$

Similarly, when the aggregator sells power in hour $n = 2$, the total consumer surplus in the analysed period is:

$$CS_{n=2}(q_{p1}^*, q_{p2}^*, q_a^*) = \frac{\beta_{11}}{2}(q_{p1}^* + q_a^*)q_{p1} + \frac{\beta_{12}}{2}(q_{p2}^* - q_a^*)^2. \tag{27}$$

Since the aggregator sells energy in one hour and buys it in another, it receives some part of the consumer surplus too. Thus, the adjusted consumer surplus, excluding the benefit for the aggregator, is:

$$CS^{adj}(q_{p1}^*, q_{p2}^*, q_a^*) = \frac{\beta_{11}}{2}(q_{p1}^* + q_a^*)^2 + \frac{\beta_{12}}{2}(q_{p2}^* - q_a^*)^2. \tag{28}$$

It is the same in both situations: when the aggregator is buying power in hour $n = 1$ or in hour $n = 2$.

Proposition 4 provides a solution for consumer surplus in the Monopoly case and adjusted consumer surplus in the Stackelberg case.

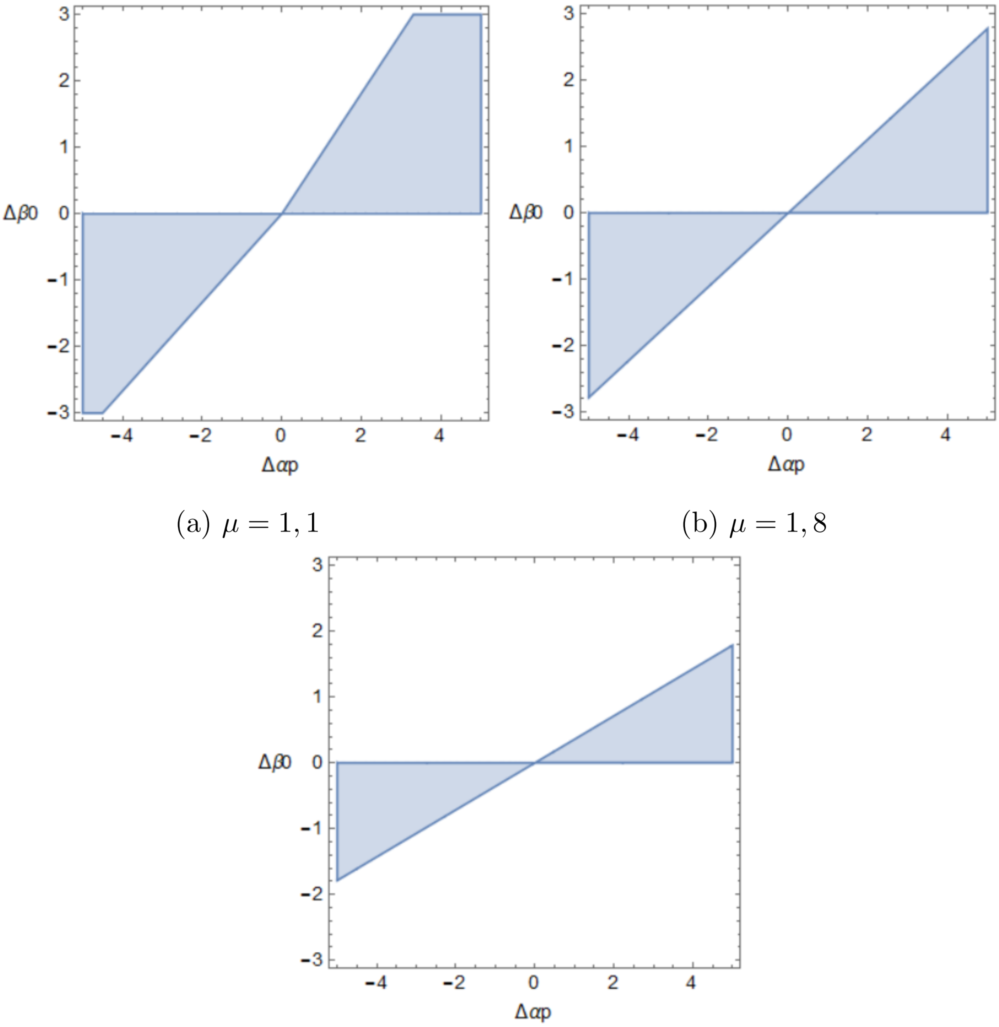
Proposition 4. *The consumer surplus:*

(i) in the Monopoly case is:

$$CS^{Mon} = \frac{1}{8}\Big(\frac{(\alpha_{p1}-\beta_{01})^2}{\beta_{11}} + \frac{(\alpha_{p2}-\beta_{02})^2}{\beta_{12}}\Big), \tag{29}$$

(ii) in the Stackelberg case is:

$$\begin{aligned} CS^{adj,Stack} = {} & \frac{1}{32(\alpha_a+\beta_{11}+\beta_{12})^2} \\ & \Big(\frac{(2\alpha_a\beta_{01}+\beta_{11}(3\beta_{01}-\beta_{02})+2\beta_{01}\beta_{12}-2\alpha_{p1}(\alpha_a+\beta_{11}+\beta_{12}))^2}{\beta_{11}} + \\ & \frac{(-2\beta_{02}(\alpha_a+\beta_{11})+\beta_{12}(\beta_{01}-3\beta_{02})+2\alpha_{p2}(\alpha_a+\beta_{11}+\beta_{12}))^2}{\beta_{12}}\Big). \end{aligned} \tag{30}$$



(a) $\mu = 1,1$

(b) $\mu = 1,8$

(c) $\mu = 2,8$

Figure 4: Areas illustrating when the adjusted consumer surplus is reduced due to the presence of the aggregator in the intraday market depending on $\Delta\alpha_p$, $\Delta\beta_0$ and μ

Since the producer, under certain market conditions, can increase its profit when the aggregator enters the intraday market, it is likely that the surplus of the original power buyers, i.e. excluding the aggregator, might be reduced. Proposition 5 reveals under which circumstances it is true.

Proposition 5. *The adjusted consumer surplus is reduced when the aggregator enters the intraday market if*

(i) $\alpha_{p1} > \alpha_{p2}$ *and* $\beta_{01} > \beta_{02}$ *and*

$$\alpha_{p1} - \alpha_{p2} > (\beta_{01} - \beta_{02}) \frac{4\alpha_a + 5(\beta_{11} + \beta_{12})}{4\alpha_a + 4(\beta_{11} + \beta_{12})}, \tag{31}$$

or

(ii) $\alpha_{p1} < \alpha_{p2}$ *and* $\beta_{01} < \beta_{02}$ *and*

$$\alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02}) \frac{4\alpha_a + 5(\beta_{11} + \beta_{12})}{4\alpha_a + 4(\beta_{11} + \beta_{12})}. \tag{32}$$

The original consumers' consumer surplus depend on the quantity of electricity available to them in each hour. The quantities in both hours can be lower or higher in the Stackelberg case compared to the Monopoly case. Also, as the price elasticity of demand in both hours is not the same, available quantities have different weights: $\beta_{11}/2$ in hour $n = 1$ and $\beta_{12}/2$ in hour $n = 2$. Therefore, the total effect of both hours is not obvious from the first glance. Proposition 5 indicates under which circumstances the total effect is negative.[10]

Graphical illustration of conditions for the reduction of the adjusted consumer surplus in the Stackelberg case is shown in Figure 4.[11] The original power buyers are likely to be harmed by the aggregator's entrance in the intraday market if the difference in the producer's marginal cost in different hours is higher, the difference in highest bids at the market is lower, and $\mu = \frac{4\alpha_a + 5(\beta_{11} + \beta_{12})}{4\alpha_a + 4(\beta_{11} + \beta_{12})}$, accounting for the aggregator's cost and the slopes of demand, is lower. Changes in μ due to changing α_a and β_1 in hours $n = 1$ and $n = 2$ are shown in Appendix H Figure H.5: lower α_a and higher sum of β_{11} and β_{12} give higher μ.

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[10] See Appendix I for more details.

[11] For 3D graphs see Appendix H Figure H.3 and Figure H.4.

Even though the aggregator harms the original power buyers in some cases, is it also possible that all market participants are better off. The conditions when all intraday market participants benefit from the aggregator's presence in the market are provided in Proposition 6.

Proposition 6. *All market participants benefit from the aggregator's presence in the intraday market if*

(i) $\beta_{01} > \beta_{02}$*:*

- $\beta_{01} > \beta_{02}$ *and* $\alpha_{p1} > \alpha_{p2}$ *and*

$$(\beta_{01} - \beta_{02})\sqrt{\frac{2\alpha_a + \beta_{11} + \beta_{12}}{2\alpha_a + 2(\beta_{11} + \beta_{12})}} < \alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11} + \beta_{12})}{4\alpha_a + 4(\beta_{11} + \beta_{12})}, \tag{33}$$

or

- $\beta_{01} > \beta_{02}$ *and* $\alpha_{p1} < \alpha_{p2}$ *and*

$$(\alpha_{p1} - \alpha_{p2})^2 > (\beta_{01} - \beta_{02})^2 \frac{2\alpha_a + \beta_{11} + \beta_{12}}{2\alpha_a + 2(\beta_{11} + \beta_{12})}; \tag{34}$$

Or

(ii) $\beta_{01} < \beta_{02}$*:*

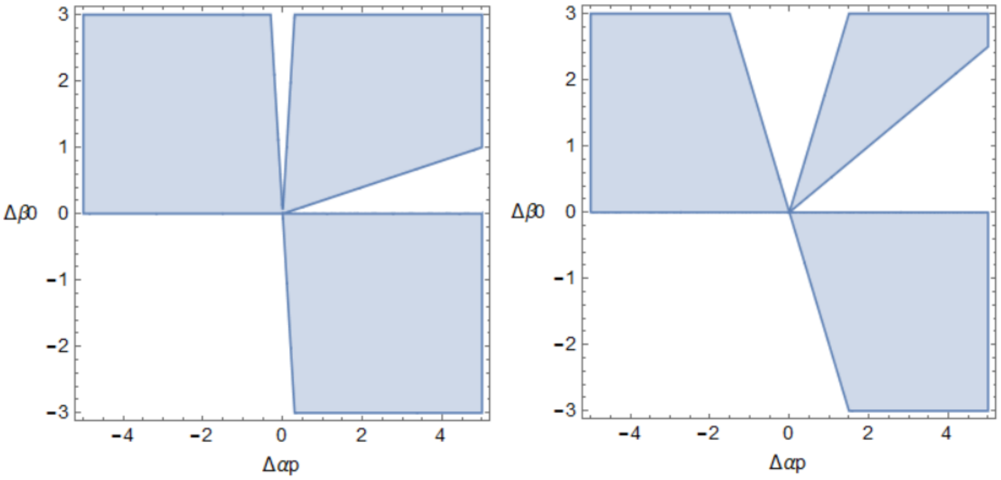
- $\beta_{01} < \beta_{02}$ *and* $\alpha_{p1} > \alpha_{p2}$ *and*

$$(\alpha_{p1} - \alpha_{p2})^2 > (\beta_{01} - \beta_{02})^2 \frac{2\alpha_a + \beta_{11} + \beta_{12}}{2\alpha_a + 2(\beta_{11} + \beta_{12})}, \tag{35}$$

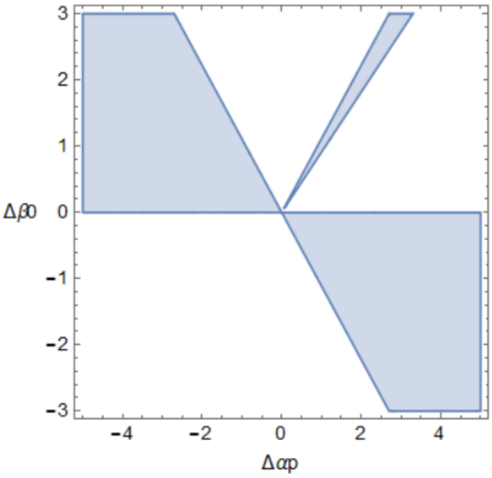
or

- $\beta_{01} < \beta_{02}$ *and* $\alpha_{p1} < \alpha_{p2}$ *and*

$$(\beta_{01} - \beta_{02})\sqrt{\frac{2\alpha_a + \beta_{11} + \beta_{12}}{2\alpha_a + 2(\beta_{11} + \beta_{12})}} < \alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11} + \beta_{12})}{4\alpha_a + 4(\beta_{11} + \beta_{12})}. \tag{36}$$



(a) $\mu = 5$, $\rho = 0,1$ (b) $\mu = 2$, $\rho = 0,5$



(c) $\mu = 1,1$, $\rho = 0,9$

Figure 5: Areas illustrating when all market participants gain from the aggregator's participation in the intraday market depending on $\Delta\alpha_p$, $\Delta\beta_0$, ρ and μ

Thus, Proposition 6 shows the conditions under which the sum of the offered quantities to the original consumers multiplied by respective weights in each hour can be higher in the Stackelberg case, and, at the same time, the producer's reduced cost outweigh the reduction in revenues in the Stackelberg case, while the aggregator receives a positive profit.

Here, the graphical illustration in Figure 5 slightly differs from the ones provided earlier – the indicators reflecting the aggregator's cost and the slopes of demand in both hours differ in left and right sides of the inequalities: $\rho = \sqrt{\frac{2\alpha_a+\beta_{11}+\beta_{12}}{2\alpha_a+2(\beta_{11}+\beta_{12})}} = \sqrt{\phi}$ and $\mu = \frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}$. As a result, the illustrated areas depend on $\Delta\alpha_p$, $\Delta\beta_0$ and two other variables, ρ and μ.

The higher μ, the lower ρ and the larger the difference in the producer's marginal cost $\Delta\alpha_p$ is, the more likely is it that all market participants will be better off. With low μ and high ρ values, it is more favourable to the market participants to have small differences in the highest bids in the market $\Delta\beta_0$. With higher μ and lower ρ values, negative $\Delta\beta_0$ are preferred to be small, while positive values are preferred to be larger. The dependence of ρ on α_a and the sum of demand slopes β_{11} and β_{12} are shown in Appendix H Figure H.6: higher α_a and lower sum of β_{11} and β_{12} result in higher ρ.

4 Numerical estimates

To illustrate that under certain conditions the producer is able to benefit from the aggregator participating in the intraday market and that the adjusted consumer surplus can be reduced, the real world data analysis of one period, or hours $n = 1$ and $n = 2$, is provided in the following sections. The necessary conditions for the producer to gain and the adjusted consumer surplus to be lower are satisfied on January 19, 2017, hours 02.00 and 03.00.

4.1 Input data

Input data includes intraday market data, the producer's marginal cost and demand flexibility data determining the aggregator's marginal cost. All parameter values are shown in Table 1.

Table 1: Parameter values

Parameter	β_{01}	β_{02}	β_{11}	β_{12}	α_{p1}	α_{p2}	α_a
Value	27,2	27,0	0,188	0,05	20,25	19,00	0,28

4.1.1 Intraday market data

Hourly intraday market data for DK2 area is retrieved from the Nord Pool website (Nord Pool, 2017*c*). It includes hourly information about highest and lowest accepted bids and traded energy volumes in all Nord Pool bidding areas. In the analysis I focus on hours 02.00 and 03.00, when the highest and lowest bids in the intraday market are 27,2 €/MWh and 22,5 €/MWh in hour 02.00, and 27,0 €/MWh and 26,0 €/MWh in hour 03.00, respectively. Traded volumes correspond to 25,0 MWh and 20,0 MWh.

This data is used to calculate parameters β_0 and β_1. β_0 is simply the highest bid order in the intraday market: 27,2 €/MWh in hour 02.00 and 27,0 €/MWh in hour 03.00. Meanwhile, the slope of demand β_1 is derived using highest and lowest bids and trades volumes (see Appendix J) and is equal to 0,188 and 0,05 in hours 02.00 and 03.00.[12]

4.1.2 Marginal production cost

In the numerical example, the producer is a gas power plant. Since power generation marginal cost corresponds to the fuel cost, in this case natural gas, the producer's marginal production cost α_p in hours 02.00 and 03.00 is equal to the natural gas "within-day" price in those hours, $\alpha_{p1} = 20,25$ €/MWh and $\alpha_{p2} = 19,00$ €/MWh (The European Energy Exchange, 2017).

4.1.3 Demand flexibility data

The flexibility in refrigeration processes is used to estimate the potential amount of flexible demand available to the aggregator. The interested reader is referred to the Appendix K for further details on the use of refrigeration processes for the demand-side management and the reasons why the flexibility from this source is chosen for this particular example.

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[12] A linear approximation of the demand curve might not always reflect the ask orders at the intraday market, because in real world the demand function is a step function. However, a linear approximation helps to present the concept of the model without additional complications and leaves the investigation of other approximations of the demand curve for future research.

It is assumed that the load of domestic refrigerators can be shifted only by one hour and with zero energy loss. The aggregator's marginal cost parameter α_a depends on the day ahead prices for the hours where the load is moved, because it is considered that the consumer is paying for consumed energy according to the day-ahead prices. Therefore, if the consumption is moved to the hour with a higher day-ahead price, the consumer must be compensated for the difference, otherwise there would be no incentive to participate in flexibility programs. For the analysed hours, the day-ahead prices are 27,14 €/MWh and 27,42 €/MWh resulting in 0,28 €/MWh difference, which is the cost of moving the first MWh of load (Nord Pool, 2017*a*). Due to the disutility of postponing the consumption (or consuming earlier), the marginal cost of using flexibility is increasing as shown in (4).[13]

4.2 Results

The data for January 19, 2017, hours 02.00 and 03.00, is used to calculate the producer's and the aggregator's equilibrium quantities, profits, intraday market prices and consumer surpluses in two cases, the Monopoly case and the Stackelberg case. The results are provided in Table 2.

Table 2: Equilibrium quantities, profits, prices and consumer surpluses based on data from January 19, 2017, hours 02.00 and 03.00, bidding area DK2 (MWh, €, €/MWh)

	q_{p1}	q_{p2}	q_a	Q^{total}	π_p	π_a	p_1	p_2	CS	CS^{adj}
Monopoly	18,484	80,000	-	98,484	384,232	-	23,725	23,000	192,116	-
Stackelberg	17,701	80,783	0,880	99,364	384,712	0,401	23,707	23,005	193,824	192,066

The producer's profit π_p in the analysed period is higher in the Stackelberg case comparing to the Monopoly case: €384,712 versus €384,232. Even though the difference is small, the real world data confirms that the conditions, necessary to satisfy Proposition 3, can appear in the real world and the producer can be better off being in a competition with an aggregator than a monopolist in the intraday market. In the analysed period, the producer's

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[13] The concept is similar to the one presented in the first chapter "Aggregation of demand-side flexibility in electricity markets: the effects of portfolio choice" section Model setup.

generated power satisfied almost all demand in both cases (total covered demand is denoted as Q^{total} in Table 2): 18,484 MWh and 80,000 MWh in the Monopoly case and 17,701 MWh and 80,783 MWh in the Stackelberg case.

The aggregator's profit in the Stackelberg case is relatively low, €0,401, since its traded quantities are also very low – only 0,880 MWh. This can be explained by rapidly increasing marginal cost with every additional MWh of used flexibility. However, the profit is still positive, which guarantees the aggregator's participation in the intraday market. Positive value of the aggregator's quantity indicates that it was selling power in hour 02.00 and buying in hour 03.00. One should also notice that even small amounts of flexibility offered by the aggregator can change the market outcomes and affect its participants. Thus, the aggregator is able to act strategically.

The larger difference in equilibrium prices for both hours can be seen in the Monopoly case: 23,725 €/MWh and 23,000 €/MWh. When aggregator enters the market, it sells energy in the first hour, increases supply and reduces the price to 23,707 €/MWh in the Stackelberg case. In the second hour, the aggregator increases the demand, because it has to buy energy to cover the shifted consumption of its consumers. Thus, the the price increases from 23,000 €/MWh in the Monopoly case to 23,005 €/MWh in the Stackelberg case.

The total consumer surplus, denoted as CS in Table 2, is lower in the Monopoly case, €192,116, and slightly increases to €193,824 when the aggregator starts trading in the market. Despite that, the original power buyers are harmed, since their surplus is reflected by the adjusted consumer surplus which excludes the aggregator's surplus in the second hour when it is buying power. The adjusted consumer surplus is slightly lower than in the Monopoly case – €192,066. This confirms that the conditions, necessary to satisfy Proposition 5, can appear in the real world and the presence of the aggregator in the intraday market might harm the original power buyers.[14]

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[14] Considering the proposed model setting, the original power buyers would be harmed in 11 two-hour periods during January 2017. Calculations are made for 409 moving two-hour periods, because out of 744 hours of January, bids were placed in both gas and electricity markets in only 409 hours.

4.3 Sensitivity analysis

Sensitivity analysis for general solutions can be found in section Equilibrium analysis (see Figures H.1–H.5). Here, I provide a numerical example to illustrate the difference in the producer's profit $\Delta\pi_p = \pi_p^{Stack} - \pi_p^{Mon}$ as well as the adjusted consumer surplus $\Delta CS^{adj} = CS^{adj,Stack} - CS^{Mon}$, depending on the producer's marginal cost α_p, the aggregator's marginal cost parameter α_a, the highest bids in the market β_0 and the slopes of demand β_1.

4.3.1 Producer's marginal cost of production α_p

The difference in the producer's profit $\Delta\pi_p$ and and the adjusted consumer surplus ΔCS^{adj} depend on the difference of the producer's marginal cost α_p and the level of its marginal cost: when the marginal cost becomes too high, the producer stops bidding in the market. Thus, the sensitivity analysis presents the effects of changing the producer's marginal cost in hour $n = 2$, which captures both the difference in its marginal cost in two hours and the level of cost in hour $n = 2$.

Figure 6 shows that the producer is mostly better off in a competition with the aggregator than being a monopolist no matter whether marginal production cost α_p in hour $n = 2$ drops or rises, since the difference in its profits remains positive most of the time (see Figure L.1 in Appendix L illustrating the producer's profits in both cases). Only when the producer's marginal cost in hour $n = 2$ comes close to its marginal cost in hour $n = 1$ ($\alpha_{p1} = 20,25$ €/MWh), in a small interval between 20,07 and 20,42 €/MWh, the Monopoly profit is slightly higher than in the Stackelberg case. Recall that the smaller difference in α_p in two hours reduces the producer's chances to benefit from the aggregator's participation in the market.

When the gap between marginal cost in two hours is increasing, the difference in profit is growing at an increasing rate. In Figure 6 $\Delta\alpha_p$ is increasing moving to the left from $\alpha_{p1} = \alpha_{p2} = 20,25$, while the negative difference $\Delta\alpha_p$ is increasing moving to the right. When α_{p2} reaches 26,60 €/MWh, the producer stops selling power in hour $n = 2$ in the Stackelberg case. Thus, further increase in α_{p2} does not affect it's total profit, because the producer is selling power only in hour $n = 1$. Now the aggregator is buying power in hour $n = 1$ and selling in hour $n = 2$. In the Monopoly case, the producer stops selling power in hour $n = 2$, when α_{p2} rises to 27,00 €/MWh. From this point, the difference in profits does not depend on the producer's marginal cost in the second hour. The reason why the producer stops selling power in hour $n = 2$ earlier in the Stackelberg than in the Monopoly case is related to the aggregator's traded quantities. By leaving the market earlier and letting the aggregator sell more power in hour $n = 2$ the producer receives higher profit in hour $n = 1$ when the aggregator has to buy energy.

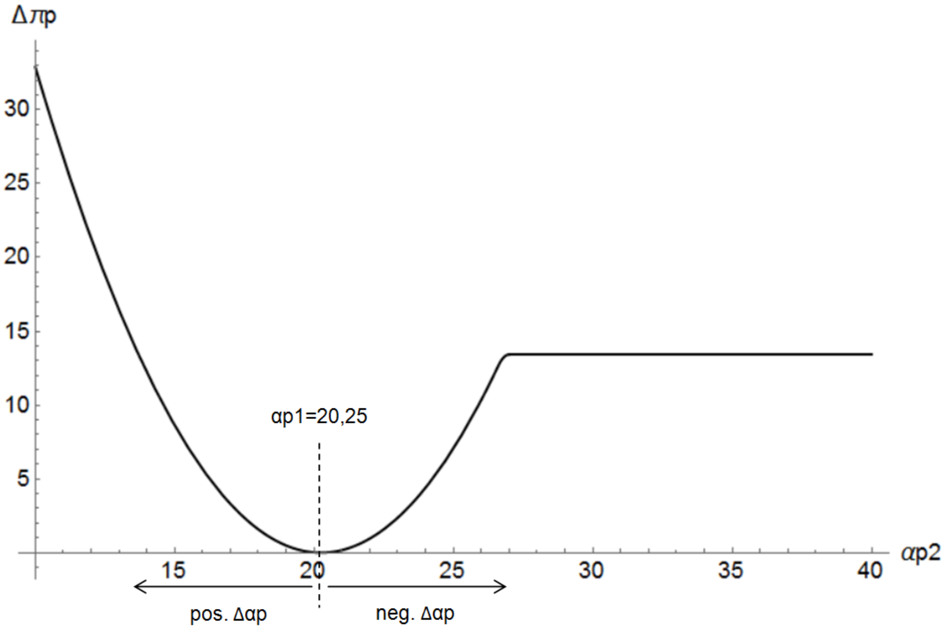

Figure 6: Difference between the producer's profit in the Stackelberg case and the Monopoly case $\Delta\pi_p$ depending on its marginal cost α_{p2}, €

The adjusted consumer surplus CS^{adj} is decreasing with increasing marginal cost of production α_{p2} in both cases (see Figure L.2 in Appendix L). The original power buyers are better off in the Monopoly case while α_{p2} is lower than 20,03 €/MWh – the difference is negative (see Figure 7). When α_{p2} exceeds this value, original power buyers prefer to have the aggregator in the intraday market. When the producer stops selling power at $\alpha_{p2} = 26,60$, the difference in CS^{adj} jumps, because the CS^{adj} remains unchanged in the Stackelberg case while it keeps shrinking in the Monopoly case, until $\alpha_{p2} = 27,00$ and the producer stops selling power in the second hour in the Monopoly case, too, and after this point the difference in CS^{adj} remains constant. This illustrates how, depending on the producer's marginal cost, the original power buyers can be better off or worse off when the aggregator is trading in the intraday market.

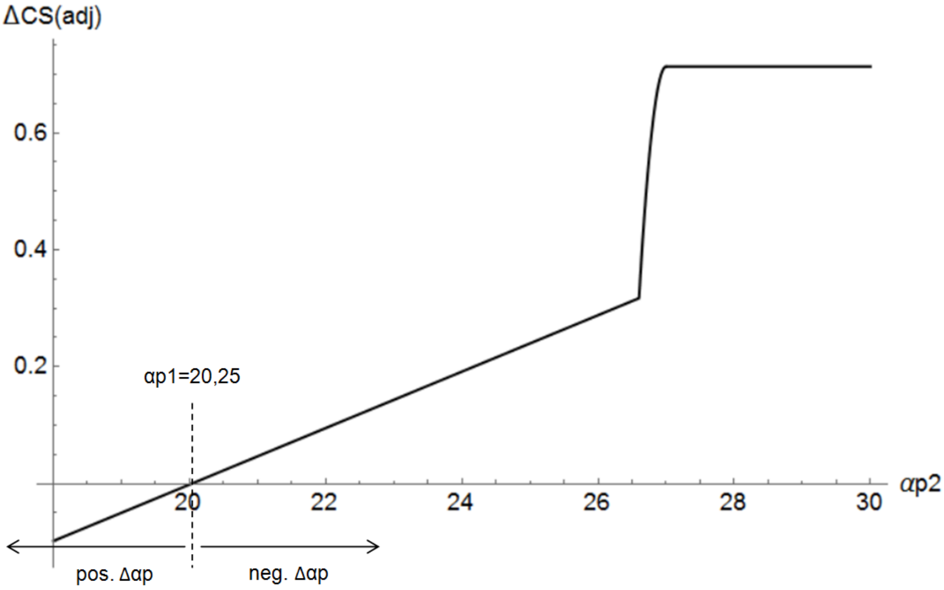

Figure 7: Difference between the adjusted consumer surplus ΔCS^{adj} depending on the producer's marginal cost α_{p2}, €

4.3.2 Aggregator's marginal cost parameter α_a

The aggregator's marginal cost also influences the producer's gain (see Figure L.3 in Appendix L). Growing aggregator's marginal cost parameter α_a results in lower quantity it offers to the intraday market. Thus, the producer is increasing its market share and getting closer to becoming a monopolist, which means that the difference between the profit in the Stackelberg case and the Monopoly case is shrinking (see Figure 8). The results indicate that in this case the producer's profit is larger when its competitor's, the aggregator's, marginal cost parameter α_a is lower.

Meanwhile, the difference in the adjusted consumer surplus is decreasing and the original power buyers are harmed (ΔCS^{adj} is negative) less when the aggregator's marginal cost becomes higher (see Figure 9 Figure L.4 in Appendix L).

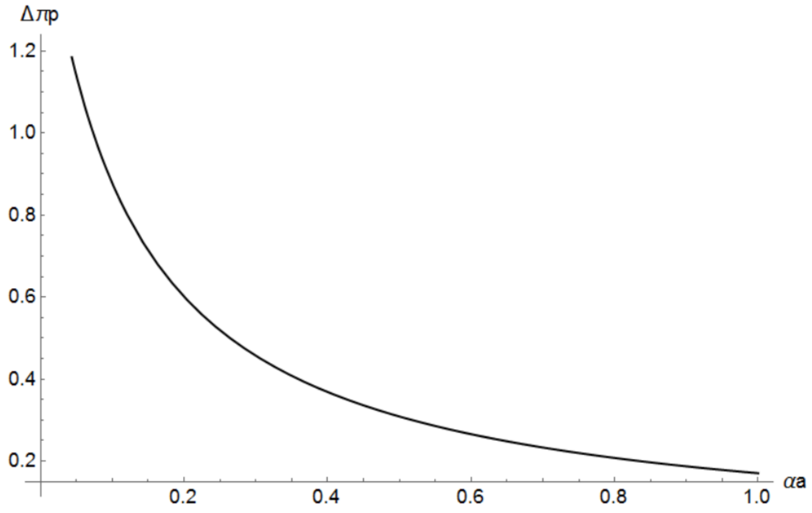

Figure 8: Difference between the producer's profit in the Stackelberg case and the Monopoly case $\Delta\pi_p$ depending on the aggregator's marginal cost parameter α_a, €

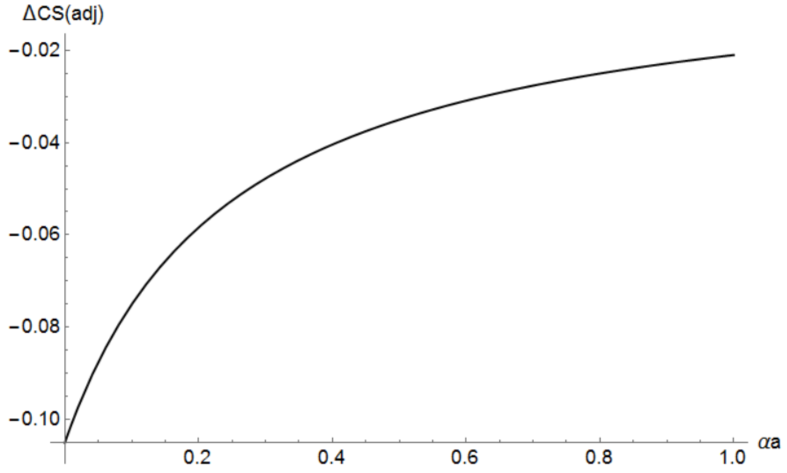

Figure 9: Difference between the adjusted consumer surplus in the Stackelberg case and the Monopoly case ΔCS^{adj} depending on the aggregator's marginal cost parameter α_a, €

4.3.3 Highest bid order in the intraday market β_0

Figure 10 shows that the difference between the producer's profits is positive, thus, the producer is better off in a competition with the aggregator, when the highest bid order in hour $n = 2$ is in the interval $(25, 78; 28, 62)$. When β_0 values are out of this interval, the producer is better off being a monopolist. This, once again, illustrates Proposition 3 that the producer has better changes to have higher profit in competition compared to the Monopoly case, if the difference in highest bids in the market is lower. Indeed, $\Delta\pi_p$ is maximised when

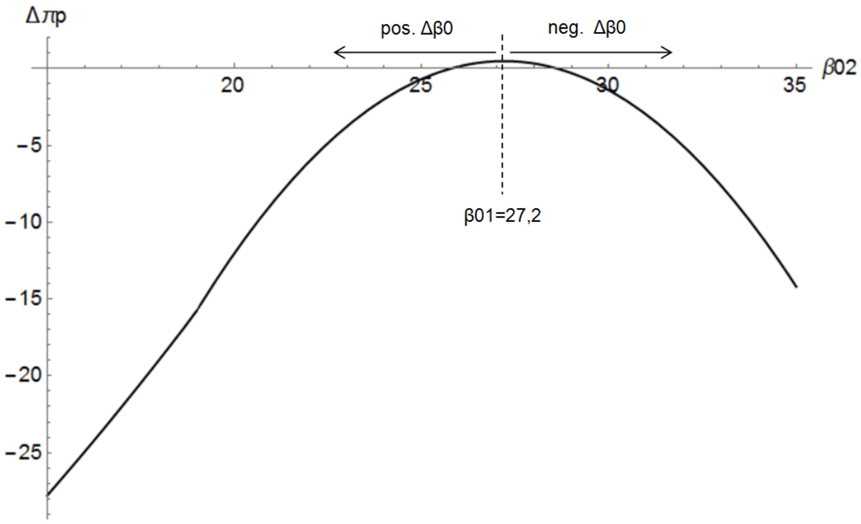

Figure 10: Difference between the producer's profit in the Stackelberg case and the Monopoly case $\Delta\pi_p$ depending on the highest bid order at the intraday market β_{02}, €

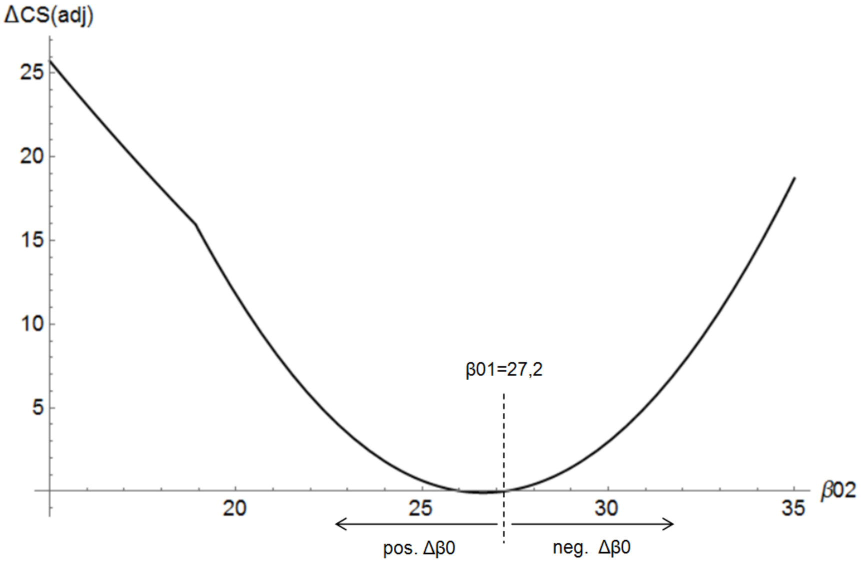

Figure 11: Difference between the adjusted consumer surplus in the Stackelberg case and the Monopoly case ΔCS^{adj} depending on the highest bid order at the intraday market β_{02}, €

$\beta_{02} = \beta_{01} = 27,2$. When the negative difference in the highest bids in the market $\Delta\beta_0$ is increasing and we are moving to the right from the point where $\beta_{02} = \beta_{01} = 27,2$, the difference in profits is decreasing and becomes negative. Similarly, when moving to the left from the point where $\Delta\beta_0 = 0$, i.e. in the direction of increasing $\Delta\beta_0$, the difference in profits is shrinking and becomes negative, too. When the highest bid order in hour $n = 2$

drops to €19,00, the producer stops selling power in hour $n = 2$, since its marginal cost becomes too high ($\alpha_{p2} = 19,00$) (see Figure L.5 in Appendix L).

As it is illustrated in Figure 11, the original consumers are worse off in the Stackelberg case if β_{02} is in the interval $(26,08; 27,2)$. Otherwise, they gain from the aggregator's presence in the market. The further from that interval β_{02} is, the faster ΔCS^{adj} grows. Although, the growth rate of ΔCS^{adj} becomes lower when β_{02} drops below €19,00 and the producer stops selling power in hour $n = 2$ (see Figure L.6 in Appendix L).

4.3.4 Slope of demand β_1

The increase in the slope of demand β_{12} leads to a lower profit for a seller (see Figure L.7 in Appendix L) and reduces the difference between the producer's profits in the Stackelberg case and the Monopoly case (see Figure 12). In the analysed period, the producer is better off in a competition with the aggregator, since $\Delta\pi_p$ stays positive when β_{12} grows. Similarly, with higher β_{12} values, the adjusted consumer surplus decreases in both cases (see Figure L.8 in Appendix L), since prices are getting higher in both hours and the producer's traded quantities are lower in hour $n = 2$. The difference in the adjusted consumer surplus remains negative when β_{12} increases (see Figure 13).

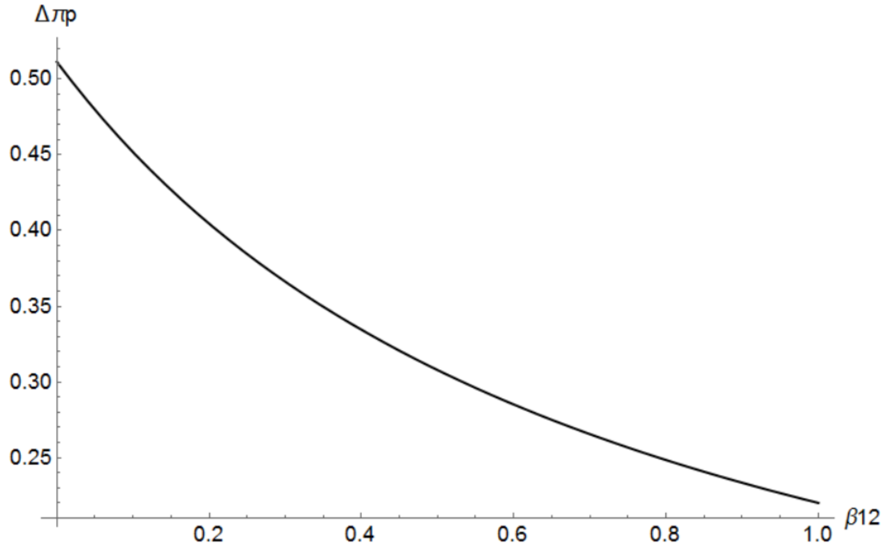

Figure 12: Difference between the producer's profit in the Stackelberg case and the Monopoly case $\Delta\pi_p$ depending on the slope of demand β_{12}, €

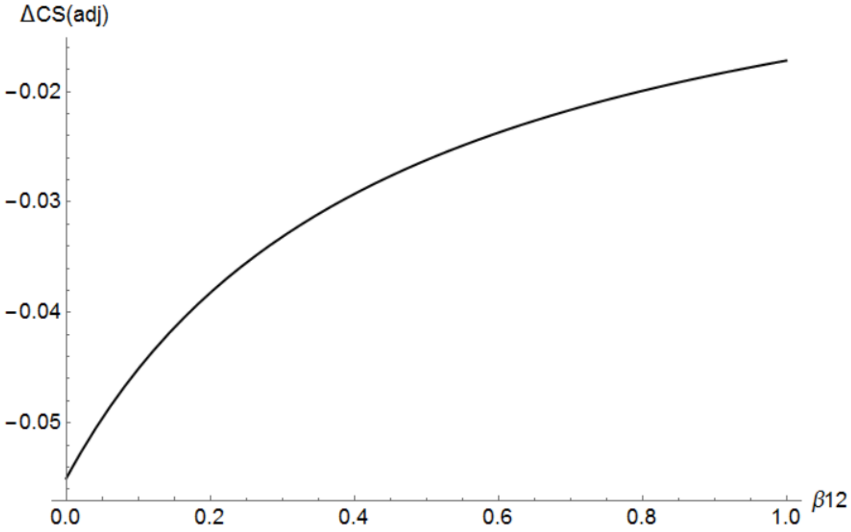

Figure 13: Difference between the adjusted consumer surplus in the Stackelberg case and the Monopoly case ΔCS^{adj} depending on the slope of demand β_{12}, €

5 Conclusion

This paper investigates whether the flexible demand aggregator's presence in the intraday market can negatively affect power buyers and bring benefit to the competing producer. A game theoretic approach is used to compare market equilibrium outcomes in two cases: the Monopoly case, where only the producer sells power in the intraday market, and the Stackelberg case, where the producer competes with a smaller aggregator.

The general equilibrium solutions indicate that under certain market conditions and the producer's marginal cost in different hours, the producer is strictly better off being in a competition with the aggregator than selling power in the intraday market as a monopolist. The reason for this unexpected outcome is the aggregator's trading pattern: the aggregator sells power in one hour, but buys it in another to compensate its consumers for the shifted load. Therefore, in one hour the aggregator increases power supply and in another – power demand. The total amount of energy offered to the market by the producer is the same either it is a monopolist or in a competition with the aggregator. Nevertheless, because of the aggregator's presence in the market and increased demand in one of the hours, the producer shifts some part of its production from one hour to another, where the marginal production cost is lower. Under favourable market conditions, such as certain slopes of demand and highest bid orders in the market, certain producer's marginal cost in different hours and certain aggregator's cost parameters, the producer is able to reduce its production cost more than its reduced revenue due to the competition and in this way increase its profit. Under certain market conditions, the adjusted consumer surplus, that excludes the surplus absorbed by the aggregator, might become smaller than in the Monopoly case. The reason for this reduction is that the quantities of electricity available to the original power buyers in each hour differ in both cases and those quantities have different weights that reflect their value. On the other hand, another outcome is possible, too: all market participants can be better off when the aggregator is trading flexible load in the intraday market.

The numerical estimation presents an example of two trading hours in the Nord Pool intraday market when the producers benefit from the aggregator's presence at the market and the adjusted consumer surplus is reduced. Here, two hypothetical players – the producer, a gas power plant, and the aggregator, that offers flexibility of refrigeration processes – compete in DK2 bidding zone on January 19, 2017, hours 02.00 and 03.00. Numerical results show that the producer's profit is indeed higher in the Stackelberg case compared to the Monopoly case. Even though the difference in profits is low, sensitivity analysis suggests that higher variation in hourly gas prices could significantly increase the difference between the producer's profits in the Monopoly and Stackelberg cases. The total consumer surplus increases when the aggregator trades in the market. However, the adjusted consumer surplus, which is the surplus that does not include the aggregator's surplus when it acts as a buyer, is slightly lower in Stackelberg case. This illustrates that under certain conditions, in some hours, the aggregator's presence in the intraday market might harm power consumers.

Further research could move in several directions. First, other demand flexibility sources could be included in the aggregator's portfolio. Different load shifting patterns with longer than one hour load shifting periods could make the aggregator less predictable and reduce the producer's advantage. Second, further analysis could include other power markets, day-ahead and balancing market, to investigate changes in market participants' bidding behaviour. Finally, further real world data investigation, including other bidding zones and longer periods of time, could bring useful insights whether the aggregator's benefits for the society can be affected significantly by its possible harm in certain time periods.

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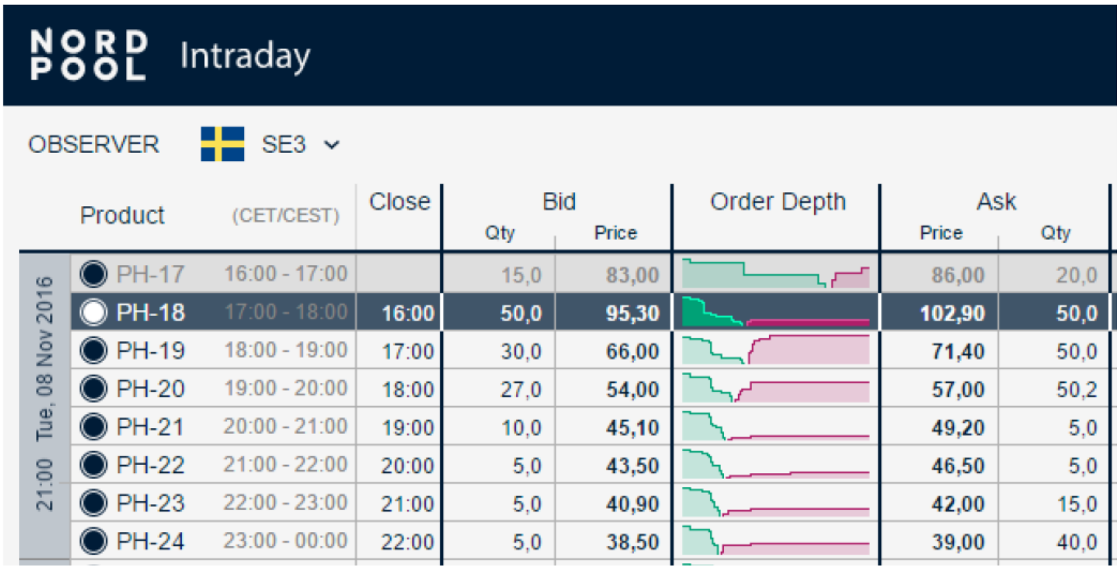
Appendix A Intraday market

The benefits of trading in the intraday market are argued by several authors. Many of them focus on renewable energy sources (RES) behaviour in the intraday market (Chaves-Ávila and Fernandes, 2015) and on wind power generators (Skajaa et al., 2015; Heydarian-Forushani et al., 2014*b*; Usaola and Moreno, 2009; Chaves-Ávila et al., 2013; Henriot, 2014), some on pumped hydro power plants (Braun and Hoffmann, 2016) and thermal power generators (Aïd et al., 2016). These benefits and successful wind power integration in the power system can be achieved only if there is enough liquidity in the intraday market (Weber, 2010). Also, the profitability of market participants depends on whether one- or two-price system has been applied for imbalance settlement, the latter being more beneficial for both the buyers and the sellers (Scharff and Amelin, 2016).

The activity of trading varies between different price zones and mostly depends on the share of wind power in the power system, transmission capacity for the intraday trading and the level of balancing prices (Scharff and Amelin, 2016). In order to know if the intraday market is functioning effectively, one should know what causes the difference in day-ahead and intraday market prices. In the effectively functioning intraday market, the difference in day-ahead and intraday market prices is caused by the wind and conventional generation forecast errors: the relative intraday prices decrease when the wind forecast errors become lower (Karanfil and Li, 2017). On the other hand, the price formation in the intraday market can lead to different optimal strategic bidding at the day-ahead market (Soysal et al., 2017).

Appendix B Illustration of aggregated demand for one hour in the intraday market

Each trader at the intraday market has an access to the market information provided by Nord Pool. Figure B.1 shows the market information screen for Swedish SE3 bidding zone. The first column indicates the product type and time of the delivery, as well as gate closure time. Bid and Ask columns show bid (buy) and ask (sell) prices for a particular product that are the best at the moment. Meanwhile, Order Depth provides information about all orders places on Bid or Ask. In this graphical representation, the Y axis ”gives an approximation as to the quantity of an order relative to the other orders in the order depth.”; and the X axis ”shows how far apart the Bid/Ask prices are from one another, relative to the other orders in the order depth” (Nord Pool, 2016*b*). Green indicates bid and red indicates ask orders. Thus, from here we can see that the approximation of the demand function for one hour is downward sloping.



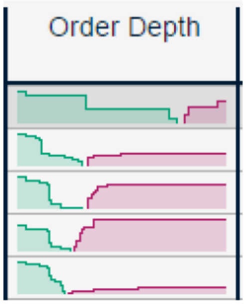
NORD POOL Intraday

OBSERVER SE3

21:00 Tue, 08 Nov 2016

Product	(CET/CEST)	Close	Bid Qty	Bid Price	Order Depth	Ask Price	Ask Qty
● PH-17	16:00 - 17:00		15,0	83,00		86,00	20,0
○ PH-18	17:00 - 18:00	16:00	50,0	95,30		102,90	50,0
● PH-19	18:00 - 19:00	17:00	30,0	66,00		71,40	50,0
● PH-20	19:00 - 20:00	18:00	27,0	54,00		57,00	50,2
● PH-21	20:00 - 21:00	19:00	10,0	45,10		49,20	5,0
● PH-22	21:00 - 22:00	20:00	5,0	43,50		46,50	5,0
● PH-23	22:00 - 23:00	21:00	5,0	40,90		42,00	15,0
● PH-24	23:00 - 00:00	22:00	5,0	38,50		39,00	40,0

(a) Market information screen



(b) Order depth

*Source: (Nord Pool, 2016*b*)*

Figure B.1: Nord Pool intraday market information screen, 8 Nov 2016

Appendix C Many producers and the aggregator

In this appendix I analyse the market situation when there is more than one producer offering power at the intraday market and the aggregator enters the intraday market. Let's compare equilibrium market outcomes in two cases: "Many producers", where several producers are selling power at the market, and "Many producers and the aggregator", where the aggregator enters the market and offers its consumers' flexibility.

Let's assume that there are K producers that are identical in terms of their characteristics, facing production cost function as in equation 3. The total quantities of power offered by all the producers to the market in hours $n = 1$ and $n = 2$ are Q_{p1} and Q_{p2}.

In the first case, Many producers, all producers are competing in a Cournot competition and make their decisions about individually offered quantities q^i_{p1} and q^i_{p2}, $i = 1, ..., K$ in period t to the market at the same time. The i^{th} producer maximises its profit function:

$$\begin{aligned}\pi^i_p(q^i_{p1}, q^i_{p2}, Q^{-i}_{p1}, Q^{-i}_{p2}) = (\beta_{01} - \beta_{11}(q^i_{p1} + Q^{-i}_{p1}))q^i_{p1} - \alpha_{p1}q^i_{p1} + \\ (\beta_{02} - \beta_{12}(q^i_{p2} + Q^{-i}_{p2}))q^i_{p2} - \alpha_{p2}q^i_{p2}, \quad (37)\end{aligned}$$

where its profit depends on its own and on its competitors' quantities. The decision problem for the i^{th} producer is

$$\pi^{i*}_p(q^i_{p1}, q^i_{p2}, Q^{-i}_{p1}, Q^{-i}_{p2}) = \max_{q^i_{p1}, q^i_{p2}} \pi^i_p(q^i_{p1}, q^i_{p2}, Q^{-i}_{p1}, Q^{-i}_{p2}). \quad (38)$$

The reaction functions of all producers are found by solving the following set of equations:

$$\left.\frac{\partial \pi^i_p(q^i_{p1})}{\partial q^i_{p1}}\right|_{q^i_{p1}=q^{i*}_{p1}} = \beta_{01} - \alpha_{p1} - q^i_{p1}\beta_{11} - (q^i_{p1} + Q^{-i}_{p1})\beta_{11} = 0, \quad (39)$$

$$\left.\frac{\partial \pi^i_p(q^i_{p2})}{\partial q^i_{p2}}\right|_{q^i_{p2}=q^{i*}_{p2}} = \beta_{02} - \alpha_{p2} - q^i_{p2}\beta_{12} - (q^i_{p2} + Q^{-i}_{p2})\beta_{12} = 0, \quad (40)$$

where $q^i_{p1} + Q^{-i}_{p1}$ is equal to $q^i_{p1}K$ and $q^i_{p2} + Q^{-i}_{p2}$ is equal to $q^i_{p2}K$, since all producers have symmetrical costs, which result in identical solutions.

Proposition 7. *A solution to the case Many producers is:*

(i) The equilibrium quantities supplied by the i^{th} *producer are*

$$q_{p1}^{i*} = \frac{\beta_{01} - \alpha_{p1}}{\beta_{11}(1+K)}, \tag{41}$$

$$q_{p2}^{i*} = \frac{\beta_{02} - \alpha_{p2}}{\beta_{12}(1+K)}. \tag{42}$$

(ii) The market prices are

$$p_1^* = \frac{\beta_{01} + \alpha_{p1}K}{1+K}, \tag{43}$$

$$p_2^* = \frac{\beta_{02} + \alpha_{p2}K}{1+K}. \tag{44}$$

(iii) The i^{th} *producer's profit is*

$$\pi_p^{i*} = \frac{(\alpha_{p2} - \beta_{02})^2\beta_{11} + (\alpha_{p1} - \beta_{01})^2\beta_{12}}{(1+K)^2\beta_{11}\beta_{12}}. \tag{45}$$

When the aggregator enters the market, it is competing with power producers in a Cournot competition. All market participants make their decisions about offered quantities at the same time.

The aggregator face the same cost function as before. Its profit function in the case Many producers and the aggregator is:

$$\pi_a(q_a, Q_{p1}, Q_{p2}) = (\beta_{01} - \beta_{11}(Q_{p1} + q_a))q_a - \alpha_a q_a^2 - (\beta_{02} - \beta_{12}(Q_{p2} - q_a))q_a, \tag{46}$$

where its profit depends on its own and on all producers' quantities. The decision problem for the aggregator is:

$$\pi_a^*(q_a, Q_{p1}, Q_{p2}) = \max_{q_a} \pi_a(q_a, Q_{p1}, Q_{p2}). \tag{47}$$

The reaction function of the aggregator is found by solving

$$\left.\frac{\partial \pi_a(q_a)}{\partial q_a}\right|_{q_a = q_a^*} = \beta_{01} - \beta_{02} - Q_{p1}\beta_{11} + Q_{p2}\beta_{12} - 2q_a(\alpha_a + \beta_{11} + \beta_{12}) = 0, \tag{48}$$

and is equal to

$$q_a^* = \frac{\beta_{01} - \beta_{02} - Q_{p1}\beta_{11} + Q_{p2}\beta_{12}}{2(\alpha_a + \beta_{11} + \beta_{12})}. \tag{49}$$

The i^{th} producer's profit function is

$$\begin{aligned}\pi_p^i(q_{p1}^i, q_{p2}^i, Q_{p1}^{-i}, Q_{p2}^{-i}, q_a) = (\beta_{01} - \beta_{11}(q_{p1}^i + Q_{p1}^{-i} + q_a))q_{p1}^i - \alpha_{p1}q_{p1}^i + \\ (\beta_{02} - \beta_{12}(q_{p2}^i + Q_{p2}^{-i} - q_a))q_{p2}^i - \alpha_{p2}q_{p2}^i.\end{aligned} \tag{50}$$

The reaction functions of all producers are found by solving the following set of equations:

$$\left.\frac{\partial \pi_p^i(q_{p1}^i)}{\partial q_{p1}^i}\right|_{q_{p1}^i = q_{p1}^{i*}} = \beta_{01} - \alpha_{p1} - (q_a + 2q_{p1}^i + Q_{p1}^{-i})\beta_{11} = 0, \tag{51}$$

$$\left.\frac{\partial \pi_p^i(q_{p2}^i)}{\partial q_{p2}^i}\right|_{q_{p2}^i = q_{p2}^{i*}} = \beta_{02} - \alpha_{p2} + (q_a - 2q_{p2}^i - Q_{p2}^{-i})\beta_{12} = 0, \tag{52}$$

and are equal to

$$q_{p1}^{i*} = \frac{\beta_{01} - \alpha_{p1} - q_a\beta_{11}}{\beta_{11}(1+K)}, \tag{53}$$

$$q_{p2}^{i*} = \frac{\beta_{02} - \alpha_{p2} - q_a\beta_{12}}{\beta_{12}(1+K)}. \tag{54}$$

Proposition 8. *A solution to the case Many producers and the aggregator is:*

(i) The equilibrium quantities supplied by the i^{th} producer and the aggregator are

$$q_{p1}^{i*} = \frac{1}{\beta_{11}(1+K)}\Big(\beta_{01} - \alpha_{p1} + \frac{((\alpha_{p2} - \alpha_{p1})K - \beta_{01} + \beta_{02})\beta_{11}}{2\alpha_a(1+K) + (2+K)(\beta_{11} + \beta_{12})}\Big), \tag{55}$$

$$q_{p2}^{i*} = \frac{1}{\beta_{12}(1+K)}\Big(\beta_{02} - \alpha_{p2} + \frac{((\alpha_{p1} - \alpha_{p2})K + \beta_{01} - \beta_{02})\beta_{12}}{2\alpha_a(1+K) + (2+K)(\beta_{11} + \beta_{12})}\Big), \tag{56}$$

$$q_a^* = \frac{(\alpha_{p1} - \alpha_{p2})K + \beta_{01} - \beta_{02}}{2\alpha_a(1+K) + (2+K)(\beta_{11} + \beta_{12})}. \tag{57}$$

(ii) The market prices are

$$p_1^* = \frac{1}{1+K}\Big(\alpha_{p1}K + \beta_{01} + \frac{((\alpha_{p2} - \alpha_{p1})K - \beta_{01} + \beta_{02})\beta_{11}}{2\alpha_a(1+K) + (2+K)(\beta_{11} + \beta_{12})}\Big), \tag{58}$$

$$\begin{aligned}p_2^* = {} & \frac{1}{(1+K)(2\alpha_a(1+K) + (2+K)(\beta_{11} + \beta_{12}))} \\ & \Big((\alpha_{p2}K + \beta_{02})(2\alpha_a(1+K) + (2+K)\beta 11) + \\ & (\beta_{01} + \beta_{02} + K(\alpha_{p1} + \alpha_{p2} + \alpha_{p2}K + \beta_{02}))\beta_{12}\Big).\end{aligned} \tag{59}$$

(iii) The i^{th} producer's and the aggregator's profits are

$$\pi_p^{i*} = \frac{1}{1+K}\Big(\frac{(\alpha_{p1}-\beta_{01})^2}{(1+K)\beta_{11}} + \frac{\alpha_{p2}^2}{\beta_{12}} - \frac{\alpha_{p2}^2 K + 2\alpha_{p2}\beta_{02} - \beta_{02}^2}{\beta_{12}(1+K)} - \frac{2\alpha_a((\alpha_{p1}-\alpha_{p2})K + \beta_{01} - \beta_{02})^2}{(2+K)(2\alpha_a(1+K) + (2+K)(\beta_{11}+\beta_{12}))^2} + \frac{((4+3K)(\alpha_{p1}-\alpha_{p2}) - (3+2K)(\beta_{01}-\beta_{02}))((\alpha_{p1}-\alpha_{p2})K + \beta_{01} - \beta_{02})}{(1+K)(2+K)(2\alpha_a(1+K) + (2+K)(\beta_{11}+\beta_{12}))}\Big). \tag{60}$$

$$\pi_a^* = \frac{((\alpha_{p1}-\alpha_{p2})K + \beta_{01} - \beta_{02})^2(\alpha_a + \beta_{11} + \beta_{12})}{(2\alpha_a(1+K) + (2+K)(\beta_{11}+\beta_{12}))^2}. \tag{61}$$

Proposition 9 provides the conditions when a producer i is strictly better off when in addition to other producers the aggregator is participating in the intraday market comparing to the situation when the only competitors are other producers.

Proposition 9. *A producer i benefits from the aggregator's presence in the intraday market if*

(i) $\alpha_{p1} > \alpha_{p2}$*:*

- $\alpha_{p1} > \alpha_{p2}$ *and* $\beta_{01} > \beta_{02}$ *and*

$$\alpha_{p1} - \alpha_{p2} > (\beta_{01} - \beta_{02})\frac{4(1+K)\alpha_a + (3+2K)(\beta_{11}+\beta_{12})}{4(1+K)\alpha_a + (4+3K)(\beta_{11}+\beta_{12})}, \tag{62}$$

or

- $\alpha_{p1} > \alpha_{p2}$ *and* $\beta_{01} < \beta_{02}$ *and*

$$(\alpha_{p1} - \alpha_{p2})K > -\beta_{01} + \beta_{02}; \tag{63}$$

Or

(ii) $\alpha_{p1} < \alpha_{p2}$*:*

- $\alpha_{p1} < \alpha_{p2}$ *and* $\beta_{01} > \beta_{02}$ *and*

$$(\alpha_{p1} - \alpha_{p2})K < -\beta_{01} + \beta_{02}, \tag{64}$$

or

- $\alpha_{p1} < \alpha_{p2}$ *and* $\beta_{01} < \beta_{02}$ *and*

$$\alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02}) \frac{4(1+K)\alpha_a + (3+2K)(\beta_{11} + \beta_{12})}{4(1+K)\alpha_a + (4+3K)(\beta_{11} + \beta_{12})}. \tag{65}$$

Proposition 9 can be proven similarly as Proposition 3 – a producer i is strictly better off in a competition with the aggregator in the intraday market if its profit in the case Many producers and the aggregator is larger than in the case Many producers. The necessary conditions include the difference between the producer's i marginal cost α_p in both hours, the difference between the highest bids in the market in both hours and a ratio, accounting for the aggregator's cost indicator α_a, demand slopes β_1 in both hours and a number of producers in the intraday market K.

The adjusted consumer surpluses in two analysed cases are shown in Proposition 10. Similarly like in the Monopoly and Stackelberg cases, consumers may be hurt by the aggregator's participation in the intraday market (i.e. $CS^{MPA} - CS^{MP} < 0$) under certain market conditions, provided in Proposition 11. Proposition 11 can be proven similarly as Proposition 5.

Proposition 10. *The adjusted consumer surplus:*

(i) In the case Many producers is

$$CS^{MP} = \frac{K^2((\alpha_{p2} - \beta_{02})^2\beta_{11} + (\alpha_{p1} - \beta_{01})^2\beta_{12})}{2(1+K)^2\beta_{11}\beta_{12}}, \tag{66}$$

(ii) In the case Many producers and the aggregator is

$$
\begin{aligned}
CS^{MPA} = {} & \frac{1}{(2(1+K)^2(2\alpha_a(1+K)+(2+K)(\beta_{11}+\beta_{12}))^2} \\
& \Bigg(\frac{1}{\beta_{12}}\Big((K(\alpha_{p2}-\beta_{02})(2\alpha_a(1+K)+(2+K)\beta_{11})+(\alpha_{p1}K+\alpha_{p2}K(1+K)+\beta_{01}- \\
& (1+K)^2\beta_{02})\beta_{12})^2\Big)+\frac{1}{\beta_{11}}\Big((\beta_{02}-\beta_{01})\beta_{11}-K^2\beta_{01}(2\alpha_a+\beta_{11}+\beta_{12})+ \\
& \alpha_{p1}K((1+K)(2\alpha_a+\beta_{11})+(2+K)\beta_{12})+K(\alpha_{p2}\beta_{11}-2\beta_{01}(\alpha_a+\beta_{11}+\beta_{12}))\Big)^2\Bigg).
\end{aligned}
\tag{67}
$$

Proposition 11. *The consumer surplus is reduced when the aggregator enters the intraday market if*

(i) $\alpha_{p1} > \alpha_{p2}$*:*

- $\alpha_{p1} > \alpha_{p2}$ *and* $\beta_{01} > \beta_{02}$ *and*

  $$\alpha_{p1}-\alpha_{p2} > (\beta_{01}-\beta_{02})\frac{4K(1+K)\alpha_a+(1+2K(2+K))(\beta_{11}+\beta_{12})}{4K(1+K)\alpha_a+K(3+2K)(\beta_{11}+\beta_{12})}, \tag{68}$$

  or

- $\alpha_{p1} > \alpha_{p2}$ *and* $\beta_{01} < \beta_{02}$ *and*

  $$(\alpha_{p1}-\alpha_{p2})K > -\beta_{01}+\beta_{02}; \tag{69}$$

Or

(ii) $\alpha_{p1} < \alpha_{p2}$*:*

- $\alpha_{p1} < \alpha_{p2}$ *and* $\beta_{01} > \beta_{02}$ *and*

  $$(\alpha_{p1}-\alpha_{p2})K < -\beta_{01}+\beta_{02}, \tag{70}$$

  or

- $\alpha_{p1} < \alpha_{p2}$ *and* $\beta_{01} < \beta_{02}$ *and*

$$\alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02}) \frac{4K(1+K)\alpha_a + (1 + 2K(2+K))(\beta_{11} + \beta_{12})}{4K(1+K)\alpha_a + K(3+2K)(\beta_{11} + \beta_{12})}. \tag{71}$$

Table C.1 shows the numerical results using the same input data as before (see Table 1) and a new parameter $K = 5$, determining the number of producers in the intraday market. With higher competition in the market, the traded quantities are about 65% larger and reach 165,423 MWh (see Table 2 and Table C.1). Prices drop from 23,000–23,725 €/MWh to 20,333–21,408 €/MWh. Consequently, the adjusted consumer surplus is significantly higher: €533,474–€533,656. The results show that, similarly like in the case of one producer, the aggregator participation in the market increases producer's i profit from €42,692 to €42,778 and adjusted consumers surplus from €533,656 to €533,474. Thus, under certain market conditions, even though there are more power suppliers in the market, the aggregator might harm the original power buyers and increase the profit of its competitors.

Table C.1: Equilibrium quantities, profits, prices and consumer surpluses based on data from January 19, 2017, hours 02.00 and 03.00, bidding area DK2 (MWh, €, €/MWh), two cases: Many producers and Many producers and the aggregator

	q^i_{p1}	q^i_{p2}	q_a	Q^{total}	π^i_p	π_a	p_1	p_2	CS	CS^{adj}
Many producers	6,161	26,667	-	164,140	42,692	-	21,408	20,333	533,656	-
Many producers and the aggregator	5,947	26,881	1,283	165,423	42,778	0,853	21,368	20,344	537,745	533,474

Appendix D The producer as an aggregator

This appendix provides the analysis of the market situation when the producer in addition to producing power acts as an aggregator and is the only power seller in the intraday market. Let's call this case "The producer as an aggregator".

The producer faces the same cost function for producing power as before (see (3)). Also, it compensates its consumers for provided flexibility (see the aggregator's cost function in (4)). The aggregator maximises its profit function in the analysed period:

$$\pi_p(q_{p1}, q_{p2}, q_a) = (\beta_{01} - \beta_{11}(q_{p1} + q_a))(q_{p1} + q_a) - \alpha_{p1}q_{p1} + (\beta_{02} - \beta_{12}(q_{p2} - q_a))(q_{p2} - q_a) - \alpha_{p2}q_{p2} - \alpha_a q_a^2. \quad (72)$$

Unlike the aggregator in previous cases, the producer does not need to buy power in the intraday market in order to compensate for the shifted load – instead it produces that amount of power and provides it to its consumers that offer flexibility. As a result, the demand curve does not shift.

Proposition 12. *A solution to the case The producer as an aggregator is:*

(i) The equilibrium quantities supplied by the producer are

$$q_{p1}^* = \frac{\alpha_a\beta_{01} + \alpha_{p2}\beta_{11} - \alpha_{p1}(\alpha_a + \beta_{11})}{2\alpha_a\beta_{11}}, \quad (73)$$

$$q_{p2}^* = \frac{-\alpha_{p2} + \beta_{02} + \frac{(\alpha_{p1}-\alpha_{p2})\beta_{12}}{\alpha_a}}{2\beta_{12}}. \quad (74)$$

$$q_a^* = \frac{\alpha_{p1} - \alpha_{p2}}{2\alpha_a}. \quad (75)$$

(ii) The market prices are

$$p_1^* = \frac{\alpha_{p1} + \beta_{01}}{2}, \quad (76)$$

$$p_2^* = \frac{\alpha_{p2} + \beta_{02}}{2}. \quad (77)$$

(iii) The producer's profit is

$$\pi_p^* = \frac{\alpha_a(\alpha_{p2} - \beta_{02})^2\beta_{11} + (\alpha_a(\alpha_{p1} - \beta_{01})^2 + (\alpha_{p1} - \alpha_{p2})^2\beta_{11})\beta_{12}}{4\alpha_a\beta_{11}\beta_{12}}. \quad (78)$$

The following proposition states that the producer is never worse off to have consumers providing flexibility and producing power comparing to being only a power producer. This is intuitive, since the producer increases its chances to receive a higher profit when it has an option to use flexibility provided by its consumers.

Proposition 13. *The producer is never worse off to have consumers providing flexibility and producing power comparing to being only a power producer.*

Proof. The producer is never worse off to act as an aggregator in addition to producing power if $\pi_p^{*PA} - \pi_p^{*Mon} > 0$, where the expressions for the producer's profit when it also acts as an aggregator π_p^{*PA} and when it is only a producer π_p^{*Mon} are provided in Proposition 7 and Proposition 1. Thus, the inequality $\pi_p^{*PA} - \pi_p^{*Mon} > 0$ can be written as:

$$\frac{\alpha_a(\alpha_{p2} - \beta_{02})^2\beta_{11} + (\alpha_a(\alpha_{p1} - \beta_{01})^2 + (\alpha_{p1} - \alpha_{p2})^2\beta_{11})\beta_{12}}{4\alpha_a\beta_{11}\beta_{12}} - \frac{\beta_{11}(\alpha_{p2} - \beta_{02})^2 + \beta_{12}(\alpha_{p1} - \beta_{01})^2}{4\beta_{11}\beta_{12}} > 0$$

Through algebra, it can be simplified as:

$$\frac{(\alpha_{p1} - \alpha_{p2})^2}{4\alpha_a} > 0,$$

which is always true. □

The consumer surplus is shown in the following proposition. One can notice, that it is the same as in the Monopoly case. Therefore, the final consumers are indifferent if the producer has an access to flexibility providers or not.

Proposition 14. *The consumer surplus when the producer acts as an aggregator in addition to producing power is*

$$CS^{PA} = \frac{\beta_{11}(\alpha_{p2} - \beta_{02})^2 + \beta_{12}(\alpha_{p1} - \beta_{01})^2}{8\beta_{11}\beta_{12}}. \tag{79}$$

Naturally, the producer never receives a lower profit in The producer as an aggregator case comparing to the Stackelberg case.

Proposition 15. *The producer never receives a lower profit in The producer as an aggregator case comparing to the Stackelberg case.*

Proof. The producer never receives a lower profit in The producer as an aggregator case comparing to the Stackelberg case if $\pi_p^{*PA} - \pi_p^{*Sta} > 0$, where the expressions for the producer's profit when it also acts as an aggregator π_p^{*PA} and when it is competing with an aggregator π_p^{*Sta} are provided in Proposition 7 and Proposition 2. Thus, the inequality $\pi_p^{*PA} - \pi_p^{*Sta} > 0$ can be written as:

$$\frac{\alpha_a(\alpha_{p2} - \beta_{02})^2\beta_{11} + (\alpha_a(\alpha_{p1} - \beta_{01})^2 + (\alpha_{p1} - \alpha_{p2})^2\beta_{11})\beta_{12}}{4\alpha_a\beta_{11}\beta_{12}} - \frac{1}{8}\Big(\frac{2(\alpha_{p1} - \beta_{01})^2}{\beta_{11}} + \frac{2(\alpha_{p2} - \beta_{02})^2}{\beta_{12}} - \frac{(\beta_{01} - \beta_{02})^2}{\alpha_a + \beta_{11} + \beta_{12}} + \frac{2(\alpha_{p1} - \alpha_{p2})^2}{2\alpha_a + \beta_{11} + \beta_{12}}\Big) > 0$$

Through algebra, it can be simplified as:

$$\frac{1}{8}\Big(\frac{(\beta_{01} - \beta_{02})^2}{\alpha_a + \beta_{11} + \beta_{12}} + \frac{2(\alpha_{p1} - \alpha_{p2})^2(\alpha_a + \beta_{11} + \beta_{12})}{\alpha_a(2\alpha_a + \beta_{11} + \beta_{12})}\Big) > 0,$$

which is always true. ☐

Since the consumer surplus in The producer as an aggregator case is equal to the consumer surplus in the Monopoly case, the conditions under which the adjusted consumer surplus is reduced when the aggregator enters the intraday market correspond to those provided in Proposition 5.

Table D.1 shows the numerical results using the same input data as before (see Table 1). The first two lines include previously analysed Monopoly and Stackelberg cases, while the third shows the results when the producer acts as an aggregator. The producer's profit in the latter case is higher – €385,627 versus €384,232 and €384,712 in the Monopoly and Stackelberg cases. This illustrates the proposition that the producer will be never worse off by having an option to sell aggregated flexibility. The consumer surplus, however, remains the same as in the Monopoly case – €192,116. Even though the total quantity produced including the amount of shifted load is higher than in the Monopoly case (€100,716 versus €98,484), part of it is not traded in the market: when the producer shifts its consumers' load, it does not need to buy it back in the market, instead it produces energy itself. Also, one can notice that the amount of shifted energy is significantly larger than in the Stackelberg case – 2,232 MWh versus 0,880 MWh.This can be explained by the producer's ability to use it directly, without buying it back in the market, since the cost of flexibility becomes only the compensation to consumers for the shifted load and pure production cost.

Table D.1: Equilibrium quantities, profits, prices and consumer surpluses based on data from January 19, 2017, hours 02.00 and 03.00, bidding area DK2 (MWh, €, €/MWh), three cases: the Monopoly, the Stackelberg, and The producer as an aggregator.

	q_{p1}	q_{p2}	q_a	Q^{total}	π_p	π_a	p_1	p_2	CS	CS^{adj}
Monopoly	18,484	80,000	-	98,484	384,232	-	23,725	23,000	192,116	-
Stackelberg	17,701	80,783	0,880	99,364	384,712	0,401	23,707	23,005	193,824	192,066
The producer as an aggregator	16,252	82,232	2,232	100,716	385,627	-	23,725	23,000	192,116	-

All in all, we see that under certain market conditions for the society it is better to have a producer who can act as an aggregator than an additional market player which trades only demand flexibility.

Appendix E Price elasticity of demand

This appendix provides a discussion about the price elasticity of demand at the equilibrium outcomes.

E.1 Equilibrium outcomes and price elasticity of demand when $\beta_{01} = \beta_{02} = \beta_0$

From the main analysis we know that when the producer's marginal cost α_{p1} and α_{p2} differ and the highest bids in the market β_{01} and β_{02} are equal ($\beta_{01} = \beta_{02} = \beta_0$), then the producer is always better off in the Stackelberg case compared to the Monopoly case (see Proposition 3).

Proposition 16. *When the highest bids in the market in both hours are equal, $\beta_{01} = \beta_{02}$:*

- *the equilibrium prices in the Stackelberg case are the same like in the Monopoly case: $p_1^{*Stack} = p_1^{*Mon}$ and $p_2^{*Stack} = p_2^{*Mon}$;*
- *the traded quantities can be written as: $q_{p1}^{*Stack} + q_a^* = q_{p1}^{*Mon}$ and $q_{p2}^{*Stack} - q_a^* = q_{p2}^{*Mon}$.*

Proof. The equilibrium prices, as well as quantities, in both cases are shown in Proposition 1 and Proposition 2. In the Monopoly case, the equilibrium prices are equal to:

$$p_1^{*Mon} = \frac{\beta_{01} + \alpha_{p1}}{2}, \tag{80}$$

$$p_2^{*Mon} = \frac{\beta_{02} + \alpha_{p2}}{2}. \tag{81}$$

Meanwhile, in the Stackelberg case, the equilibrium prices are equal to:

$$p_1^{*Stack} = \frac{\alpha_{p1} + \beta_{01}}{2} + \frac{\beta_{11}(\beta_{02} - \beta_{01})}{4(\alpha_a + \beta_{11} + \beta_{12})}, \tag{82}$$

$$p_2^{*Stack} = \frac{2(\alpha_{p2} + \beta_{02})(\alpha_a + \beta_{11}) + \beta_{12}(2\alpha_{p2} + \beta_{01} + \beta_{02})}{4(\alpha_a + \beta_{11} + \beta_{12})}. \tag{83}$$

When $\beta_{01} = \beta_{02} = \beta_0$,

$$p_1^{*Stack} = \frac{\alpha_{p1} + \beta_0}{2} = p_1^{*Mon}.$$

When $\beta_{01} = \beta_{02} = \beta_0$, p_1^{*Stack} can be rewritten as:

$$p_1^{*Stack} = \frac{2(\alpha_{p2} + \beta_0)(\alpha_a + \beta_{11} + \beta_{12})}{4(\alpha_a + \beta_{11} + \beta_{12})} = \frac{\alpha_{p2} + \beta_0}{2} = p_2^{*Mon}.$$

The equilibrium quantities in the Monopoly case are:

$$q_{p1}^{*Mon} = \frac{\beta_{01} - \alpha_{p1}}{2\beta_{11}}, \tag{84}$$

$$q_{p2}^{*Mon} = \frac{\beta_{02} - \alpha_{p2}}{2\beta_{12}}. \tag{85}$$

The equilibrium quantities in the Stackelberg case are:

$$q_{p1}^{*Stack} = \frac{1}{2}\Big(\frac{\beta_{01} - \alpha_{p1}}{\beta_{11}} + \frac{\alpha_{p2} - \alpha_{p1}}{2\alpha_a + \beta_{11} + \beta_{12}}\Big), \tag{86}$$

$$q_{p2}^{*Stack} = \frac{1}{2}\Big(\frac{\beta_{02} - \alpha_{p2}}{\beta_{12}} + \frac{\alpha_{p1} - \alpha_{p2}}{2\alpha_a + \beta_{11} + \beta_{12}}\Big), \tag{87}$$

$$q_a^* = \frac{1}{4}\Big(\frac{\beta_{01} - \beta_{02}}{\alpha_a + \beta_{11} + \beta_{12}} + \frac{2(\alpha_{p1} - \alpha_{p2})}{2\alpha_a + \beta_{11} + \beta_{12}}\Big). \tag{88}$$

When $\beta_{01} = \beta_{02} = \beta_0$,

$$\begin{aligned} q_{p1}^{*Stack} + q_a^* = \frac{1}{2}\Big(\frac{\beta_0 - \alpha_{p1}}{\beta_{11}} + \frac{\alpha_{p2} - \alpha_{p1}}{2\alpha_a + \beta_{11} + \beta_{12}}\Big) + \frac{1}{4}\Big(\frac{\beta_0 - \beta_0}{\alpha_a + \beta_{11} + \beta_{12}} + \frac{2(\alpha_{p1} - \alpha_{p2})}{2\alpha_a + \beta_{11} + \beta_{12}}\Big) = \\ = \frac{\beta_0 - \alpha_{p1}}{2\beta_{11}} = q_{p1}^{*Mon}, \end{aligned}$$

$$\begin{aligned} q_{p2}^{*Stack} - q_a^* = \frac{1}{2}\Big(\frac{\beta_0 - \alpha_{p2}}{\beta_{12}} + \frac{\alpha_{p1} - \alpha_{p2}}{2\alpha_a + \beta_{11} + \beta_{12}}\Big) - \frac{1}{4}\Big(\frac{\beta_0 - \beta_0}{\alpha_a + \beta_{11} + \beta_{12}} + \frac{2(\alpha_{p1} - \alpha_{p2})}{2\alpha_a + \beta_{11} + \beta_{12}}\Big) = \\ = \frac{\beta_0 - \alpha_{p2}}{2\beta_{12}} = q_{p2}^{*Mon}. \end{aligned}$$

□

The formula for the point-price elasticity of demand E is:

$$E = \frac{1}{\beta_1}\frac{p}{Q}, \tag{89}$$

where β_1 is the slope of the demand, p is the price and Q is total traded quantity.[15] In the Monopoly case, the price elasticity of demand at equilibrium outcomes in two hours is:

$$E_1^{*Mon} = \frac{1}{\beta_{11}}\frac{p_1^{*Mon}}{q_{p1}^{*Mon}}, \tag{90}$$

$$E_2^{*Mon} = \frac{1}{\beta_{12}}\frac{p_2^{*Mon}}{q_{p2}^{*Mon}}. \tag{91}$$

In order to write the expressions for the price elasticity of demand in the Stackelberg case, let's analyse two situations: when the aggregator is buying power in hour $n = 1$, i.e. q_a is positive, and when it is buying power in hour $n = 2$, i.e. q_a is negative. When $\beta_{01} = \beta_{02} = \beta_0$, q_a is positive when $\alpha_{p1} > \alpha_{p2}$ and negative when $\alpha_{p1} < \alpha_{p2}$ (see equation 88).

So, when $q_a > 0$, the price elasticity of demand in two hours at the equilibrium outcomes are:

$$E_{1,q_a>0}^{*Stack} = \frac{1}{\beta_{11}}\frac{p_1^{*Stack}}{q_{p1}^{*Stack} + q_a}, \tag{92}$$

$$E_{2,q_a>0}^{*Stack} = \frac{1}{\beta_{12}}\frac{p_1^{*Stack}}{q_{p2}^{*Stack}}, \tag{93}$$

Since $q_{p1}^{*Stack} + q_a = q_{p1}^{*Mon}$ and $p_1^{*Stack} = p_1^{*Mon}$, $E_{1,q_a>0}^{*Stack} = E_1^{*Mon}$.

Since $q_{p2}^{*Stack} > q_{p2}^{*Mon}$ ($q_{p2}^{*Stack} = q_{p2}^{*Mon} + q_a$) and $p_2^{*Stack} = p_2^{*Mon}$, $E_{2,q_a>0}^{*Stack} < E_2^{*Mon}$.

When $q_a < 0$, the price elasticity of demand in two hours at the equilibrium outcomes are:

$$E_{1,q_a<0}^{*Stack} = \frac{1}{\beta_{11}}\frac{p_1^{*Stack}}{q_{p1}^{*Stack}}, \tag{94}$$

$$E_{2,q_a<0}^{*Stack} = \frac{1}{\beta_{12}}\frac{p_1^{*Stack}}{q_{p2}^{*Stack} - q_a}, \tag{95}$$

Since $q_{p1}^{*Stack} > q_p^{*Mon}$ ($q_{p1}^{*Stack} = q_{p1}^{*Mon} - q_a$) and $p_1^{*Stack} = p_1^{*Mon}$, $E_{1,q_a<0}^{*Stack} < E_1^{*Mon}$.

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[15] The price elasticity of demand usually has a negative value due to the negative slope of demand. However, in this paper, β_1 value is positive because of the inverse demand function (see equation 1). Therefore, the value of E becomes positive, too.

Since $q_{p2}^{*Stack} - q_a = q_{p2}^{*Mon}$ and $p_2^{*Stack} = p_2^{*Mon}$, $E_{2,q_a<0}^{*Stack} = E_2^{*Mon}$.

Thus, when $\beta_{01} = \beta_{02} = \beta_0$, the equilibrium prices in the Stackelberg case are equal to the equilibrium prices in the Monopoly case. If $q_a > 0$, the producer competes with the aggregator in hour $n = 1$. Price elasticity of demand in hour $n = 1$ is the same in both cases. Also, we know that the producer sells less power in the Stackelberg case than being a monopolist. In hour $n = 2$, the aggregator increases the demand and the producer sells more power in Stackelberg case than in the Monopoly case. Also, the producer targets less price elastic buyers compared to the Monopoly case. As a result, in the Stackelberg case in hour $n = 1$ the producer's profit is lower than in the Monopoly case: it sells less power at the same price. However, in hour $n = 2$, the producer sells more power than in the Monopoly case at the same price and its profit in hour $n = 2$ is higher. We can also prove that the positive change in the producer's profit is always larger then the negative change.

If $q_a > 0$, the producer competes with the aggregator in hour $n = 2$. The price elasticity of demand in hour $n = 2$ is the same in both cases. Also, we know that the producer sells less power in the Stackelberg case compared to being a monopolist. In hour $n = 1$, the aggregator increases the demand and the producer sells more than in the Monopoly case. The producer targets less price elastic buyers compared to the Monopoly case. As a result, in the Stackelberg case in hour $n = 2$, the producer's profit is lower than in the Monopoly case: the producers sells less power at the same price. Meanwhile, in hour $n = 1$, the producers sells more power at the same price and receives a larger profit in the Stackelberg case. We can prove that the positive change in the producer's profit is larger than the negative change. Therefore, the producer is always better off in the Stackelberg case when the highest bids in the market in two hours are equal.

Proposition 17. *When the highest bids in the market in both hours are equal,* $\beta_{01} = \beta_{02}$*, the producer is always better off being in a Stackelberg competition with the aggregator than being a monopolist.*

Proof. The producer is better off in the Stackelberg case when $\pi^{*Stack} - \pi^{*Mon} > 0$.

$$\pi^{*Stack} - \pi^{*Mon} = (p_1^* - \alpha_{p1})q_{p1}^{*Stack} + (p_2^* - \alpha_{p2})q_{p2}^{*Stack} - (p_1^* - \alpha_{p1})q_{p1}^{*Mon} - (p_2^* - \alpha_{p2})q_{p2}^{*Mon} =$$

$$= (p_1^* - \alpha_{p1})(q_{p1}^{*Stack} - q_{p1}^{*Mon}) + (p_2^* - \alpha_{p2})(q_{p2}^{*Stack} - q_{p2}^{Mon}) =$$

$$= \frac{(-\alpha_{p1} + \beta_0)(-\alpha_{p1} + \alpha_{p2}) + (-\alpha_{p2} + \beta_0)(\alpha_{p1} - \alpha_{p2})}{4(2\alpha_a + \beta_{11} + \beta_{12})} = \frac{(\alpha_{p1} - \alpha_{p2})^2}{4(2\alpha_a + \beta_{11} + \beta_{12})}.$$

Since $(\alpha_{p1} - \alpha_{p2})^2 > 0$ and $4(2\alpha_a + \beta_{11} + \beta_{12}) > 0$, $\pi^{*Stack} - \pi^{*Mon} > 0$. □

E.2 Price elasticity of demand and a numerical example

In a general case, analysed in the paper, one cannot tell if the price elasticity of demand at equilibrium outcomes is higher or lower in a certain case – that depends on all input variables. Therefore, instead of a general analysis, I provide a numerical example and a sensitivity analysis using the same input data as before (see Table 1).

Proposition 18. *The price elasticity of demand at the equilibrium outcomes in two hours:*

(i) in the Monopoly case is:

$$E_1^{*Mon} = \frac{\alpha_{p1} + \beta_{01}}{-\alpha_{p1} + \beta_{01}}, \tag{96}$$

$$E_2^{*Mon} = \frac{\alpha_{p2} + \beta_{02}}{-\alpha_{p2} + \beta_{02}}; \tag{97}$$

(ii) in the Stackelberg case:

- *when $q_a > 0$ is:*

$$E_{1,q_a>0}^{*Stack} = \frac{2\alpha_a\beta_{01} + (\beta_{01} + \beta_{02})\beta_{11} + 2\beta_{01}\beta_{12} + 2\alpha_{p1}(\alpha_a + \beta_{11} + \beta_{12})}{2\alpha_a\beta_{01} + (3\beta_{01} - \beta_{02})\beta_{11} + 2\beta_{01}\beta_{12} - 2\alpha_{p1}(\alpha_a + \beta_{11} + \beta_{12})}, \tag{98}$$

$$E_{2,q_a>0}^{*Stack} = -\frac{(2\alpha_a + \beta_{11} + \beta_{12})(2(\alpha_{p2} + \beta_{02})(\alpha_a + \beta_{11}) + (2\alpha_{p2} + \beta_{01} + \beta_{02})\beta_{12})}{2(\alpha_a + \beta_{11} + \beta_{12})((\alpha_{p2} - \beta_{02})(2\alpha_a + \beta_{11}) - (\alpha_{p1} - 2\alpha_{p2} + \beta_{02})\beta_{12})}, \tag{99}$$

- *when $q_a < 0$ is:*

$$E_{1,q_a<0}^{*Stack} = \frac{2(\alpha_{p1} + \beta_{01}) + \frac{(-\beta_{01} + \beta_{02})\beta_{11}}{\alpha_a + \beta_{11} + \beta_{12}}}{2(-\alpha_{p1} + \beta_{01} + \frac{(-\alpha_{p1} + \alpha_{p2})\beta_{11}}{2\alpha_a + \beta_{11} + \beta_{12}})}, \tag{100}$$

$$E_{2,q_a<0}^{*Stack} = \frac{2(\alpha_{p2} + \beta_{02})(\alpha_a + \beta_{11}) + (2\alpha_{p2} + \beta_{01} + \beta_{02})\beta_{12}}{2\beta_{02}(\alpha_a + \beta_{11}) - \beta_{01}\beta_{12} + 3\beta_{02}\beta_{12} - 2\alpha_{p2}(\alpha_a + \beta_{11} + \beta_{12})}. \tag{101}$$

The expressions in the Proposition 18 are based on (89)–(95).

In the numerical example, the price elasticity of demand at the equilibrium is -6,83 and -5,75 in hour $n = 1$ and hour $n = 2$ in the Monopoly case. In the Stackelberg case, the producer competes with the aggregator in hour $n = 1$ and they target slightly less elastic buyers compared to the Monopoly case (the price elasticity of demand is -6,79). In hour $n = 2$, the aggregator is increasing demand and the producer targets less elastic consumers than being a monopolist (the price elasticity of demand is -5,70).

The sensitivity analysis shows how the price elasticity of demand at the equilibrium depends on the slopes of demand, the highest bids in the market, and the producer's and the aggregator's cost.

Figure E.1 illustrates the price elasticity of demand E^{*Mon} in the Monopoly case. In both hours, it depends only on two parameters – the highest bid in the market in that hour β_0 and the marginal cost of production in that hour α_p. The dependency in both hours is the same, therefore, the graph represents the effects on E^{*Mon} in both hours: the producer targets more elastic buyers when the highest bid in the market is lower and the marginal cost of production is higher.[16]

In the Stackelberg case, the price elasticity of demand is affected by all parameters which often drive the elasticity in opposite directions. For example, the price elasticity of demand is decreasing with the increasing slope of demand in that hour and increasing with the increasing slope of demand in the other hour (see figures E.2–E.3). Similarly, it is decreasing with the increasing highest bid in the market in that hour and increasing with the increasing highest bid in the market in the other hour (see figures E.4–E.5). The producer targets more elastic buyers when the marginal cost of production is increasing in that hour and decreasing in the other (see figures E.6–E.7). Finally, the increasing aggregator's cost parameter α_a results in the higher price elasticity of demand in both hours (see figure E.8).

Figures E.9–E.15 illustrate the differences in the targeted buyers' price elasticity in the Monopoly and in the Stackelberg cases $\Delta E = E^{*Mon} - E^{*Stack}$. The price elasticity of

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[16] Notice that in figures E.1–E.15 the value of the price elasticity of demand is shown as positive.

demand is higher in the Monopoly case, but difference decreases when the slope of demand in that hour is lower and the slope of demand in the other hour is higher (see figures E.9–E.10). Depending on the highest bids in the market, the producer can choose more or less elastic buyers in the Stackelberg case in hour $n = 1$, i.e. when it is competing with the aggregator. In hour $n = 2$, the difference in elasticity is increasing with decreasing highest bids in the market in two hours (see figures E.11–E.12). Similarly, in hour $n = 2$, the producer can choose more or less elastic buyers in the Stackelberg depending on its marginal cost of production in both hours. In hour $n = 1$, the difference in elasticity is decreasing with decreasing marginal cost in hour $n = 1$, while the marginal cost in hour $n = 2$ has only a very mild effect (see figures E.13–E.14). The higher aggregator's cost parameter leads to lower differences in elasticity in both hours (see figure E.15).

From the sensitivity analysis we see that one cannot tell whether the producer will target more or less price elastic buyers in the situations when it is better off in the Stackelberg case compared to being a monopolist. In the Stackelberg case, the price elasticity of demand at equilibrium outcomes depends on all parameters affecting it in the opposite directions and cannot be used as a predictor of higher or lower profit for a producer.

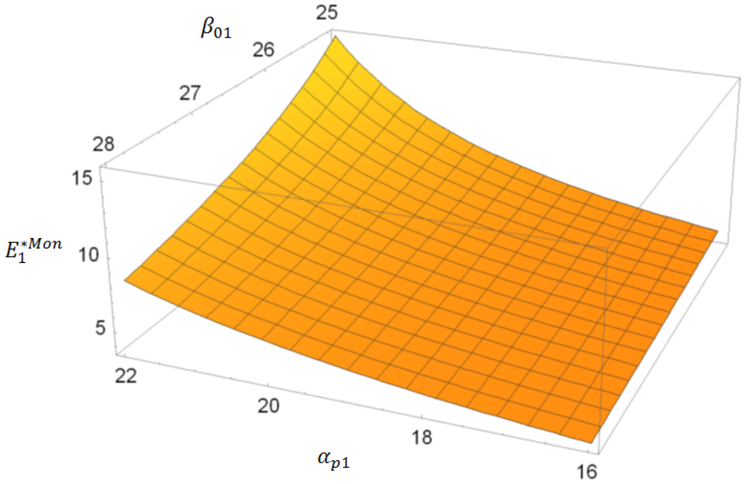

Figure E.1: The price elasticity of demand E_1^{*Mon} in hour $n = 1$ in the Monopoly case depending on the highest bid in the market β_{01} (€/MWh) and the producer's marginal cost of production α_{p1} (€/MWh) in hour $n = 1$

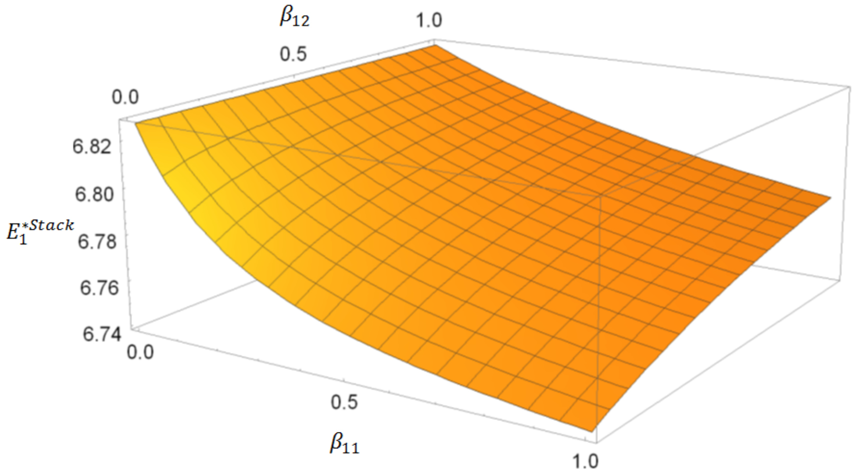

Figure E.2: The price elasticity of demand E_1^{*Stack} in hour $n = 1$ in the Stackelberg case depending on the slopes of demand β_{11} in hour $n = 1$ and β_{12} in hour $n = 2$

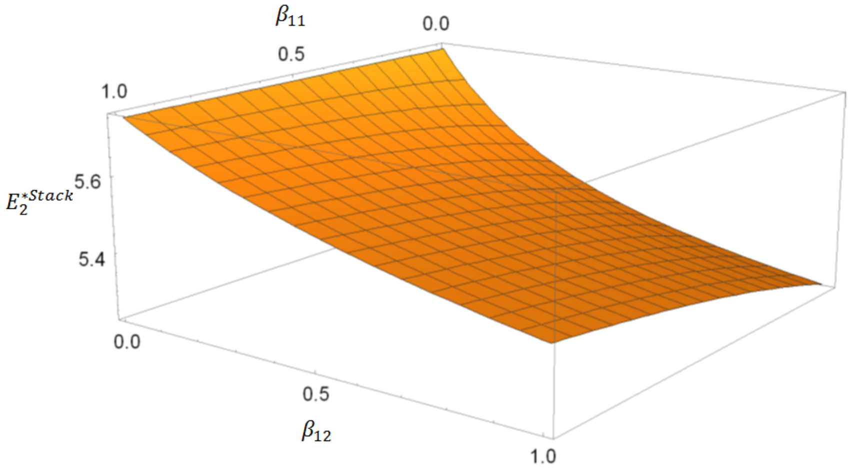

Figure E.3: The price elasticity of demand E_2^{*Stack} in hour $n = 2$ in the Stackelberg case depending on the slopes of demand β_{11} in hour $n = 1$ and β_{12} in hour $n = 2$

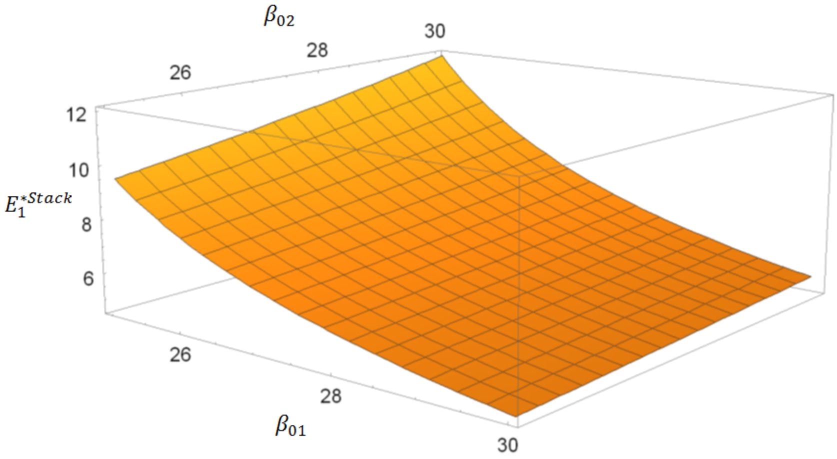

Figure E.4: The price elasticity of demand E_1^{*Stack} in hour $n = 1$ in the Stackelberg case depending on the highest bids in the market β_{01} (€/MWh) in hour $n = 1$ and β_{02} (€/MWh) in hour $n = 2$

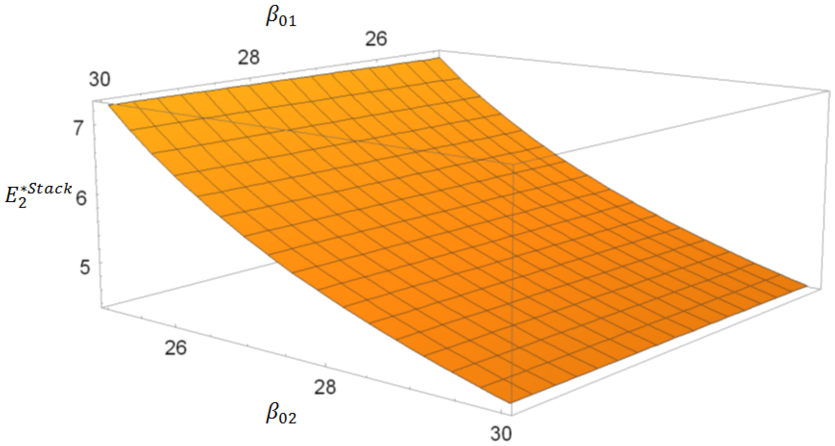

Figure E.5: The price elasticity of demand E_2^{*Stack} in hour $n = 2$ in the Stackelberg case depending on the highest bids in the market β_{01} (€/MWh) in hour $n = 1$ and β_{02} (€/MWh) in hour $n = 2$

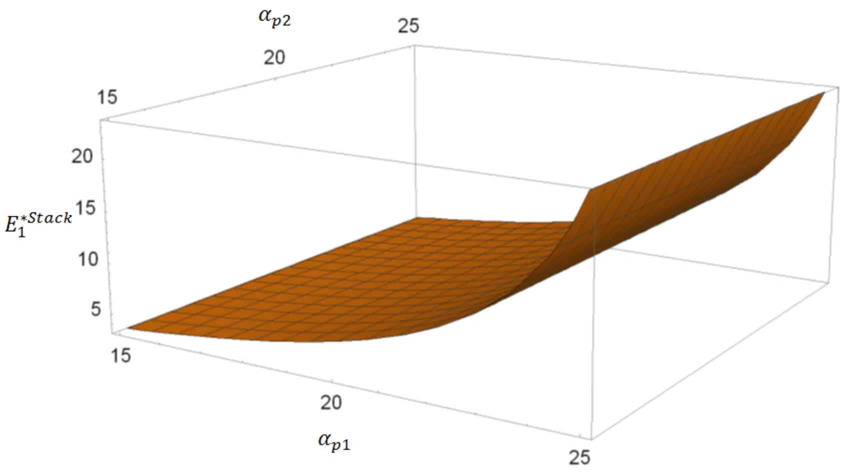

Figure E.6: The price elasticity of demand E_1^{*Stack} in hour $n = 1$ in the Stackelberg case depending on the producer's marginal cost α_{p1} (€/MWh) in hour $n = 1$ and α_{p2} (€/MWh) in hour $n = 2$

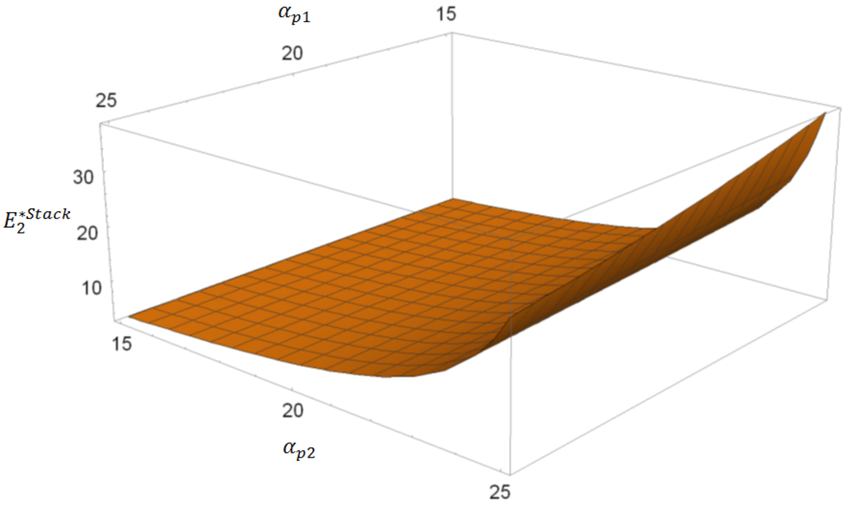

Figure E.7: The price elasticity of demand E_2^{*Stack} in hour $n = 2$ in the Stackelberg case depending on the producer's marginal cost α_{p1} (€/MWh) in hour $n = 1$ and α_{p2} (€/MWh) in hour $n = 2$

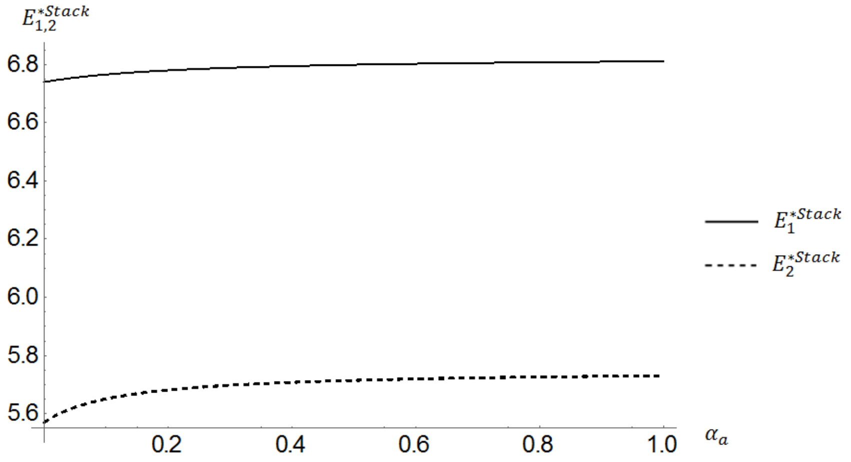

Figure E.8: The price elasticity of demand E_1^{*Stack} in hour $n = 1$ and E_2^{*Stack} in hour $n = 2$ in the Stackelberg case depending on the aggregator's cost parameter α_a (€/MWh)

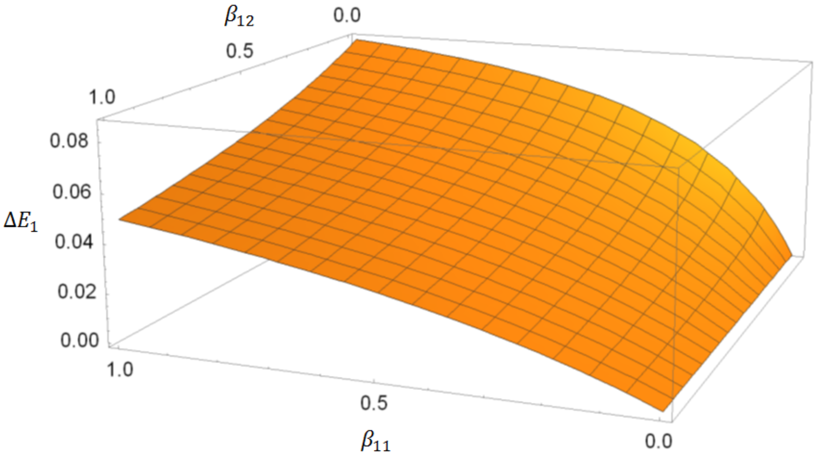

Figure E.9: The difference in the price elasticity of demand $\Delta E_1 = E_1^{*Mon} - E_1^{*Stack}$ in hour $n = 1$ in the Stackelberg and Monopoly cases depending on the slopes of demand β_{11} in hour $n = 1$ and β_{12} in hour $n = 2$

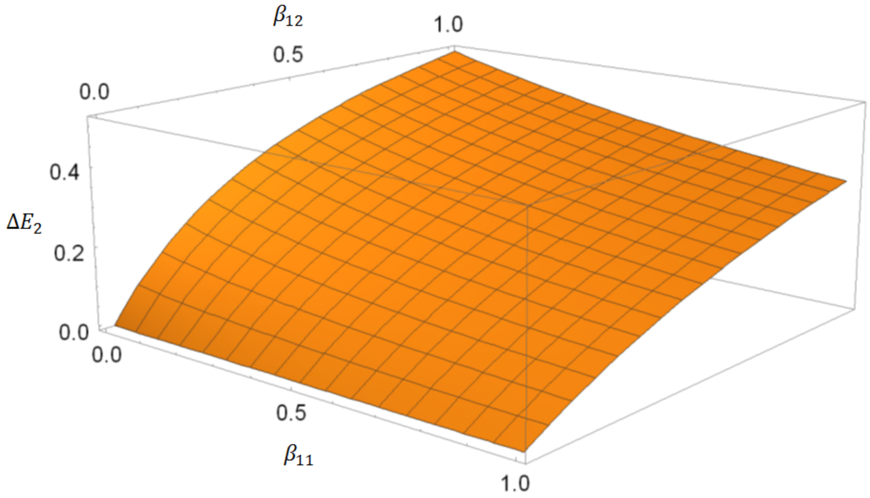

Figure E.10: The difference in the price elasticity of demand $\Delta E_2 = E_2^{*Mon} - E_2^{*Stack}$ in hour $n = 2$ in the Stackelberg and Monopoly cases depending on the slopes of demand β_{11} in hour $n = 1$ and β_{12} in hour $n = 2$

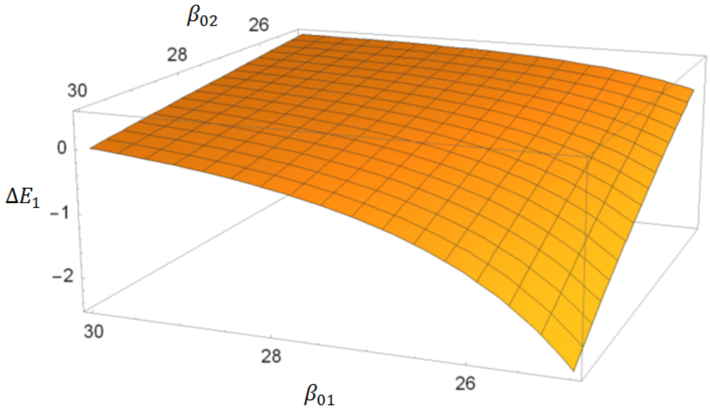

Figure E.11: The difference in the price elasticity of demand $\Delta E_1 = E_1^{*Mon} - E_1^{*Stack}$ in hour $n = 1$ in the Stackelberg and Monopoly cases depending on the highest bids in the market β_{01} (€/MWh) in hour $n = 1$ and β_{02} (€/MWh) in hour $n = 2$

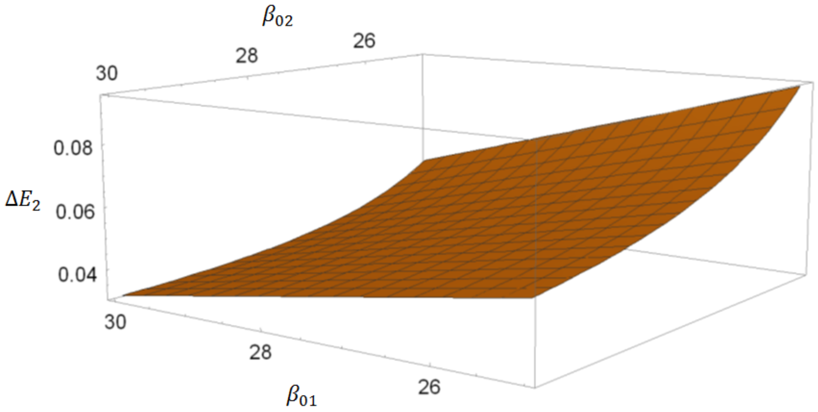

Figure E.12: The difference in the price elasticity of demand $\Delta E_2 = E_2^{*Mon} - E_2^{*Stack}$ in hour $n = 2$ in the Stackelberg and Monopoly cases depending on the highest bids in the market β_{01} (€/MWh) in hour $n = 1$ and β_{02} (€/MWh) in hour $n = 2$

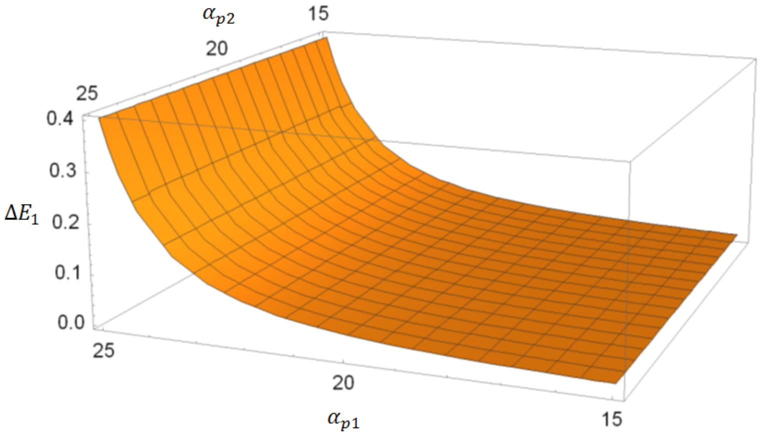

Figure E.13: The difference in the price elasticity of demand $\Delta E_1 = E_1^{*Mon} - E_1^{*Stack}$ in hour $n = 1$ in the Stackelberg and Monopoly cases depending on the producer's marginal cost α_{p1} (€/MWh) in hour $n = 1$ and α_{p2} (€/MWh) in hour $n = 2$

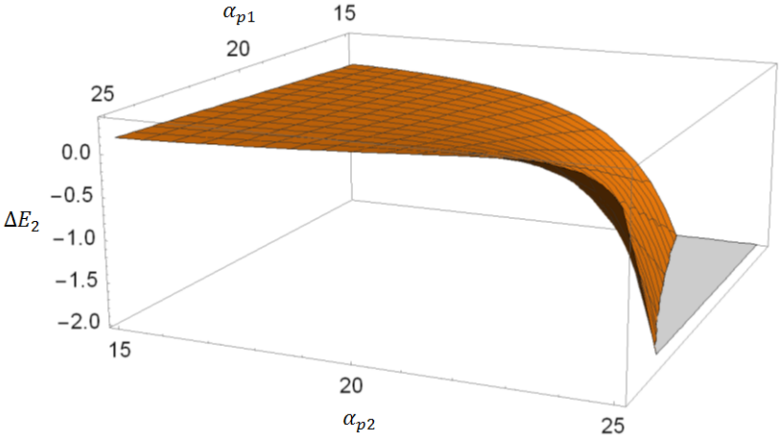

Figure E.14: The difference in the price elasticity of demand $\Delta E_2 = E_2^{*Mon} - E_2^{*Stack}$ in hour $n = 2$ in the Stackelberg and Monopoly cases depending on the producer's marginal cost α_{p1} (€/MWh) in hour $n = 1$ and α_{p2} (€/MWh) in hour $n = 2$

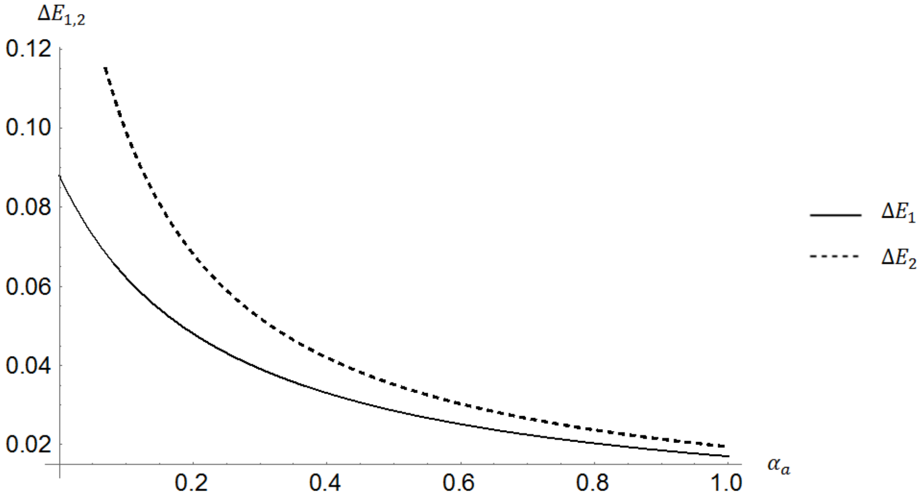

Figure E.15: The difference in the price elasticity of demand $\Delta E_1 = E_1^{*Mon} - E_1^{*Stack}$ in hour $n = 1$ and $\Delta E_2 = E_2^{*Mon} - E_2^{*Stack}$ in hour $n = 2$ in the Stackelberg and Monopoly cases depending on the aggregator's cost parameter α_a (€/MWh)

Appendix F Proofs

F.1 The proof of Proposition 3

Proof. The producer is strictly better off in a Stackelberg competition with the aggregator than being a monopolist if $\pi_p^{*Sta} - \pi_p^{*Mon} > 0$, where the expressions for the producer's profit as a monopolist π_p^{*Mon} and in a Stackelberg competition with the aggregator π_p^{*Sta} are provided in Proposition 1 and Proposition 2. Thus, the inequality $\pi_p^{*Sta} - \pi_p^{*Mon} > 0$ can be written as:

$$\frac{1}{8}\Big(\frac{2(\alpha_{p1}-\beta_{01})^2}{\beta_{11}} + \frac{2(\alpha_{p2}-\beta_{02})^2}{\beta_{12}} - \frac{(\beta_{01}-\beta_{02})^2}{\alpha_a+\beta_{11}+\beta_{12}} + \frac{2(\alpha_{p1}-\alpha_{p2})^2}{2\alpha_a+\beta_{11}+\beta_{12}}\Big) - \frac{\beta_{11}(\alpha_{p2}-\beta_{02})^2+\beta_{12}(\alpha_{p1}-\beta_{01})^2}{4\beta_{11}\beta_{12}} > 0.$$

Through algebra, it can be simplified as:

$$\frac{(\alpha_{p1}-\alpha_{p2})^2}{4(2\alpha_a+\beta_{11}+\beta_{12})} - \frac{(\beta_{01}-\beta_{02})^2}{8(\alpha_a+\beta_{11}+\beta_{12})} > 0.$$

Since $4(2\alpha_a+\beta_{11}+\beta_{12}) > 0$, it can be written as:

$$(\alpha_{p1}-\alpha_{p2})^2 > (\beta_{01}-\beta_{02})^2\frac{2\alpha_a+\beta_{11}+\beta_{12}}{2\alpha_a+2(\beta_{11}+\beta_{12})},$$

where $0 < \frac{2\alpha_a+\beta_{11}+\beta_{12}}{2\alpha_a+2(\beta_{11}+\beta_{12})} < 1$. □

F.2 The proof of Proposition 5

Proof. In the Stackelberg case, the adjusted consumer surplus is reduced when the aggregator enters the intraday market if $CS^{adj,Stack} - CS^{ajd,Mon} < 0$. The adjusted consumer surpluses are provided in Proposition 6 and the latter inequality can be written as:

$$\frac{1}{32(\alpha_a+\beta_{11}+\beta_{12})^2}\Big(\frac{(2\alpha_a\beta_{01}+\beta_{11}(3\beta_{01}-\beta_{02})+2\beta_{01}\beta_{12}-2\alpha_{p1}(\alpha_a+\beta_{11}+\beta_{12}))^2}{\beta_{11}} + \frac{(-2\beta_{02}(\alpha_a+\beta_{11})+\beta_{12}(\beta_{01}-3\beta_{02})+2\alpha_{p2}(\alpha_a+\beta_{11}+\beta_{12}))^2}{\beta_{12}}\Big) - \frac{1}{8}\Big(\frac{(\alpha_{p1}-\beta_{01})^2}{\beta_{11}} + \frac{(\alpha_{p2}-\beta_{02})^2}{\beta_{12}}\Big) < 0. \quad (102)$$

Through algebra, it can be simplified as:

$$\frac{(\beta_{01}-\beta_{02})\big(4(\alpha_a+\beta_{11}+\beta_{12})(\alpha_{p2}-\alpha_{p1})+(\beta_{01}-\beta_{02})(4\alpha_a+5(\beta_{11}+\beta_{12}))\big)}{32(\alpha_a+\beta_{11}+\beta_{12})^2}<0. \quad (103)$$

Since $32(\alpha_a+\beta_{11}+\beta_{12})^2>0$, then:

$$(\beta_{01}-\beta_{02})\big(4(\alpha_a+\beta_{11}+\beta_{12})(\alpha_{p2}-\alpha_{p1})+(\beta_{01}-\beta_{02})(4\alpha_a+5(\beta_{11}+\beta_{12}))\big)\;<\;0. \quad (104)$$

For the latter inequality to hold, we must have:

(i) $(\beta_{01}-\beta_{02})>0$ and
$4(\alpha_a+\beta_{11}+\beta_{12})(\alpha_{p2}-\alpha_{p1})+(\beta_{01}-\beta_{02})(4\alpha_a+5(\beta_{11}+\beta_{12}))<0$ or

(ii) $(\beta_{01}-\beta_{02})<0$ and
$4(\alpha_a+\beta_{11}+\beta_{12})(\alpha_{p2}-\alpha_{p1})+(\beta_{01}-\beta_{02})(4\alpha_a+5(\beta_{11}+\beta_{12}))>0$.

Since $4(\alpha_a+\beta_{11}+\beta_{12})>0$, through algebra it can be written as:

(i) $\beta_{01}>\beta_{02}$ and
$\alpha_{p1}-\alpha_{p2}>(\beta_{01}-\beta_{02})\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}$ or

(ii) $\beta_{01}<\beta_{02}$ and
$\alpha_{p1}-\alpha_{p2}<(\beta_{01}-\beta_{02})\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}$.

Notice that $4\alpha_a+5(\beta_{11}+\beta_{12})<4\alpha_a+4(\beta_{11}+\beta_{12})$, therefore $\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}>1$. In order for both inequalities in (i) or (ii) to hold, we must have that

(i) $\alpha_{p1}>\alpha_{p2}$ and
$\beta_{01}>\beta_{02}$ and $\alpha_{p1}-\alpha_{p2}>(\beta_{01}-\beta_{02})\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}$.
If $\alpha_{p1}\leq\alpha_{p2}$, then one of the inequalities in (i) would not hold.

(ii) $\alpha_{p1}<\alpha_{p2}$ and
$\beta_{01}<\beta_{02}$ and $\alpha_{p1}-\alpha_{p2}<(\beta_{01}-\beta_{02})\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}$.
If $\alpha_{p1}\geq\alpha_{p2}$, then one of the inequalities in (ii) would not hold.

□

F.3 The proof of Proposition 6

Proof. The conditions for the producer to increase its profit when the aggregator participates in the intraday market are provided in Proposition 3. The conditions for the reduction of the adjusted consumer surplus are stated in Proposition 5. Following these conditions, one can find the intervals where all intraday market participants benefit from the aggregator's presence at the market. Thus, we know that the producer is better off when:

$$(\alpha_{p1} - \alpha_{p2})^2 > (\beta_{01} - \beta_{02})^2 \frac{2\alpha_a + \beta_{11} + \beta_{12}}{2\alpha_a + 2(\beta_{11} + \beta_{12})}, \tag{105}$$

Similarly, like in the proof of Proposition 5, for the adjusted consumer surplus to be higher, $CS^{adj,Stack} - CS^{Mon} > 0$, we must have:

(i) $\beta_{01} > \beta_{02}$ and
$\alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}$;

Or

(ii) $\beta_{01} < \beta_{02}$ and
$\alpha_{p1} - \alpha_{p2} > (\beta_{01} - \beta_{02})\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}$.

Notice that $4\alpha_a + 5(\beta_{11} + \beta_{12}) > 4\alpha_a + 4(\beta_{11} + \beta_{12})$, therefore $\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})} > 1$. In order for both inequalities in (i) or (ii) to hold, we must have that

(i) $\beta_{01} > \beta_{02}$:

- $\beta_{01} > \beta_{02}$ and $\alpha_{p1} > \alpha_{p2}$ and
  $\alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}$, or

- $\beta_{01} > \beta_{02}$ and $\alpha_{p1} < \alpha_{p2}$ and
  $\alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a+5(\beta_{11}+\beta_{12})}{4\alpha_a+4(\beta_{11}+\beta_{12})}$, which is always satisfied;

Or

(ii) $\beta_{01} < \beta_{02}$:

- $\beta_{01} < \beta_{02}$ and $\alpha_{p1} > \alpha_{p2}$ and
  $\alpha_{p1} - \alpha_{p2} > (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11}+\beta_{12})}{4\alpha_a + 4(\beta_{11}+\beta_{12})}$, which is always satisfied, or

- $\beta_{01} < \beta_{02}$ and $\alpha_{p1} < \alpha_{p2}$ and
  $\alpha_{p1} - \alpha_{p2} > (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11}+\beta_{12})}{4\alpha_a + 4(\beta_{11}+\beta_{12})}$.

In order for all market participants to be better off:

(i) $\beta_{01} > \beta_{02}$:

- $\beta_{01} > \beta_{02}$ and $\alpha_{p1} > \alpha_{p2}$ and
  $\alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11}+\beta_{12})}{4\alpha_a + 4(\beta_{11}+\beta_{12})}$ (condition for $CS^{adj,Stack} > CS^{Mon}$)
  and
  $(\alpha_{p1} - \alpha_{p2})^2 > (\beta_{01} - \beta_{02})^2\frac{2\alpha_a + \beta_{11}+\beta_{12}}{2\alpha_a + 2(\beta_{11}+\beta_{12})}$ (condition for the producer to benefit)

  Since $\alpha_{p1} - \alpha_{p2}$ and $\beta_{01} - \beta_{02}$ are positive values, after taking square roots we can write the latter inequalities as:

$$(\beta_{01} - \beta_{02})\sqrt{\frac{2\alpha_a + \beta_{11} + \beta_{12}}{2\alpha_a + 2(\beta_{11} + \beta_{12})}} < \alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11} + \beta_{12})}{4\alpha_a + 4(\beta_{11} + \beta_{12})}; \tag{106}$$

  or

- $\beta_{01} > \beta_{02}$ and $\alpha_{p1} < \alpha_{p2}$ and
  $(\alpha_{p1} - \alpha_{p2})^2 > (\beta_{01} - \beta_{02})^2\frac{2\alpha_a + \beta_{11}+\beta_{12}}{2\alpha_a + 2(\beta_{11}+\beta_{12})}$ (condition for the producer to benefit).
  $\alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11}+\beta_{12})}{4\alpha_a + 4(\beta_{11}+\beta_{12})}$ is always satisfied and $CS^{adj,Stack} > CS^{Mon}$;

Or

(ii) $\beta_{01} < \beta_{02}$:

- $\beta_{01} < \beta_{02}$ and $\alpha_{p1} > \alpha_{p2}$ and
  $(\alpha_{p1} - \alpha_{p2})^2 > (\beta_{01} - \beta_{02})^2\frac{2\alpha_a + \beta_{11}+\beta_{12}}{2\alpha_a + 2(\beta_{11}+\beta_{12})}$ (condition for the producer to benefit).

$\alpha_{p1} - \alpha_{p2} > (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11}+\beta_{12})}{4\alpha_a + 4(\beta_{11}+\beta_{12})}$ is always satisfied and $CS^{adj,Stack} > CS^{Mon}$;

or

- $\beta_{01} < \beta_{02}$ and $\alpha_{p1} < \alpha_{p2}$ and
  $\alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11}+\beta_{12})}{4\alpha_a + 4(\beta_{11}+\beta_{12})}$ (condition for $CS^{adj,Stack} > CS^{Mon}$)
  and
  $(\alpha_{p1} - \alpha_{p2})^2 > (\beta_{01} - \beta_{02})^2 \frac{2\alpha_a + \beta_{11} + \beta_{12}}{2\alpha_a + 2(\beta_{11}+\beta_{12})}$ (condition for the producer to benefit).

Since $\alpha_{p1} - \alpha_{p2}$ and $\beta_{01} - \beta_{02}$ are negative values, after taking square roots we can write the latter inequalities as:

$$(\beta_{01} - \beta_{02})\sqrt{\frac{2\alpha_a + \beta_{11} + \beta_{12}}{2\alpha_a + 2(\beta_{11}+\beta_{12})}} < \alpha_{p1} - \alpha_{p2} < (\beta_{01} - \beta_{02})\frac{4\alpha_a + 5(\beta_{11}+\beta_{12})}{4\alpha_a + 4(\beta_{11}+\beta_{12})}. \tag{107}$$

□

Appendix G The differences in the producer's revenue and cost in both cases

G.1 The difference in the producer's revenue

The producer's total revenue in the Monopoly case R_p^{*Mon} is:

$$R_p^{*Mon} = q_{p1}^{*Mon} p_1^{*Mon} + q_{p1}^{*Mon} p_1^{*Mon} = \frac{1}{4}\Big(\frac{\beta_{01}^2 - \alpha_{p1}^2}{\beta_{11}} + \frac{\beta_{02}^2 - \alpha_{p2}^2}{\beta_{12}}\Big). \tag{108}$$

The producer's total revenue in the Stackelberg case R_p^{*Stack} is:

$$R_p^{*Stack} = q_{p1}^{*Stack} p_1^{*Stack} + q_{p1}^{*Stack} p_1^{*Stack} = \\ \frac{1}{4}\Big(\frac{\beta_{01}^2 - \alpha_{p1}^2}{\beta_{11}} + \frac{\beta_{02}^2 - \alpha_{p2}^2}{\beta_{12}}\Big) - \frac{1}{8}\Big(\frac{(\beta_{01} - \beta_{02})^2}{\alpha_a + \beta_{11} + \beta_{12}} + \frac{2(\alpha_{p1} - \alpha_{p2})^2}{2\alpha_a + \beta_{11} + \beta_{12}}\Big). \tag{109}$$

Thus, the difference in the producer's total revenue in the Stackelberg and the Monopoly case ΔR_p is:

$$\Delta R_p = R_p^{*Stack} - R_p^{*Mon} = -\frac{1}{8}\Big(\frac{(\beta_{01} - \beta_{02})^2}{\alpha_a + \beta_{11} + \beta_{12}} + \frac{2(\alpha_{p1} - \alpha_{p2})^2}{2\alpha_a + \beta_{11} + \beta_{12}}\Big). \tag{110}$$

From the latter equation we see that the difference is never positive and the producer's total revenue in the Stackelberg case is always lower or equal to its total revenue in the Monopoly case.

G.2 The difference in the producer's cost

The producer's total cost in the Monopoly case C_p^{*Mon} is:

$$C_p^{*Mon} = q_{p1}^{*Mon}\alpha_{p1} + q_{p1}^{*Mon}\alpha_{p2} = \frac{\alpha_{p1}(\beta_{01} - \alpha_{p1})}{2\beta_{11}} + \frac{\alpha_{p2}(\beta_{02} - \alpha_{p2})}{2\beta_{12}}. \tag{111}$$

The producer's total cost in the Stackelberg case C_p^{*Stack} is:

$$C_p^{*Stack} = q_{p1}^{*Stack}\alpha_{p1} + q_{p1}^{*Stack}\alpha_{p2} = \frac{\alpha_{p1}(\beta_{01} - \alpha_{p1})}{2\beta_{11}} + \frac{\alpha_{p2}(\beta_{02} - \alpha_{p2})}{2\beta_{12}} - \frac{(\alpha_{p1} - \alpha_{p2})^2}{2(2\alpha_a + \beta_{11} + \beta_{12})}. \tag{112}$$

Thus, the difference in the producer's total cost in the Stackelberg and the Monopoly case ΔC_p is:

$$\Delta C_p = C_p^{*Stack} - C_p^{*Mon} = -\frac{(\alpha_{p1} - \alpha_{p2})^2}{2(2\alpha_a + \beta_{11} + \beta_{12})}. \tag{113}$$

From the latter equation we see that the difference is never positive and the producer's total cost in the Stackelberg case is always lower or equal to its total cost in the Monopoly case.

Appendix H Additional figures for Equilibrium analysis section

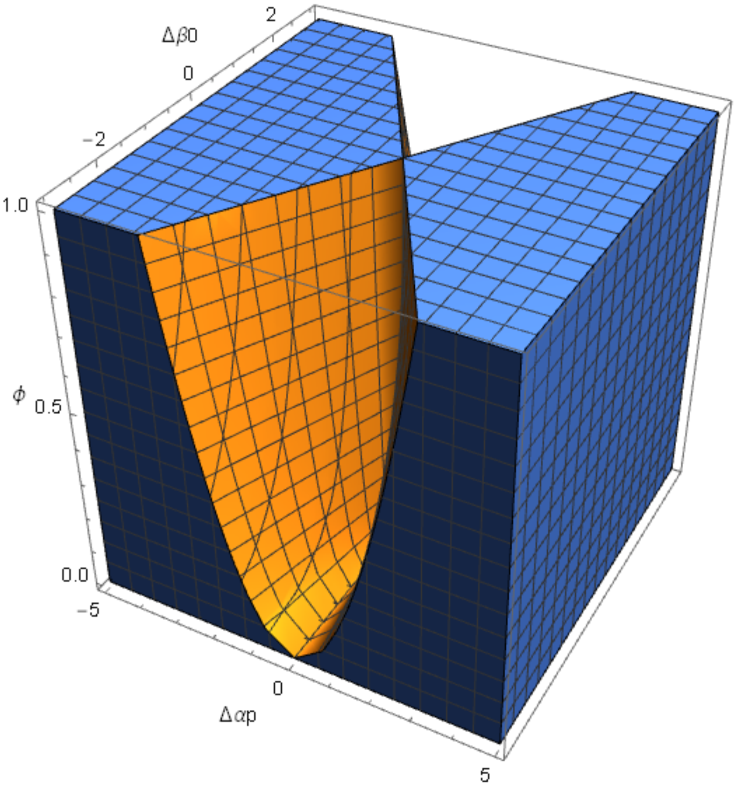

Figure H.1: Area illustrating when the producer benefits from being in a competition with the aggregator in the intraday market depending on $\Delta\alpha_p$, $\Delta\beta_0$ and ϕ (3D graph)

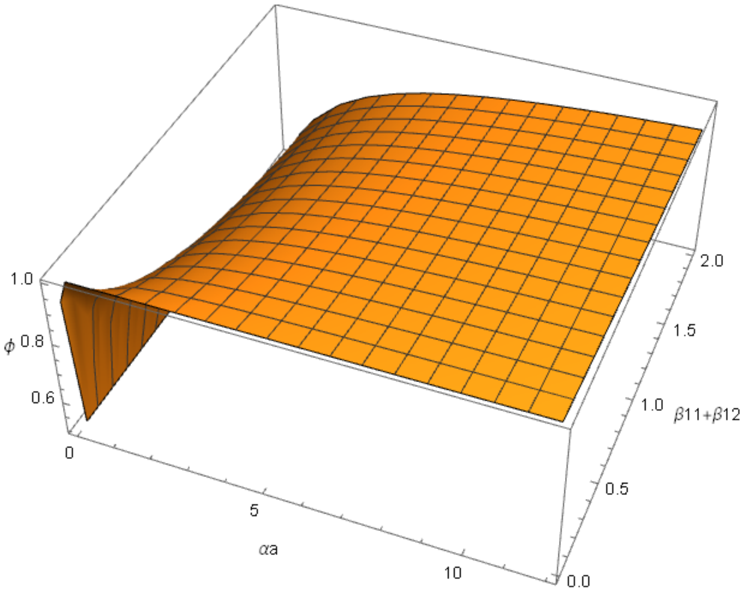

Figure H.2: Changes in ϕ due to changing α_a and β_1 in hours $n = 1$ and $n = 2$

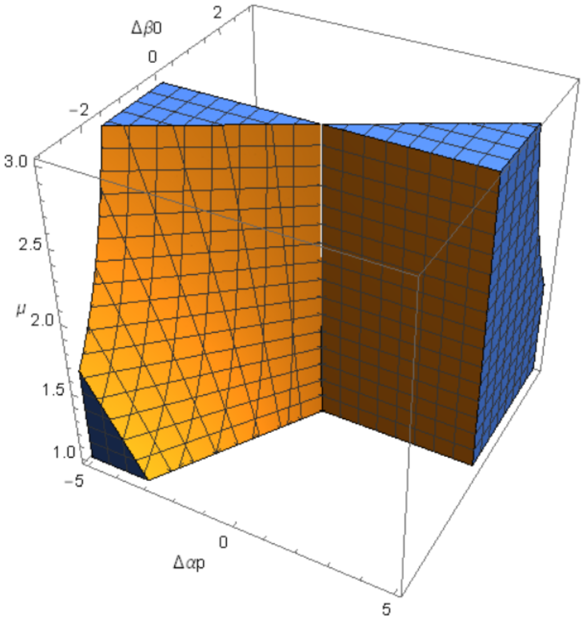

Figure H.3: Area illustrating when the adjusted consumer surplus is reduced due to the presence of the aggregator in the intraday market depending on $\Delta\alpha_p$, $\Delta\beta_0$ and μ

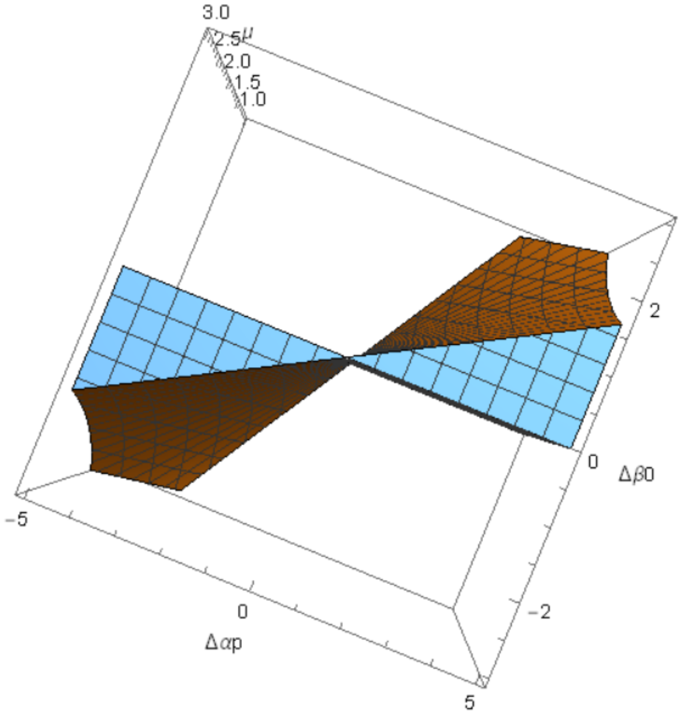

Figure H.4: Area illustrating when the adjusted consumer surplus is reduced due to the presence of the aggregator in the intraday market depending on $\Delta\alpha_p$, $\Delta\beta_0$ and μ (a different angle)

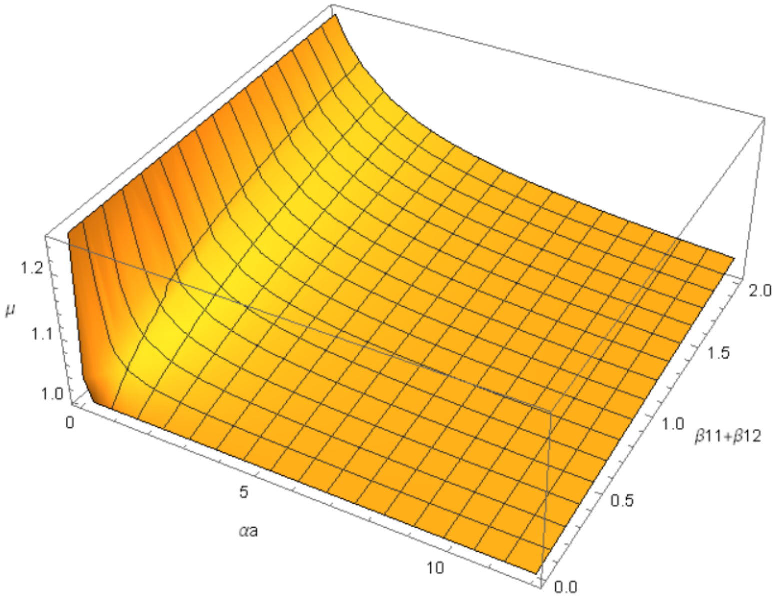

Figure H.5: Changes in μ due to changing α_a and β_1 in hours $n = 1$ and $n = 2$

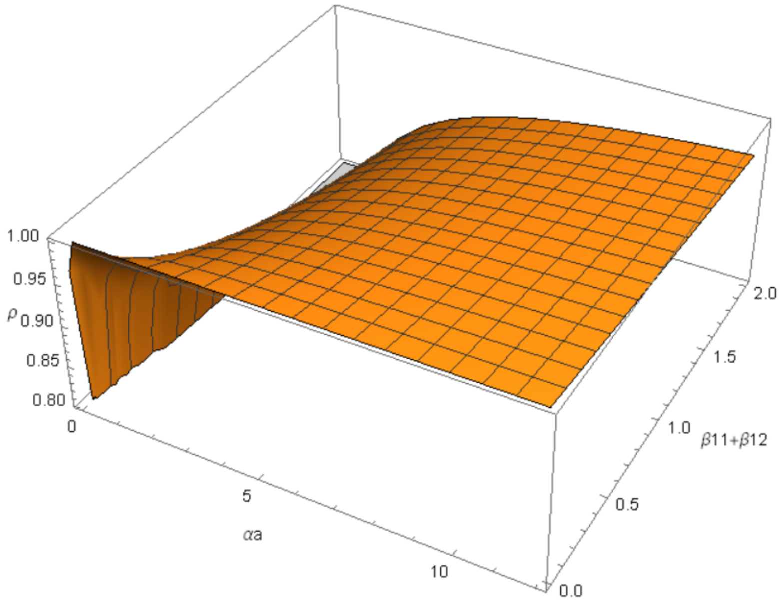

Figure H.6: Changes in ρ due to changing α_a and β_1 in hours $n = 1$ and $n = 2$

Appendix I The difference in the original consumers' consumer surplus

The original consumers' consumer surplus in the Monopoly and the Stackelberg case differ due to different quantities that the producer and the aggregator are offering to them in each hour. The quantities available to the original consumers are denoted $Q_1^{*adj,Stack}$ and $Q_2^{*adj,Stack}$ and are equal to:

$$Q_1^{*adj,Stack} = q_{p1}^{*Stack} + q_a^*, \tag{114}$$

$$Q_2^{*adj,Stack} = q_{p2}^{*Stack} - q_a^*. \tag{115}$$

The difference in the original consumers' consumer surplus in the Stackelberg and the Monopoly case ΔCS^{*adj} can be written as:

$$\Delta CS^{*adj} = \frac{\beta_{11}}{2}(Q_1^{*adj,Stack} - Q_1^{*Mon}) + \frac{\beta_{12}}{2}(Q_2^{*adj,Stack} - Q_2^{*Mon}). \tag{116}$$

Here Q_1^{*Mon} and Q_2^{*Mon} are the producer's offered quantities in both hours. It is hard to tell from the first glance, whether the difference is positive or negative. For example, if the producer's marginal cost is higher in the first hour, it sells less in hour $n = 1$ and more in hour $n = 2$ compared to the Monopoly case; if the aggregator is selling power in the first hour, i.e. q_a^* is positive, it is not obvious whether Q_1^{*Mon} is more or less than $Q_1^{*adj,Stack}$. Similarly, in the second hour, it is hard to tell if in the Stackelberg case the producer increases its offered quantity by a larger amount than bought by the aggregator. In addition, the total effect to the difference in original consumers' consumer surpluses is affected by different weights for the quantities in each hour, $\beta_{11}/2$ and $\beta_{12}/2$. Proposition 5 and Proposition 6 show that under certain market conditions this difference can be negative or positive.

Appendix J Estimation of β_0 and β_1

The inverse demand function at the intraday market is expressed as $p(Q) = \beta_0 - \beta_1 Q$. To find the intercept β_0 and the slope β_1 for one hour, we need two points indicating quantities and respective prices.

The total amount of traded energy at the intraday market in hour 02.00 on January 19, 2017 is 25,0 MWh and the lowest accepted bid order is 22,5 €/MWh, which determines the first point. The second point is indicated by the highest accepted bid order, 27,2 €/MWh, and zero quantity. Thus, we are solving a simple system of two equations with two unknowns:

$$\begin{cases} 22,5 = \beta_0 - 25,0\beta_1 \\ 27,2 = \beta_0 - 0\beta_1 \end{cases}, \tag{117}$$

which gives $\beta_0 = 27,2$ and $\beta_1 = 0,188$.

Similarly, for hour 03.00, the system of equations is:

$$\begin{cases} 26,0 = \beta_0 - 20,0\beta_1 \\ 27,0 = \beta_0 - 0\beta_1 \end{cases}, \tag{118}$$

which gives $\beta_0 = 27,0$ and $\beta_1 = 0,05$.

Appendix K Demand flexibility data and the use of refrigeration processes in the demand-side management

Refrigerator is one of the home appliances that accounts for a considerable amount of annual household energy consumption. According to the DONG Energy El & Gas AS report on electricity consumption of households in Denmark (DONG Energy, 2013), an average annual consumption of a household living in a house is 4500 kWh. Depending on the size, type and production year, the consumption of a refrigerator can vary between 71 kWh to 548 kWh per year: refrigerator with freezer, 220+90 l, old – 548 kWh; refrigerator with freezer, 220+66 l, new – 293 kWh; refrigerator, 240 l, old – 290 kWh; refrigerator, 290 l, new – 71 kWh.

Energy consumption pattern, or refrigeration cycle, is another important factor determining the potential for load shifting. An ordinary household refrigerator with fresh food storage compartment and frozen food storage compartment, 141 l and 79 l respectively, modelled in (Cheng et al., 2011), uses 186 kWh per year (0,51 kWh per 24 hours). Its total cycle time is 61,6 minutes: on-time – 21 minute, off-time – 40,6 minutes.

In the presented numerical example, the aggregator controls a number of refrigerators, each consuming 0,0335 kWh per hour. Thus, for instance, to accumulate 10 MWh of shiftable load per hour the aggregator should have an access to control around 300 thousands domestic refrigerators. In order to pool larger amounts of shiftable refrigeration load, the aggregator could also include small commercial refrigerators and commercial refrigeration systems in refrigerated warehouses and food retailing (Grein and Pehnt, 2011).

Appendix L Additional figures for Sensitivity analysis section

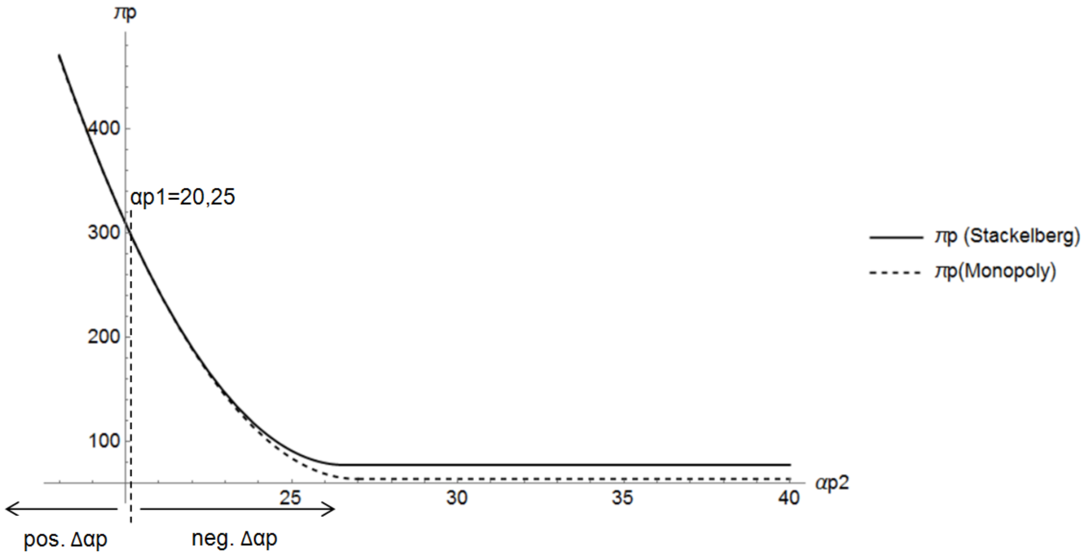

Figure L.1: The producer's profit π_p in the Stackelberg and Monopoly cases depending on its marginal cost α_{p2}, €

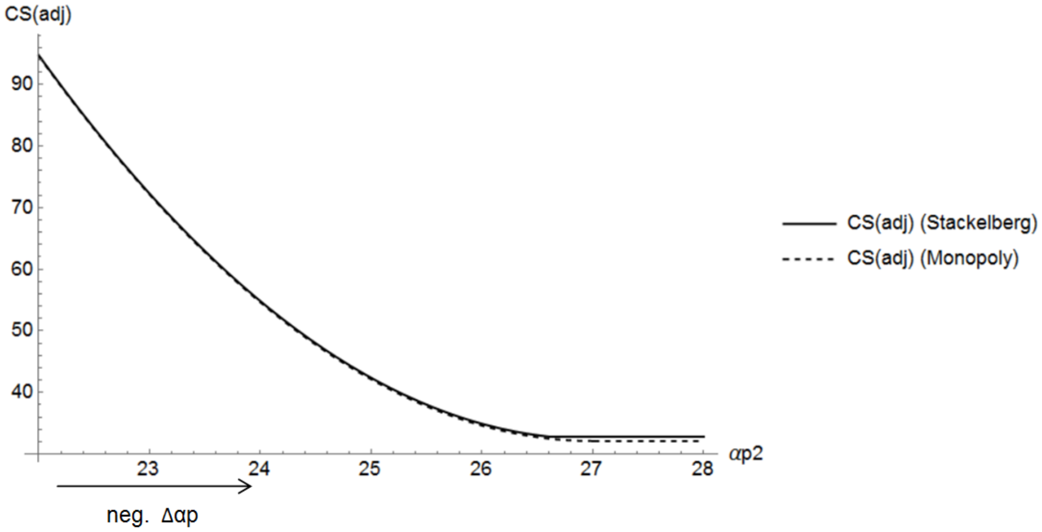

Figure L.2: The adjusted consumer surplus CS^{adj} in the Stackelberg and Monopoly cases depending on the producer's marginal cost α_{p2}, €

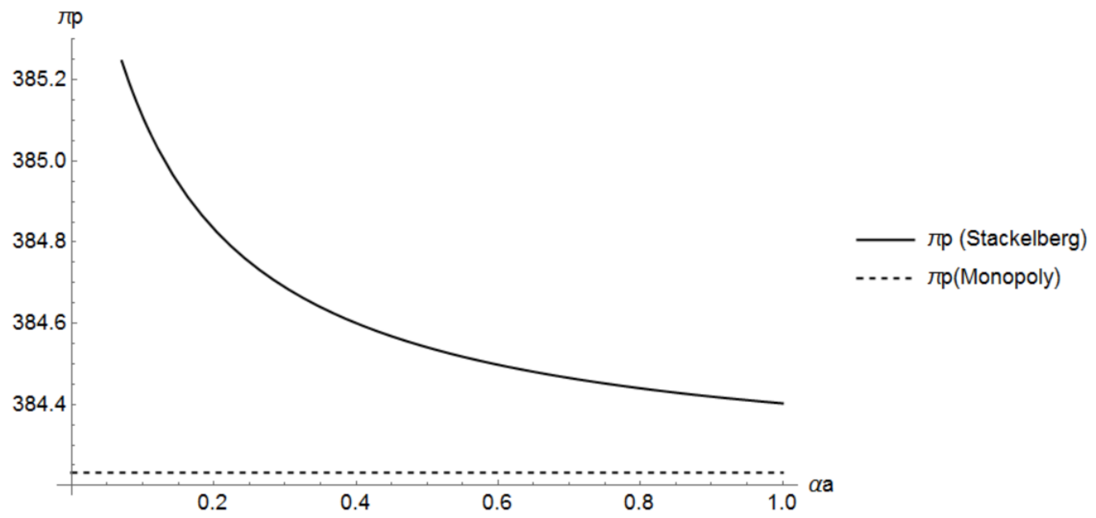

Figure L.3: The producer's profit π_p in the Stackelberg and Monopoly cases depending on the aggregator's marginal cost parameter α_a, €

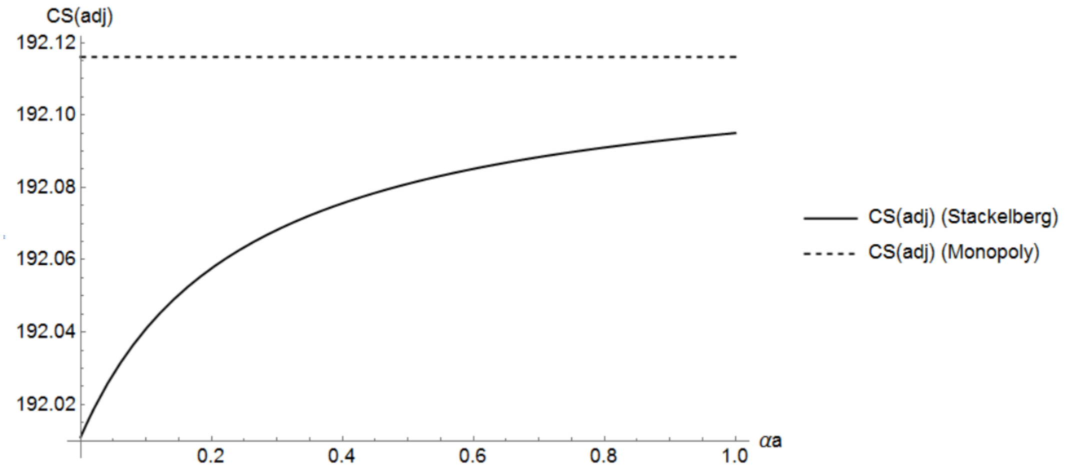

Figure L.4: The adjusted consumer surplus CS^{adj} in the Stackelberg and Monopoly cases depending on the aggregator's marginal cost parameter α_a, €

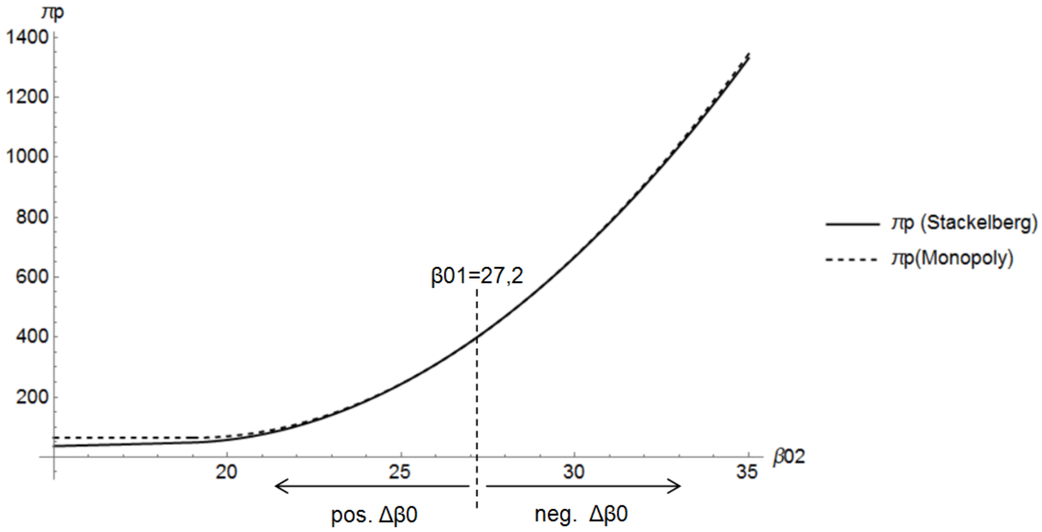

Figure L.5: The producer's profit π_p in the Stackelberg and Monopoly cases depending on the highest bid order at the intraday market β_{02}, €

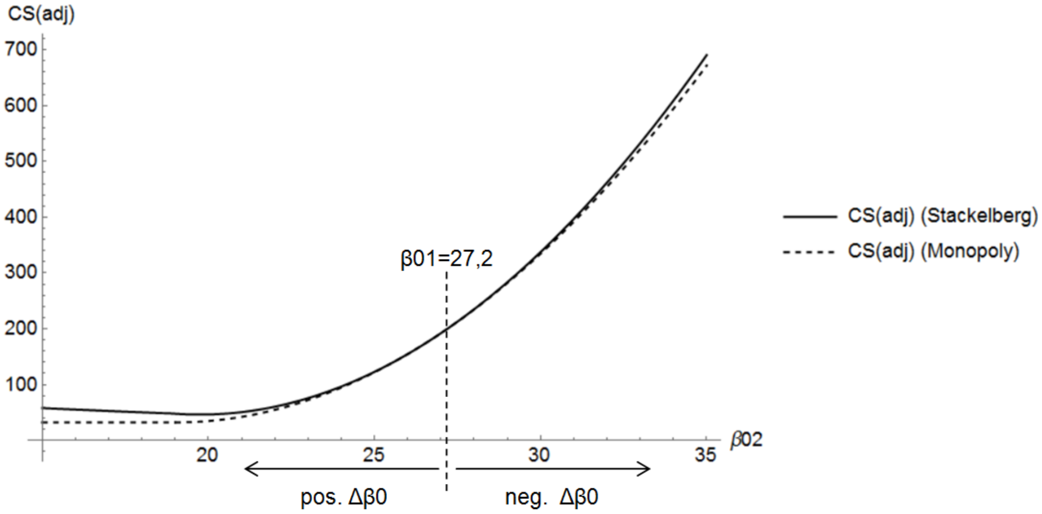

Figure L.6: The adjusted consumer surplus CS^{adj} in the Stackelberg and Monopoly cases depending on the highest bid order at the intraday market β_{02}, €

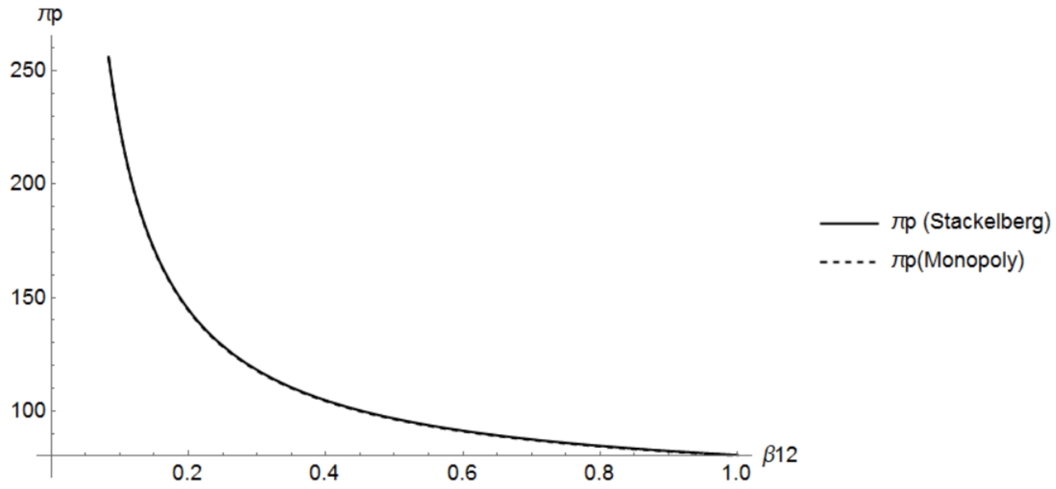

Figure L.7: The producer's profit π_p in the Stackelberg and Monopoly cases depending on the slope of demand β_{12}, €

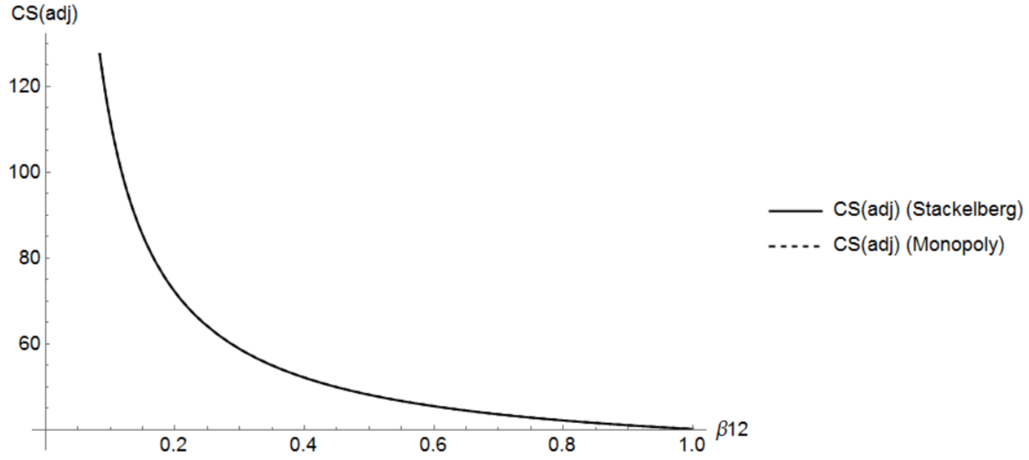

Figure L.8: The adjusted consumer surplus CS^{adj} in the Stackelberg and Monopoly cases depending on the slope of demand β_{12}, €

Conclusion

This Ph.D. thesis contributes to the demand-side management literature by providing the analysis of the flexible demand aggregator's effects on the electricity markets and the welfare of power consumers. The three chapters examine the entrance of the aggregator in the power markets from different perspectives: the aggregator's, a large power consumer's and the producer's.

The first chapter focuses on the performance of the aggregator, which has a portfolio of different flexibility sources: EVs, HPs and/or such home appliances like washing machines, dryers and dish washers. I investigated the effects of the portfolio choice on the imbalance payments and compensation to consumers that provide flexibility using Nord Pool power market data for Denmark's bidding area DK2. The results show that different compositions of flexibility sources influence both the imbalance payments and compensation to consumers. However, there is no significant additional value in combining all flexibility sources in one portfolio unless there is a fixed contract cost. Thus, it is likely that the aggregator would choose to specialise in certain types of flexibility sources. In addition, I found that the compensation for provided flexibility is very low and would hardly incentivise the consumers to participate in demand-side management programs.

The second chapter studies the aggregator's presence in the market from a large power consumer's with flexible load perspective. It investigates whether the cooperative governance structures in flexible electricity demand aggregation and trading could bring value to the market participants and final power consumers compared to situations where demand flexibility is traded individually or via the investor owned aggregator. A large consumer is not likely to offer its flexibility directly to the intraday market, since the transaction cost, that include fixed flexible demand coordination cost and market access fees are too high. The results show that when large consumers have no possibility to form a cooperative and offer their flexibility to the aggregator, the aggregator absorbs the profit. However, large consumers yield a profit if they form a cooperative and compete with the aggregator. Thus, cooperative governance structures lowers the equilibrium market prices and leads to the highest consumer surplus.

The third chapter analyses the aggregator's presence in the intraday market from the producer's perspective and investigates whether the flexible demand aggregator's presence in the intraday market can reduce the consumer surplus of power buyers and increase the profit to the competing producer. A game-theoretic approach is used to compare market equilibrium outcomes two cases: Monopoly case, where only the producer sells power in the intraday market, and Stackelberg case, where the producer competes with a smaller aggregator. The results suggest that under certain market conditions and the producer's marginal cost in different hours, the producer is strictly better off being in a competition with the aggregator than selling power in the intraday market as a monopolist. However, under favourable market conditions, another outcome is also possible: all market participants can be better off when the aggregator is trading flexibility in the intraday market.

The demand-side management and the aggregation of flexible demand will undoubtedly contribute to the successful integration of large renewable energy amounts in the power systems and will be a useful tool to deal with the power system stability challenges. However, in terms of implementing the demand-side management, it is important to understand that among many advantages of a new market player offering flexible demand aggregation services there are some negative aspects too that need to be investigated further.

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Creativity as Balancing 'Constrainedness'

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    relationsopbygning?

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