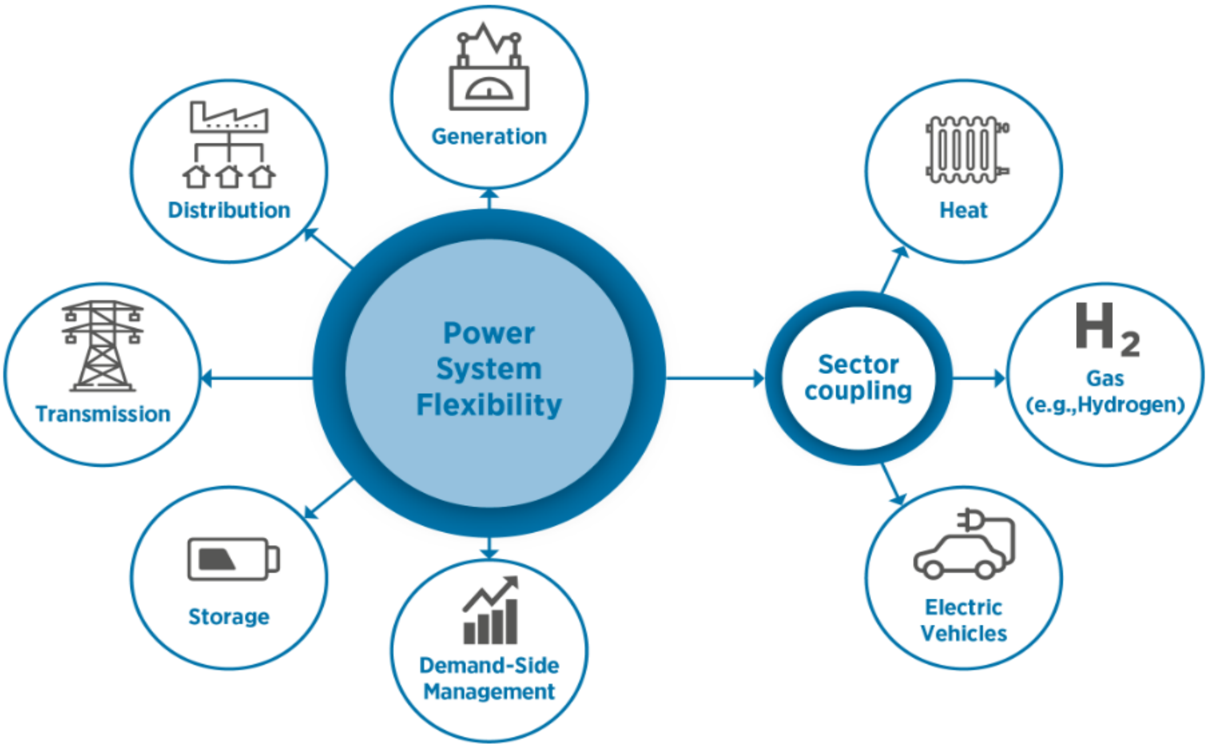

Optimal Aggregation of Demand Side Resources for Power System Flexibility

Jonasz Jan Firlej

Electrical Power Systems and High Voltage Technology, EPSH4-1033, 2022-05

Master Thesis

STUDENT REPORT
AALBORG UNIVERSITY

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During the work on the thesis, MatLAB software was used.

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Abstract:

The thesis investigates the techniques that may be used by an aggregating company for better utilization of the assets owned by its clients to obtain profits by taking into account the volatility of energy prices on the Day-Ahead Market. In further parts of the thesis a concept of energy cluster is analysed, with focus on how aggregation can not only benefit the retailer, but also the members of such energy community, by helping them fulfill their objectives on decreasing their dependence on external resources. Not only the price incentives' and optimization algorithms' influence will be simulated, but also further development of a microgrid i.e. additional installations that may contribute to this cause.

Summary

Due to climate reasons, power systems are going through a process of energy transition away from fossil fuels towards renewable energy sources and energy efficiency. Most of such low-emission generation facilities are located closer to the end-users and connected directly to the distribution grid instead of transmission grid like large central power plants have always been.

Many such installations are not owned by energy companies, but by the same people or entities that consume the energy at the end. They are interested in utilizing as much of locally generated energy as possible, not to completely rely on the supply from the national grid, which delivers energy at higher prices. Many people share the same interests and would like to work together and form an energy cluster, where these generation resources, as well as some of controllable loads could be shared to achieve those goals.

This requires coordination and management, which can be achieved by selecting different end-users that want to share their distributed assets to utilize them as efficiently as possible. This process is called aggregation and can be performed by companies that want to increase their business activity from retail supply of electricity services to more active role in shaping the demand curve over time. Increasing the resources managed by a single entity, which is an aggregator in this case, allows it to take part in energy market game as small players are not permitted to bid on most energy exchanges.

Aggregator can use different tools to optimize his business portfolio. In second and third chapter of the thesis, different pricing mechanisms and optimization algorithms are introduced and their impact on the demand side management and resulting profits is presented.

Fourth chapter investigates the concept of energy clusters and microgrids deeper. Different aggregation techniques are shown based on the tools presented in previous chapters to assess their performance when they are applied together on a given pool of available resources in different proportions. Further, influence of increasing the microgrid by adding different newly installed resources like larger generation capacity or introduction of energy storage is evaluated and compared with only influencing the consumption of original components using price incentives or op-

timization algorithms.

Fifth chapter contains detailed discussion about the results obtained from the simulations and discuss the impact of aggregators and energy clusters on different players present in the energy sector. It will also mention different business opportunities available for aggregators that were not part of the project.

Last chapter will conclude the work on the project and propose future work.

Preface

This project is conducted by a student in the 10th semester at Aalborg University as a part of the Electrical Power Systems and High Voltage Master's program. The theme of the semester is *Master's thesis*, and the project's title is *Optimal Aggregation of Demand Side Resources for Power System Flexibility*. The project investigates the techniques that may be used for optimization of aggregation of various distributed resources.

The author would like to thank his supervisors Jayakrishnan Radhakrishna Pillai and Sanjay Chaudhary from AAU for guidance, inspiration, and valuable, constructive feedback during the project period.

Readers guide

Figures and tables in the report are numbered within the respective chapter. The first digit indicates the number of the chapter, while the second digits stand for the number of the figure inside the chapter (e.g. Figure 2.3 is the third figure in the second chapter). Explanatory text is found under the given figures and above the tables. On page **ix**, a Table of Contents is given. When viewing this report as a PDF, hyperlinks in the table of contents will allow fast navigation to the desired sections. The bibliography can be found on page 65. The entries are sorted in order of their appearance in the text. The appendices can be found after the bibliography and are labelled with letters. If a source is used to cite a specific piece of information, the source will appear before the period [source no.]. If a paragraph paraphrases information from a source, it will appear after the period at the end of the paragraph. [source no.]

Aalborg University, May 26, 2022

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Chapter 1

Introduction

In this chapter, the motivation and background of the project are presented. Afterwards, further problem analysis is drawn to point out potential challenges. In the end, based on the problem analysis, a research question for this project is stated.

1.1 Motivation

Power systems in recent years have been going through significant changes. Climate change which is a major political and environmental issue is being caused by greenhouse gases emissions coming mainly from burning fossil fuels to produce energy, which is utilized as electrical energy, thermal energy for heating purposes or to power the vehicles, equipped with an internal combustion engine (ICE), used for transport. Climate policy requires major changes in our energy systems. Firstly it focuses on transforming the electrical energy generation away from fossil fuels into low- or zero-carbon technologies like nuclear energy or renewable energy sources (RES) such as hydropower, wind turbines or photovoltaic (PV) panels. A quarter of the entire CO2 emission comes from the electrical energy generation plants powered by fossil fuels [1]. For the energy transformation to be successful, also other factors must be taken into account, those are the security of supply and low economic cost for the final consumers. Second aspect of today's climate policy is the electrification of the sectors that have been using fossil fuels directly, without conversion into electrical form of energy, those are in particular transportation and heating. People right now are facing a strong diffusion of electric vehicles (EVs), which are replacing ICE cars, and heat pumps (HPs) which are being serve for heating purposes instead of traditionally used gas, oil or coal fired boilers.

Both aspects of this energy transformation - changes in the generation and electrification of further sectors - lead to significant changes in the power systems. Most of the newly built low-carbon energy sources (PV panels and wind turbines) rely on the natural phenomena that are stochastic and do not provide a stable power supply which is independent on the weather and time of the day. Electrification of further sectors in the meantime increases the amount of energy that needs to be produced. In recent years, power system and the generators in particular have to face negative energy prices, which means that in such period of negative prices, the generator pays the consumer to use the energy, often when the consumer was not going to consume it before, but such monetary gratification persuades him to do. Such situation occurs when there is a big surplus of generation exceeding the consumption and the possibilities of export. It is obviously undesired from the generators' and system's point of view and it may be more profitable to just stop the production when negative prices occur. However with further diffusion of RES it is expected that such situations will be more common. [2]

This leads to a change in the paradigm of the power system. Traditionally, large centralized power plants are connected to the transmission lines, energy flows further through distribution lines to the final consumers and the power generation follows the changing load to match it. Power systems of the future will have more distributed generation (directly connected to distribution grid or even the consumers) and will not be able to generate energy at any time like fossil fuel, nuclear or hydro power plants. Also such smaller units will likely have more limited ability to control and to provide ancillary network services like frequency control. For this reason a lot of focus is given to solutions that can alter the demand for energy to make it closer to the generation output from stochastic energy sources or to store energy for later use.

Change in the paradigm is also labelled as the change from generation-follows-load towards load-follows-generation. This is a big challenge for power system operator as a lot of consumption is not controllable and energy must be supplied to it at any time. For this reason, controllable loads start having a stronger role in energy management, as they can consume energy at the more desired moment (from the power system's point of view). Many of the controllable loads are large industrial consumers, but with occurring electrification of heating and transportation sector there is more flexibility available also among smaller consumers including residential. However such small players like households can't usually take part in the energy markets and their flexibility would not be utilized in the most efficient way. For this reason many companies have been founded, that act as a middle-man between such small consumers and the system operator. Such companies will be called aggregators later in the thesis, as they aggregate flexible loads from different smaller consumers and take part in various energy markets as a single player offering its assets, very similarly to the retailers today [3][4]. Typically they act as a *virtual power plant*, as by decreasing the consumption of some users a similar effect is achieved to increasing the generation output from producers, however their activity on energy markets and business models may differ [4]. Grid utilities are strongly interested in using these distributed assets in an aggregated way for the purpose of improving the performance of power systems, increase the flexibility of the entire system to make it work better during the further diffusion of RES, most of which operate stochastically and facilitate grid ancillary services.

To be efficient, aggregators must choose the end-users they aggregate wisely and develop good framework that would benefit both them and the consumers that offer their loads to be party managed by an aggregator. It is requires similar actions to energy retailers, that buy energy on different energy markets like day-ahead, futures or spot market at variable prices and later sell it to the end-users typically at a flat tariff, independent from the volatile prices on energy exchanges. However to encourage the end-users owning flexible resources like EVs to join an aggregation scheme, different incentives must be used. Consumers must be divided into different groups depending on their consumption pattern and willingness to offer different amounts of flexibility to the aggregator. Data from smart meters, which are being installed widely can be used to schedule the consumption and prepare better for trading session on the energy exchange. Many of the load owners are also prosumers, having PV panels installed in their households or small wind turbines (especially in rural areas). Those assets can also be integrated into the portfolio of the aggregator to obtain further monetary profits. Crucial for the development of aggregators market is the availability of load data in dense time intervals. Rights of such prosumers are desribed in directive [5] on the promotion of the use of energy from renewable sources. Danish implementation of this directive is known as Market Model 3.0 - [6] and it describes many potential solutions to develop larger flexibility, such as making the access to the market easier for more actors, regular forecasting of market development, publishing network development plans etc.

1.2 Problem formulation

As mentioned in section 1.1 aggregators are not just retailers and therefore the framework of their relationship with the end-users must be different. The end-user is offering his flexible assets like an EV to be used by some extent by the aggregator, based on the information on prices at the energy markets. For giving up some of the freedom of charging his EV whenever he wants, the consumer agrees to alter his load for a certain reward. Such framework may include when the consumer must use the energy with the flexible loads, how much energy should he consume and how the aggregator may control the consumption of the consumer. Continuing with the example of an EV and its charging station, the parties may agree on the time at which the car must be connected to the charger and how the aggregator may control the charging speed. However, aggregator may still have some clients in his portfolio for whom he acts only like a retailer. [3]

Aggregated demand has different characteristics and flexibility in particular, depending on the selection of consumers and the framework of the partnership between aggregator and clients. Aggregation should be optimized in terms of economic profits, congestion management and customers comfort, also taking into account the constraints coming from electrical grid, customer's preferences and rules of chosen energy markets. It also has to take into account the diversity of the loads - both spacial, as the geographic distance can make a big difference and temporal, as for example a bakery will have its largest consumption when households have their lowest. Aggregator is responsible for developing his portfolio in a way he can be a reliable player and take part in different energy markets. [3]

For this reason the chosen flexible and variable loads must be modelled in order to develop relevant and reliable algorithms and methodology to aggregate large enough amounts of loads in order to take part in the transactions on the energy markets. Using collected data and developed models energy consumption may be scheduled with different accuracy for different time-frame and based on that the aggregator may offer his assets on different energy markets like day-ahead market and balancing market or purchase energy to fulfill the customers' demands.

Such aggregator should also take into account the generation from distributed generation that consumers would like to consume on their own as in most scenarios they are the owners of PV panels or some wind turbines and would like to utilize the self-produced energy, as it is cheaper for them than buying energy from the national grid. What can also be taken into account are the possibilities to store energy and feed in into the national grid or using it internally by the consumers taking part in the aggregation scheme. The assets that could be contained in aggregator's portfolio and his relationship with the larger market players can be seen in the Figure 1.1. [3]

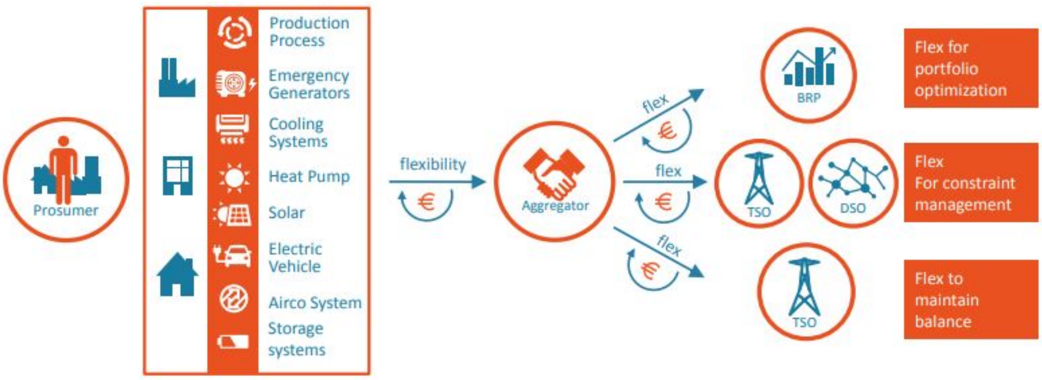

Figure 1.1: Aggregators relationship with the end-users and energy market [3]

Optimization should focus on the mentioned factors - maximizing the utilization of self-produced renewable energy and maximizing the economic profit, while ensuring the safety of supply and preventing congestions. For this reason different components of the aggregator's portfolio must be modelled in a realistic and reliable way and different aggregation techniques and incentives for end-users must be developed and tested and the results must be compared and analysed.

1.3 Project objectives

The main objective of the project is to develop a relevant model for aggregation of a larger number of flexible loads and distributed generation. This is aimed to maximize the energy consumed, which comes from RES, ensuring economical and reliable operation of the grid, as well as to provide guidelines for optimal aggregation and flexible operation of demand-side participating parties. To successfully achieve the project objective, some working subtasks have been concluded:

- Analyse the flexibility provided by different installations that may be subject to aggregation like EVs, HPs and distributed generation like PV panels, wind turbines as well as energy storage solutions
- Develop models for energy consumption from individual flexible loads such as EVs and develop similar models for energy generation from distributed power plants like PV panels and wind turbines
- Develop and explain in detail different methods to optimally aggregate the loads from various consumers and their different behaviour
- Analyse the chosen aggregation methods for enhancing the self-consumption from RES with regard to the energy prices occurring at different times and for the resulting economic profit

1.4 Methodology

For the purpose of achieving the project objectives, firstly a sufficient literature study must be performed. Analysis of the state of the art of the considered technologies will be crucial to develop reliable model and create effective aggregation and schedule algorithms. Second field, which will be analysed for the state of the art, is the analysis of selected energy markets like the day-ahead market.

Based on the literature review, relevant energy consumption and generation models are built in MatLAB, different for different technologies and various consumer's behaviour. It is followed by development of different aggregation methods and selection of consumers. Based on the simulations, different improvements for the aggregation can be introduced and the results of these improvements are analysed.

Main tool for analysis will be MatLAB.

1.5 Limitations and assumptions

The project has several limitations and assumptions that need to be taken into account:

- There is a infinite number of aggregation scenarios, as a different number and type of consumers may be aggregated and there are unlimited options on how many and which consumers should be included. For this reason only selected aggregation scenarios can be simulated and analysed.
- Only selected technologies will be modelled. Variety of loads in the power system is vast and many of them must be simplified and cannot be modelled in very precise way.
- Project will not analyse dynamic behaviour in short time-scale. Time intervals will be 1 hour long and based on the data from 2021 and 2020 (if the latter is necessary).
- Economic part of the analysis will take into account only the prices from the Day-Ahead Market. Intra-day and intra-hour market services are not considered in the project. It is assumed that aggregator does not purchase energy from different sources at different prices, for example he does not have any long-term supply contracts.
- Any energy trade between the end-users under the aggregator is neglected. It is assumed that all energy generated by distributed sources is to be used by all consumers under the aggregation scheme.
- DSOs and TSOs grid constraints and economic model will not be considered. Economic calculations take into account only the trade of energy, excluding taxes and transmission and distribution fees
- Energy exported to the external grid does not impact the aggregator's income. It is assumed that the owner of RES gets all money from selling energy from his installation to the end-users outside of analysed area.

1.6 Content of the report

Chapter 2 of this thesis will introduce the state of the art, which will explain the characteristics of the electricity market, role and business principles of aggregators, as well as the operational properties and energy consumption of different technologies that are used in distributed generation and flexible consumption.

Chapter 3 will, firstly show how different controllable loads within the power system that will be aggregated can be modelled individually, and secondly explain the charging mechanisms and pricing schemes that can be used to shape the electricity demand over time. Different pricing schemes will be further simulated to compare the economic results and the most profitable pricing mechanisms will be chosen for further analysis.

Chapter 4 will introduce the concept of energy clusters and microgrids. Based on the simulations performed in previous chapter, the components that have been modelled will be put together and aggregated. Different shares of the loads will be tested to check which is the most efficient economically and in terms of utilization of locally generated renewable energy. Proposed energy cluster will be complemented with some stochastic and random events that haven't been considered in chapter 3. It will also be simulated how additional resources influence the results.

Chapter 5 will include a detailed discussion on the considered problem based on the results from simulations in the previous chapters. It will propose solutions that could further improve the performance of optimization algorithms. It will also discuss interests of parties that haven't been considered in the project and evaluate if the objectives were successfully fulfilled.

Chapter 6 will conclude the content of entire report and propose the future work.

Chapter 2

Grid assets and markets considered for load aggregation

In this chapter, the brief description of various electricity markets, relevance of aggregators and state-of-the-art on flexibility from distributed energy resources are presented. It will introduce the characteristics of a day-ahead and spot market in Europe and the mechanism of how the prices are being determined. Further, different grid assets that are considered as either flexible loads or distributed renewable generation will be presented to form a theoretical basis of the modelling of them in MatLAB.

2.1 Electricity market

2.1.1 Brief history of energy market liberalization in Europe

Starting in the 1990s in the Nordic countries, the trade of energy between suppliers and different consumers, as well as middle-men, was a subject to wide liberalization, deregulation and demonopolization. Power exchanges, as we know them today, were established to serve the purpose of determining the prices for different markets, as energy became a more differentiated commodity and can be traded separately depending on the time of purchase and delivery. Such markets for electricity are day-ahead market, intraday market, balancing market, futures market, options market etc. Modern power exchanges also trade with CO2 allowances or with different energy fuels like gas or coal.

Liberalization in the Nordic countries was quickly followed by the EU and in 1996, 2003, 2009 and 2019 four liberalization directives were published and member states had to reform their energy sectors to match the new European law. Current law regarding the energy markets in Europe can be found in [7], which is an EU directive on common rules for the internal market for electricity and amending Directive 2012/27/EU.

The UK was going through electricity market liberalization around the same time as Nordic countries. It is labelled as a benchmark, as it was a strongly regulated sector with large state ownership in one of the largest countries in Europe. For this reason main components of liberalization reform that other countries with similarities to the UK's energy market could follow are often called 'the British model', which according to [8] includes six main elements:

- creation of a wholesale spot market as the main price-setting arena
- creation of retail competition so that all consumers can choose their electricity supplier
- corporate separation of network activities from activities that would be market-driven
- corporate separation between generation and retail supply
- adoption of incentive regulation to set the prices for monopoly activities
- sale of publicly-owned assets to private investors

Figure 2.1 shows the relationships between different market players in a liberalised energy market. It shows that operation of the electricity grids and technical management of a power system is clearly separated from the trade of energy as a commodity. [9]

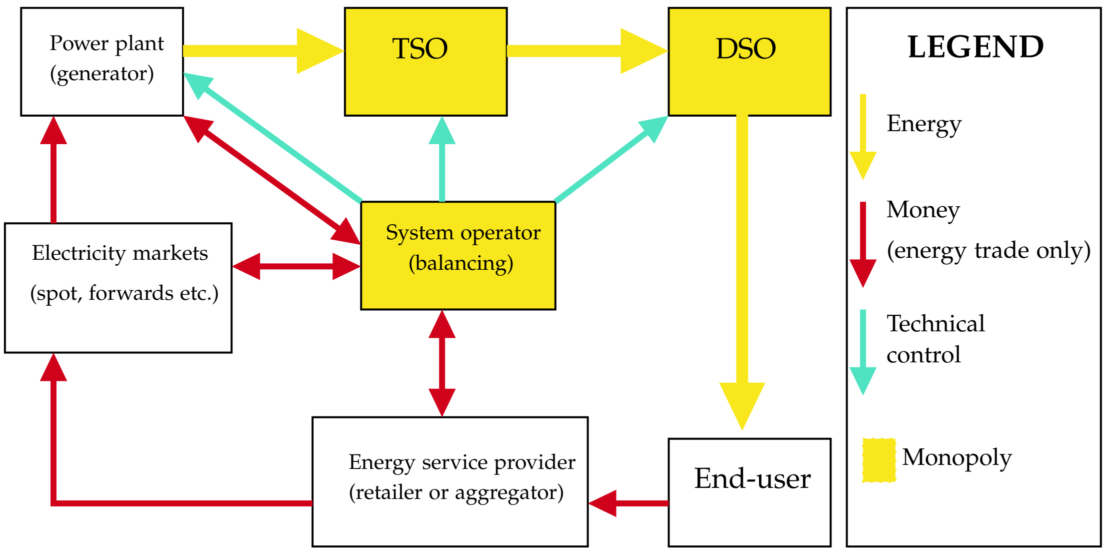

Figure 2.1: Simplified diagram showing different roles in a liberalised electricity market

2.1.2 Types of markets

In order to understand the differences between electricity markets, terms from theory of economics should be used that describe various market types and financial products that can be observed not only in energy markets, but also on financial or food markets. They have been explained in a detailed way in appendix A. Therefore Table 2.1 will only give examples of those market types and financial products in terms of electricity markets in Europe.

Type of market	Examples on electricity markets
Spot market	Nord-Pool Elbas
Forward market	Nord-Pool Elspot (day-ahead market) Long-term bilateral contracts
Futures contracts	EEX Power Futures
Options	EEX Power Options
Contracts for differences	Usually a public support tool for some energy generation investments

Table 2.1: Summary of market types

2.1.3 Characteristics of day-ahead market and the mechanism behind pricing

Energy can be traded on several markets in different ways. Those market types are explained in details in appendix A, where terms like spot market, forwards, futures or options are introduced.

Day-ahead market, as the name suggests, is used to trade the energy that will be produced, delivered and consumed the day after the trading session. The product traded on the market is energy, that will be delivered at a specific, given time on the next day. Therefore for example, energy delivery at a time period between 10 and 11 AM is traded completely independently from energy delivery between 3 and 4 PM, as it was a different commodity.

One of the leading energy exchanges that manages the day-ahead market is Nord-Pool and prices there are determined using, what is called a merit order [10]. The sellers (which are typically the generators) offer their assets at a marginal cost and are later ranked based on an ascending order of price. Marginal cost is the change of the total cost of production when quantity increases by a certain unit i.e. cost of producing one more unit of a certain good. Sellers' bids tell us the minimum price at which they are willing to sell energy and those prices create a supply curve by an ascending order. Similarly a demand curve is determined based on the buyers' bids on how much they are willing to pay (maximum price a buyer can accept) for a certain amount of energy at a given time in a descending order. Later the two curves are compared and the price at which both meet is the final price at which energy will be delivered at a given time. This price is called a market clearing price. At the same time the volume of the traded energy is determined, which is called market clearing volume. The mechanism is presented in the Figure 2.2. [10] [4]

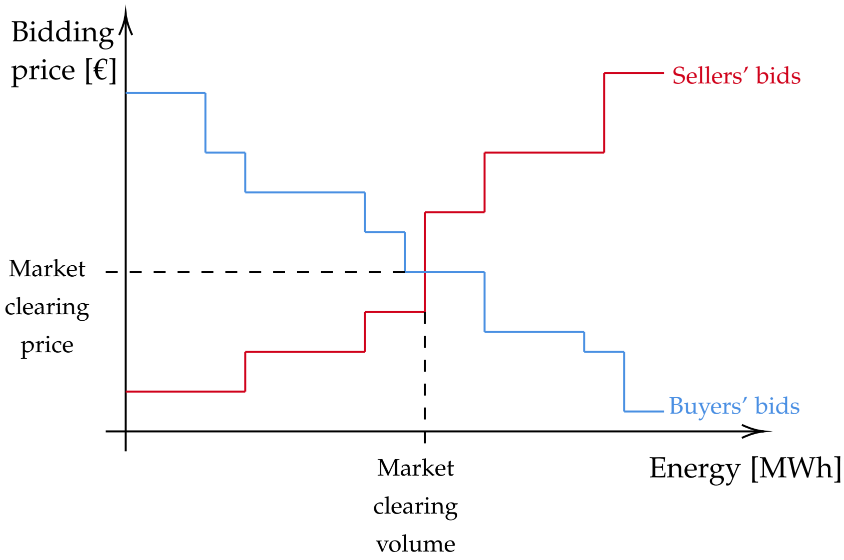

Figure 2.2: Pricing mechanism based on the merit order

Prices are set on a day before. In Nord-Pool, at 10 AM the available capacities of generators and interconnectors are published. Both buyers and sellers have to submit their bids until 12. Submitted orders are matched with other orders in the pan-European market coupling process - the Single Day-Ahead Coupling (SDAC) - through a common algorithm called Euphemia. In the matching process, the single price for each hour and each bidding zone is set where the curves for sell price and buy price meet, taking into account network constraints. [11]

Timeline of a typical day-ahead market trade is presented in the Figure 2.3. It can be clearly seen that each day, the prices are set for the time period between 12 and 36 hours after the market closure at 12:00. Therefore it can be said that day-ahead market is a type of forward market, where delivery occurs 12-36h after the trade was settled and both sides agreed on the price.

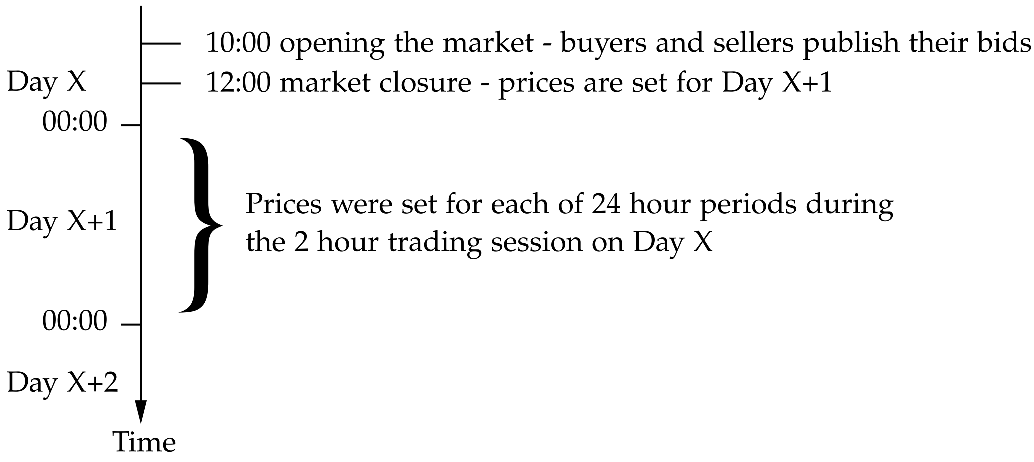

Figure 2.3: Timeline of the price settlement on a day-ahead market

Nord-Pool operates the Day-Ahead market for the Nordic countries under the name Elspot (other countries where trade is managed by Nord-Pool have different names), which could be misleading as it does not have the main characteristic of pure spot market (which was explained in appendix A), which is the time between trade settlement and delivery being as short as possible. [12] [4]

2.1.4 Reserve and spot market

Energy traded on the day-ahead market (and longer-term markets like futures, forwards or options) usually does not represent the actual and exact consumption at a given time of delivery. This can be due to many unpredictable reasons like an outage in a power plant or a large change in consumption, as many end-users especially households do not take active part in energy trading - their retailer does so. [4]

Such situations lead to a mismatch between supply and demand contracted on the day-ahead and similar markets and the generation and load occurring in the power system. To prevent technical problems, the system operator must adjust the amount of energy produced and consumed to match the actual, measured needs instead of the ones traded. For this reason energy is additionally traded shortly before the execution of the delivery. This market is called reserve market, balancing market or managed spot market. It should not be mistaken with balancing services - those are managed by TSOs, not by energy exchanges and are more of a service providing technical stability of the grid, rather than a trade of energy. In Nord-Pool it is labelled as Elbas-market and covers Nordic countries and Germany. [4] [12]

It is very similar to spot market, which is a type of market where the execution of a trade contract between buyer and seller occurs immediately at the time of the trade and the goods traded are are delivered and/or collected immediately.

Since on energy market the technical constraints do not allow to develop a pure spot market, therefore at a certain time interval before the execution of delivery - for example 1 hour before - the system operator analyses the supply and demand that have been contracted before and compares it with the most accurate forecast available. The mismatch that occurs has to be resolved, therefore the players (both generators and consumers) offer their assets to the system operator at prices, which closely represent their spot market prices. Depending on the situation, generators may offer to increase their output and consumers to decrease their load for a certain gratification, or otherwise generators may offer to decrease their contracted generation "buying back" the energy they sold for a lower price and consumers may offer to consume more energy than they were to initially, but since they did not need it that much, they would typically be expecting a low price for this excess energy. [4]

This is were negative prices are most likely to occur. Many generators are unable to decrease their output as some units (like large thermal or nuclear) have high start-up costs or they operate slowly and may not be able to reduce their production until the execution time. In such situations it may be more profitable in a longer term to keep the plant running and pay the consumers to utilize the excess power. In the same way negative prices may occur on the day-ahead market, as renewable generators have higher priority for grid access and low marginal costs. If a generator due to technical constraints must keep the plant running, he may have to bid a negative price to be included in the market clearing volume, it may therefore lead to a negative market clearing price also on the day-ahead market. It happens however less often than on the managed spot market as production can be adjusted easier when more time is given. [4] [13]

Prices from Elbas market are published by Nord-Pool under the name 'Regulating prices' and in each 1h time window there are two prices given - UP and DOWN price. UP represents the money a generator is payed for increasing his output (or consumer for decreasing his load) in €/MWh and DOWN price vice versa.

What should also be mentioned is that managed spot market used for balancing purposes should not be mistaken with intraday market. Intraday market is close to ideal spot market as explained in appendix A, because trade occurs shortly before the physical delivery (for Nord-Pool 15, 30 or 60 minutes before), but system operator does not intervene in it unlike a managed spot market, which is strongly regulated to provide security of supply. Prices on an intraday market are formed in the same way as in Day-Ahead market using a merit order. Nord-Pool does not publish the prices from the intraday market, therefore they will not be used during the course of this project. [14]

2.2 Aggregator

2.2.1 Definition of an aggregator

Important part of the project is to create a good model for an aggregator and provide guidelines on how such entities may operate efficiently when utilizing flexible demand-side resources that we are currently facing the diffusion of. Therefore it must be explained in details who aggregator actually is.

Today, most end-users of electricity do not trade energy on any energy exchange or in direct contracts with the generators (over-the-counter). They have relatively small installed load capacities and therefore are not allowed to bid on an energy exchange, as for Nord-Pool, minimum trading size (required capacity) of a bidder is 1MW. [15]

End-users, considered for this project, are most interested in stability and predictability, therefore most of them have flat tariffs on their consumption or sometimes may be also interested in time-of-use (TOU) tariffs. What is most important to them, is to know in a long advance how much electricity consumption on a given time will cost them, as they are not willing to analyse the prices and plan their daily activity based on that. Therefore end-users are supplied by retailers, that buy energy on the wholesale market at the volatile market prices and later resell it to the final consumers at the prices they agreed on before. Retailers act as middle-man between energy market and end-users. Also retail supply of energy is a competitive market and the end-user has a right to choose his energy service provider. [4]

Retailers may have a few tariff options that end-users can choose from, like aforementioned flat or ToU tariffs, but they may also offer energy at the prices that reflect the ones from day-ahead market and consumer is informed a day before about the hourly prices on the following day or even real-time-prices (RTP) that consumer does not know until the moment of consumption. Tariffs for households and smaller commercial or industrial end-users are usually regulated by regulatory authorities which for Denmark is Danish Utility Regulator (DUR). In some pricing mechanisms that will be analysed, the end-users is to pay the market price plus a commission that makes the aggregator's profit. In such case, the speculative role is moved from an aggregator to the end-user who makes the most profits or losses out of changes in the prices on electricity markets. In pricing mechanisms with fixed retail prices it is an aggregator that takes the risk of volatile market prices and if it is higher than the retail tariff, then he must sell energy at a loss.

Aggregator, as understood in this project, is a type of retailer, that apart from just buying the energy on the wholesale market and selling it to the consumers on the (mostly) regulated market takes more active part in shaping the demand over time. Aggregator can actively utilize the flexible demand-side assets that allow him to optimize the load curve and shift the controllable loads to different time period by remotely controlling the dispatch of some consuming devices like EV chargers. When an end-user signs a contract with aggregator instead of regular retailer, he gives up some of his freedom to consume energy whenever he likes to allow the aggregator to decide on some components of his load. Such contract would obviously require a financial gratification for the end-user to convince him to sign it.

2.2.2 Role of aggregator

Aggregators will play a stronger role in the power system than regular retailers. They do not only act as a middle-man in the trade of energy, but also have a strong influence on the load curve of their users. Therefore they provide flexibility of the power system that is provided by some assets owned by their clients like EVs.

Power system flexibility at the same time, according to Denmark's Market Model 3.0 must be utilised as a cost-effective tool in the operation of the grid [6].

Flexibility operated by aggregators can have various positive effects on the power system. For example it allows to decrease the peak values of energy consumption, by shifting the consumption to later time or by implementing some algorithms helping decrease the peak load, while maintaining the total energy consumption and fulfilling consumers' needs like heating or cooling [16].

Secondly, knowing that electrification of transport and heating sector will lead to an increased consumption of electricity, large investments in the grid infrastructure will be conducted. Therefore using aggregators and flexibility of many of the newly installed loads can be a good way to prevent building distribution lines with oversized transmission capacity, which would not be fully utilized if without aggregators' influence on the behaviour of end-users. [6]

Thirdly, knowing the geographic location of more players on the electricity markets and more detailed information on the customers' behaviour, thanks to their participation (through an aggregator) in the energy markets, better predictions and plans about the future consumption can be made. It can lead to more cost-efficient development of grid infrastructure. [6]

Finally, aggregation and smart dispatch of controllable loads that can follow the signals coming from electricity markets and RES generation in the power system. It is a good tool for realising the paradigm of load-follows-generation that will play a stronger role with the ongoing energy transition.

2.3 Overview of flexibility of distributed technologies

Aggregator, unlike regular retailers, pays a stronger attention to technologies that increase the flexibility and the load can be largely increased or decreased in a relatively short time, instead of aiming at the most predictable load profiles that behave similarly every given time interval (day, week or year) and most importantly independently from the variable prices occurring at energy markets. As the aggregator's goals are increasing the utilization of self-produced renewable energy and make profit on the volatile energy prices, especially by consuming energy when the prices are low (or even negative) using the highly flexible loads. This section will explain the flexibility provided by different types of loads. [3]

2.3.1 Electric vehicles

As mentioned in chapter 1, currently we are facing quick diffusion of EVs and electrification of transport sector. Electric vehicles use relatively large amounts of electrical energy, for example Lotus Evija has energy consumption of 17.25kWh/100km [17], Nissan Leaf 17.1kWh/100km [18] and Renault Zoe 17.7kWh/100km [19] when an average American uses 10.72kWh each day in his household [20]. In order to provide desired range, EVs are equipped with a battery, which has to be charged to be ready for a longer drive. Aforementioned Lotus Evija is equipped with a battery having 70kWh capacity, which is almost a weekly consumption of a single person in the US. Therefore, an EV charger in order to provide relatively short charging time must be a large load compared to other house appliances. Typical fast DC chargers installed in publicly available charging stations have a maximum capacity of 20-30kW, while home installed slow chargers usually have a capacity of 3.7kW [21]. Typical consumption pattern for most drivers is charging in the night for the daily commute. In Denmark the average daily distance driven by a single car is 39.5km, with a standard devation of 28.8km. Data from paper [22] will be later used to model the availability of EV battery storage. It will be assumed that drivers' behaviour will follow the normal distribution. Also, around 70% of vehicles are connected for charging only once a day, and 65% of EVs are fully charged during the first connection. It means that fully recharging an exemplary Lotus would require 6.9kWh if its utilization follows the average values. [22]

As stated in [23] the EV owners may have different approaches to when and on which rules they would like to charge their cars. Some drivers may allow the aggregator to decide when and how fast their car will be charged when it's connected to the charger. Aggregator could then determine and control the charging speed, so chargers may not only be controlled as ON/OFF. Using smart meters and software inside the chargers the aggregators could remotely set up the charging process in order to optimize the consumption with regard to energy prices or availability of locally produced renewable energy.

Based on the paper [23] several types of framework - schemes - between EV owners and aggregator will be considered in the thesis:

- dumb charging - the EV is not controlled by the aggregator and the charging is only defined by the owner and starts immediately when the EV is plugged.
- ToU tariffs - consists in having different prices for peak and off-peak hours, the owner can still decide when he wants to charge and charging starts immediately when the EV is plugged just like in dumb charging scheme.
- smart charging - consists in a active management system where the aggregator has complete control over the EV charger. It requires a charger with an adjustable charging rates.
- energy availability scheme - the control scheme charges the EV based on the real-time available generation, where the load (demand) follows the electrical energy generation (supply) signal, for the project only the locally produced available excess generation will be considered. This scheme can be particularly attractive to prosumers, as self-consumption of self-produced energy is more profitable for them, than feeding it to the grid.
- energy price scheme - the charge will only start based on the price that the EV owner is willing to pay

Depending on the scheme, EVs may provide very large flexibility for the power system, as depending on the availability of energy and its prices it can increase the consumption of energy up to a large value and of the most desired by the aggregator rate of increase of the charging rate. Current ICT technology allows such operation to fully control the charging speed remotely by the aggregator. Obviously the EV owner must chose a scheme when he allows the aggregator to do so. He may even allow the aggregator to use the EV for vehicle-to-grid (V2G) operation, when a previously charged battery is used to feed-in the energy to the grid when there is a strong consumption in the grid that is not met by generators. Such operation however is not going to be analysed in this project, as it will add to the battery wear-off, which in principle should be used for transportation purposes. However it should be noted that aggregator may use the custumer's EV in this way. [23]

Proportions of these user schemes must be chosen wisely by the aggregator in order to efficiently plan its activity on the energy markets as a buyer. It must be also considered that drivers choosing each of the scheme, will also use their cars differently and their daily usage of the car will vary. Chapter 3 will explain in more detailed way how different types of drivers will be modelled, according to the chosen scheme and driving patterns.

2.3.2 Heat pumps

Similar to transportation sector, there is also an ongoing energy transition occurring in heating sector in particular its electrification. An energy-efficient technology, which quickly grows in popularity, used for this purpose are electric heat pumps, as they can provide much larger amount of heat for the same amount of consumed electric energy than resistance heaters [24]. It is described by coefficient of performance (COP), which is the result of dividing the thermal output (measured in watts) by the electric power consumed by the heat pump. It is usually around 3 for most HPs. [22]

Heating has more limitations than EVs when it comes to the flexibility potential. Firstly, unlike energy stored in a battery it can relatively quickly dissipate when the HP stops consuming electrical energy, due to imperfect thermal insulation of buildings that are subject to heating. Therefore heating the building in the time period of no human presence to higher temperatures than necessary may lead to waste of energy, as heat may be lost before anyone uses it. Secondly, during the "operation" of the building, when its inhabitants or users are inside, there is a relatively small range of temperatures in which people will feel comfortable. For this reason if the aggregator is to control the consumption of HPs, he must not exceed the maximum and minimum allowed temperature that should be kept inside the building. This is an important constraint that must be taken into account when optimizing the consumption and buying energy on the market.

2.4 Conclusion

Electricity markets are very complex and energy can be purchased in various ways and different periods occurring before delivery, which can be too difficult to operate in for most end-users of electricity. At the same time, there is an ongoing diffusion of flexible demand-side energy consuming technologies like EV chargers. System operators are interested in utilizing those assets to improve the functioning of the power system and retailers are interested in making profits by including them in their customer portfolio. For this reason retailers should adjust their business and by becoming aggregators take a more active part in forming the demand curve. For end-users, who would own and use those flexible resources, to agree to such conditions would require also an attractive offer and participation in the income coming from using those resources in the most desired (from the system operator's point of view) way.

Different resources present different flexibility levels, from high in case of EVs, through smaller like for HPs to no flexibility at all like PV panels. This chapter explained the technical and economical aspects of flexibility related to those technologies and information about electricity markets that can be important for aggregators. Next chapter will explain in details how those information will be used to develop relevant models for aggregators, that could be further used to compare and improve different aggregation techniques.

Chapter 3

Modelling and aggregation of flexible demand units

In this chapter models of different distributed assets will be introduced, in particular the energy consumption of different loads and different aggregation schemes. Generic models suitable for different modifications like different ToU tariffs, different smart charging hours or different maximum and minimum indoor temperatures required for HP operation will be introduced. Details of different pricing schemes will be also explained in this chapter. Those will be compared with each other and the most profitable one will be chosen.

3.1 Modelling EVs as a flexible load

EVs are the most important asset an aggregator would have access to, as they have large needs for energy compared to other domestic appliances and also they allow large control over the charging process, which means large flexibility. Modelling of such load must consider different distances driven daily by different drivers, which corresponds to different available amount of energy that the EV battery can be charged at the end of the day. Secondly, five schemes for charging EVs are described in 2.3.1.

3.1.1 Energy consumption of EVs

Energy consumed by EVs during daily drive can be calculated in a relatively simple way. Paper [22] provides information about the driving patterns of Danish drivers. Mean distance driven daily by a single car is equal to 39.5 km and its standard deviation is 29.8 km. Assuming the distance driven daily follows the normal distribution, a cumulative distribution function curve can be created as shown in Figure 3.1. Using normal distribution, selected percentile values are presented in Table 3.1. Based on these values 5 types of drivers will be modelled, as each driver type will represent 20% of all drivers in terms of distance driven. Each of them will be the median value of his 20% interval i.e. 10th percentile, 30th etc. The values selected for further simulations to model the five driving patterns are underlined in the Table 3.1.

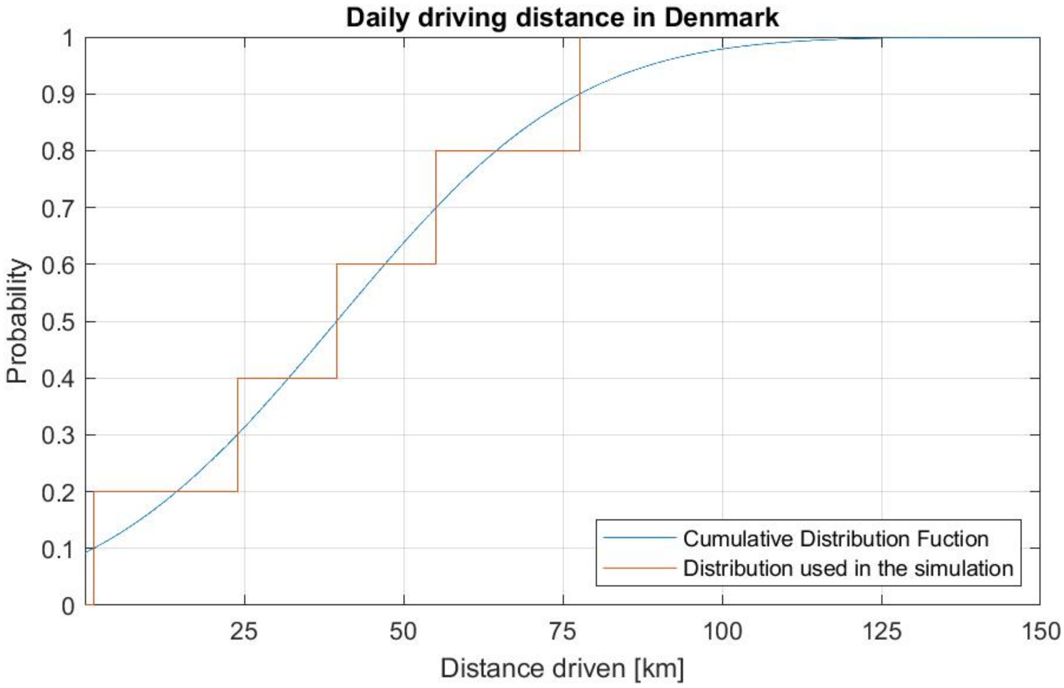

Figure 3.1: Daily driving distance in Denmark

Percentile name	10th	30th	50th	70th	90th
Percentile value [km]	1.3	23.9	39.5	55.1	77.7

Table 3.1: Deciles of daily driven distance

Charging the EVs will be simulated depending on the aggregation scheme that the owner has chosen - dumb charging, ToU tariff, smart charging etc. It is assumed that the chosen charging scheme, has no impact on the driving patterns and the distribution presented in the Figure 3.1 is relevant for all drivers, no matter how they charge their cars.

Driving influences the State-of-Charge (SOC) of the battery, which is the level charge of an electric battery, relative to its capacity. It is measured in percentages - 100% for full and 0% for empty. SOC is not only used for EV batteries, but also for battery storage used in power systems and for small batteries used in electronics. In the project it will be used to model the consumption of EV chargers and duration of the charging process, as well as to model the battery storage.

$$SOC = \frac{Remaining\,capacity\ [kWh]}{Rated\,capacity\ [kWh]}\,[\%] \tag{3.1}$$

$$SOC_t = SOC_{t0} + \frac{100}{Rated\,capacity\ [kWh]} \int_{t0}^{t} V_{grid} \cdot I_{cb}\,(T)\,dT \tag{3.2}$$

$$T_{charge}\,[h] = \frac{SOC_{MAX}\,[\%] - SOC_{t0}\,[\%]}{100\%} \cdot \frac{Rated\,capacity\ [kWh]}{V_{grid} \cdot I_{cb}\,[kW]} \tag{3.3}$$

Energy consumption of the charger will be simulated using SOC equations, presented above in particular equation (3.2) [22]. It can be transformed to calculate the time required to fully charge the EV when initial state of charge is known. Then equation (3.3) can be used for this purpose.

If a battery is to be used for energy storage instead of transportation, the SOC is to be kept between 10% and 90%.

State of charge at the beginning of the charging event is calculated based on the distances driven, simply by multiplying the distance with an average consumption of energy that a car has used. For simplification it will be assumed that the average consumption is equal to 17.25kWh/100km as in [17].

Details of each scheme and how they are modelled will be presented in next subsections.

3.1.2 Dumb charging

Dumb charging is a scheme that is operating under similar or same framework as most end-users do. They may plug in the EV to the charger at any time they want to and the charging process will start immediately afterwards. The users choosing this scheme will pay a flat tariff and therefore the energy price (and its volatility over time) will not influence their behaviour. Prices from energy markets (in particular the Elspot Day-Ahead prices) will on the other hand determine the costs of the aggregators, as he purchases energy at market prices. Aggregator's income will be simply a multiplication of energy consumption and the constant price (without transmission fees and without taxes and levies). Flat tariff price used in the simulation for this scheme is going to be 120,55 øre/kWh [25].

In this charging scheme, the aggregator takes a role of a retailer and speculator and does not have any remote control on the consumption of his customers. He makes profits by purchasing energy at volatile market prices and selling at a regulated price. Analysis of the Day-Ahead Market prices that has been performed, showed that the flat tariff price of 120.55 øre/kWh stands for the 85th percentile of the market prices dataset occurring in 2021, which means that for 85% of the year, selling energy at this price brings profit and for 15% of the year energy is sold at a loss. Details will be shown in chapter 3.2.

Drivers using dumb-charging scheme are going to start charging right after they arrive home. The distribution of the arrival times around the day is taken from the paper [26] and is presented in Figure 3.2.

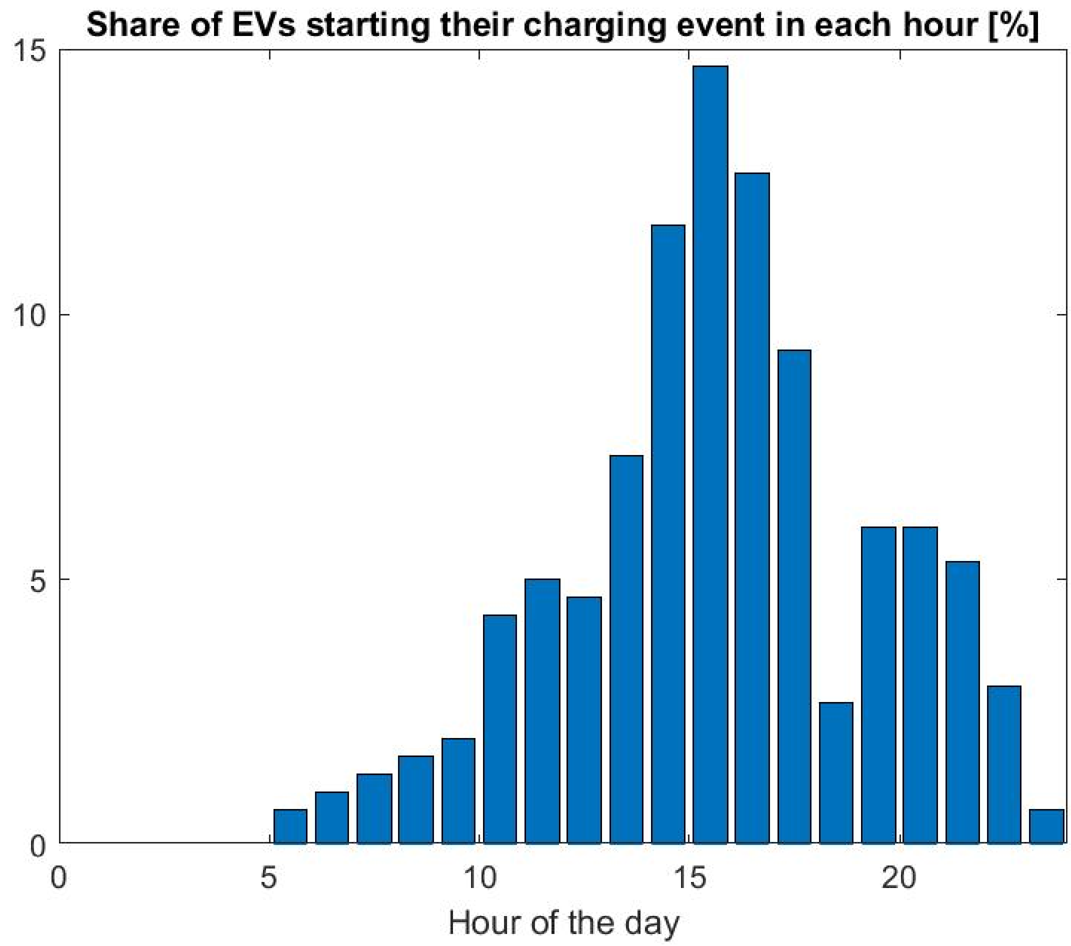

Figure 3.2: Share of cars starting their charging event every hour

Drivers who use dumb charging scheme will be initially simulated to leave the car charging until it is fully charged, at which point the charger will automatically stop taking energy from the grid. For simplification, it will be assumed that all drivers use a similar type of slow charger, which has a capacity of 3.7kW and once they return home and plug in their car to the charger it will work with full capacity until battery is fully charged [21].

Hourly consumption of each of 5 driver type, after plugging in the car to the charger is shown in Table 3.2.

Table 3.2: Energy consumed by a charger over time

Driver type	Distance [km]	Electricity consumed [kWh]				
		Total	Hour 1	Hour 2	Hour 3	Hour 4
1	1.3	0.22425	0.22425	0	0	0
2	23.9	4.12275	3.7	0.42275	0	0
3	39.5	6.81375	3.7	3.11375	0	0
4	55.1	9.50475	3.7	3.7	2.10475	0
5	77.7	13.40325	3.7	3.7	3.7	2.30325

If all five driver types were charging, their energy consumption and duration of charging process would look as portrayed in the Figure 3.3. Each color represents the hourly consumption of each driver type.

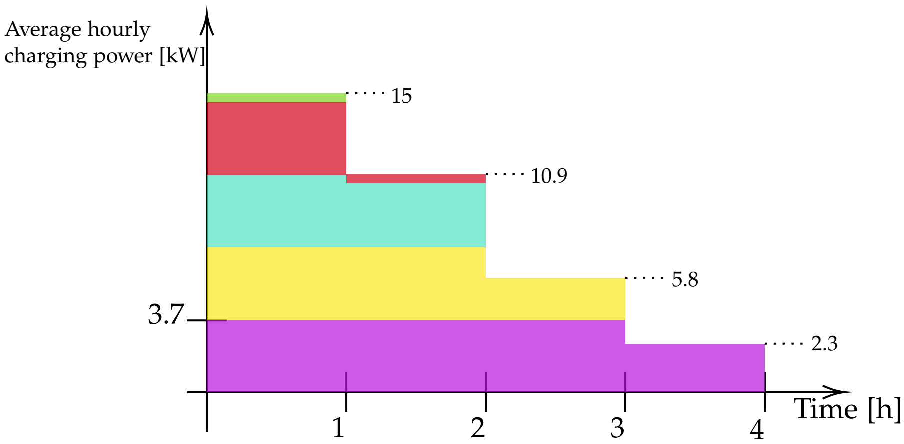

Figure 3.3: Charging duration and energy consumption of 5 driver types

Those values will be multiplied by number of cars starting or continuing their charging at a given time to obtain overall consumption, based on the percentages shown in Figure 3.2. It is assumed that at hour x a given percentage of drivers arrive home and their cars are starting its charging (is in the Hour 1 of charging) and cars that started charging an hour earlier, at time x-1 will be in their Hour 2 of charging process, and so on and so forth.

3.1.3 Price elasticity of demand

Time-of-use tariffs can be implemented to the power system provided that smart meters are being installed which is an ongoing process in Europe. In many countries including Denmark all traditional Ferraris meters have already been fully replaced by smart meters, able to be read remotely. End-users pay a price for energy they consume depending on the time of consumption. Typically energy will be more expensive in peak hours when the load in the power system is the highest and cheaper in off-peak hours. What is important for ToU tariffs is that energy prices in each time period is agreed prior to the actual consumption and the end-users know in advance what they will pay. ToU tariffs used in the project will vary between 80% and 120% of the tariff of 120.55øre/kWh. Different ToU tariffs will be tested in Chapter 4.

Economical background behind ToU tariffs is based on a phenomenon called *price elasticity of demand*, which is a value that tells how big a change in demand for a certain good will be after a change in price of the same good.

$$E_d = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta P}{P}} \tag{3.4}$$

Formula for calculating this value is presented by the equation (3.4).

In the formula Q and P represent the traded volume and price before the price change and ΔQ and ΔP represent the change in the volume and price respectively. [4]

For vast majority of the goods price elasticity of demand is negative, which means that after price for a good increases, the demand decreases and vice-versa. Price elasticity is different for each good and each market, however it can be measured. There is a large research activity put into examining price elasticity, as it usually is not a constant value and it varies over time and also is different among different people. According to a paper [27], in Denmark price elasticity for electricity demand (excluding electric heating) is equal to -0.75, however the aggregator should monitor the behaviour of his consumers as the real-life value might be different. This value will be used for a theoretical model in this project. In real-life application, a value specific for the analysed group of consumers should be determined as fast as possible for better forecasting. For the value of -0.75, it can be said that demand for electricity in Denmark is inelastic as it lies between 0 and -1. [4]

Based on that, ToU tariffs prove to be a tool to shift demand from one time period to another. One of the main goals of system operators is to avoid congestions in transmission lines and avoid dispatching the most expensive peak power plants like the ones using gas turbines. For this reason consumption during peak time (if possible) should be shifted to an off-peak time and this is why ToU tariffs can be implemented to fulfill this goal. From aggregators' point of view it is also important as energy on power exchanges in peak time is typically the most expensive, while in off-peak time the price is lower or even negative. For this reason higher tariffs in the first and lower in the latter will shift some of the demand to more desirable time, compared to a situation with a flat tariff.

It is assumed that end-users choosing the ToU-tariff scheme want to keep the comfort of charging their cars at any time until the battery is full, just like in the dumb charging scheme, but are willing to save some money by shifting some of their consumption to a period in which electricity is cheaper.

As such end-users will still consume same amount of electricity (compared to dumb charging users) after they plug in their car to the charger, the change in overall consumption will depend of the number of EV owners changing their behaviour and postponing the charging to different time. This is where price elasticity is assumed to have the influence on the demand, not on the charging itself.

$$Q_{new} = Q_{old} \left(1 - E_d \frac{P_{old} - P_{new}}{P_{old}}\right) \tag{3.5}$$

It leads, to the formulation of an equation that will be used to calculate the demand for charging after implementing ToU tariffs. As detailed implementation may vary, for example price levels may be larger or smaller and peak and off-peak periods may be determined differently, the formula (3.5) is a general one. It will be used to calculate the number of cars starting their charging process at a given time after energy price in this particular time period changed. [4]

Traded volumes Q in this formula are the percentages of EV owners choosing to start charging their cars at a given time, where Q_{old} stands for the value with a flat tariff price P_{old}, taken from Figure 3.2. Q_{new} stands for the volume after a price change to a ToU price P_{new}.

Formula (3.4) can be used to calculate the demand in any aggregation scheme that does not allow the aggregator to remotely control the EV charging process. As long as it is up to the end-user when he will start charging his car and aggregator only sets the energy price, the consumer behaviour can be modelled by this equation.

Determining the ToU tariffs

ToU tariffs can differ from each other. One major difference between different ToU implementations is the price difference between different periods. Second important characteristic to consider is when different tariffs will be applied - how to specifically determine when does the peak, off-peak and mid-peak periods start and finish.

ToU tariffs will be determined based on the Day-Ahead market prices in the previous year. Average prices occurring each hour will be ranked and compared with each other. Hours at which prices are above a chosen upper quantile are labelled as *Peak* hours, similarly hours with average prices below a chosen lower quantile will be labelled as *Off-peak* hours. When an average hourly price at a given daytime is between those quantiles, then such periods will be called *Mid-peak* hours. Algorithm used in the simulations to determine the ToU tariffs is presented in the Figure 3.4.

Initially, the mid-peak price will be the same as the flat tariff price, peak price will be 20% higher and off-peak 20% lower. However the developed MatLab function allows to choose both the prices for each of these periods, as well as to determine the upper and lower quantiles to set those periods.

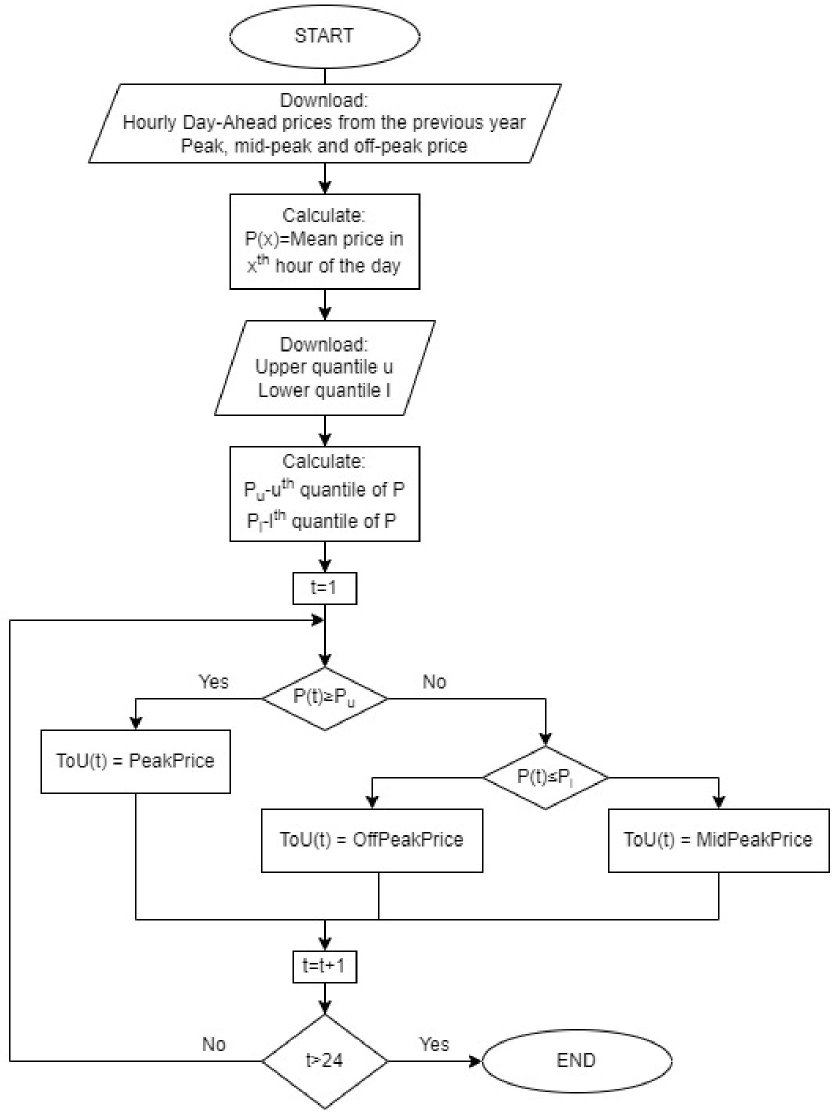

Figure 3.4: Flowchart showing the algorithm used to determine the ToU tariffs

Average energy price on the Day-Ahead market in the bidding area of DK1 in 2020 divided into time of the day is presented in the Figure 3.5. Periods with the highest and lowest average price are going to be the peak and off-peak hours respectively and others will be mid-peak hours with the same price as the dumb-charging flat tariff. 925

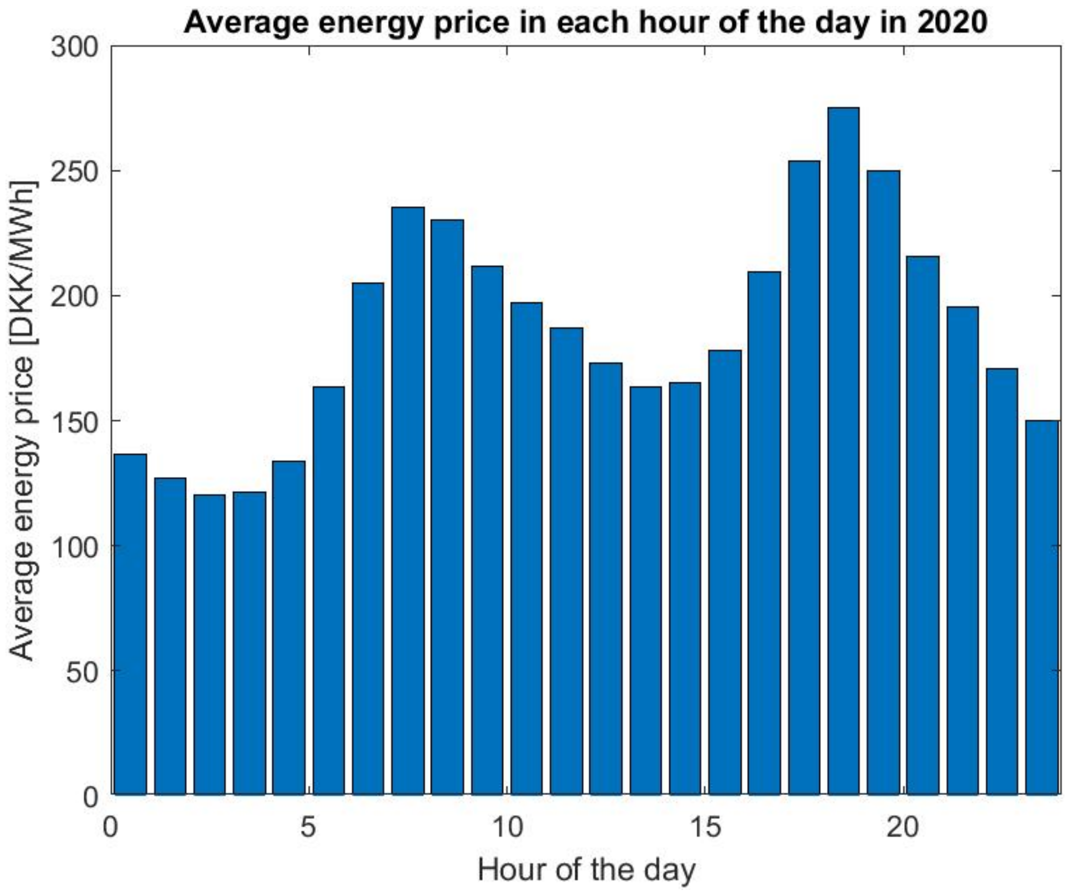

Figure 3.5: Average energy price in each hour of a day

Flex Settlement

There is another pricing mechanism that is being implemented in Denmark in recent years. It is called Flexafregning (Flex settlement) [28]. The end-user is informed a day in advance about the prices on the next day, based on the Day-Ahead market prices that have been determined with the merit order method at 12:00 on the day prior to consumption. End-user can chose when to consume the energy, therefore it can be assumed that the consumption after implementing those tariffs acts according to formula (3.5). Therefore it can be easily simulated using similar MatLab function as ToU tariffs. In the simulations it will be assumed that the end-user choosing flex settlement pays the price from Day-Ahead market plus a commission of 5% or 0.05DKK/kWh. Both pricing schemes will be simulated and compared in the next section.

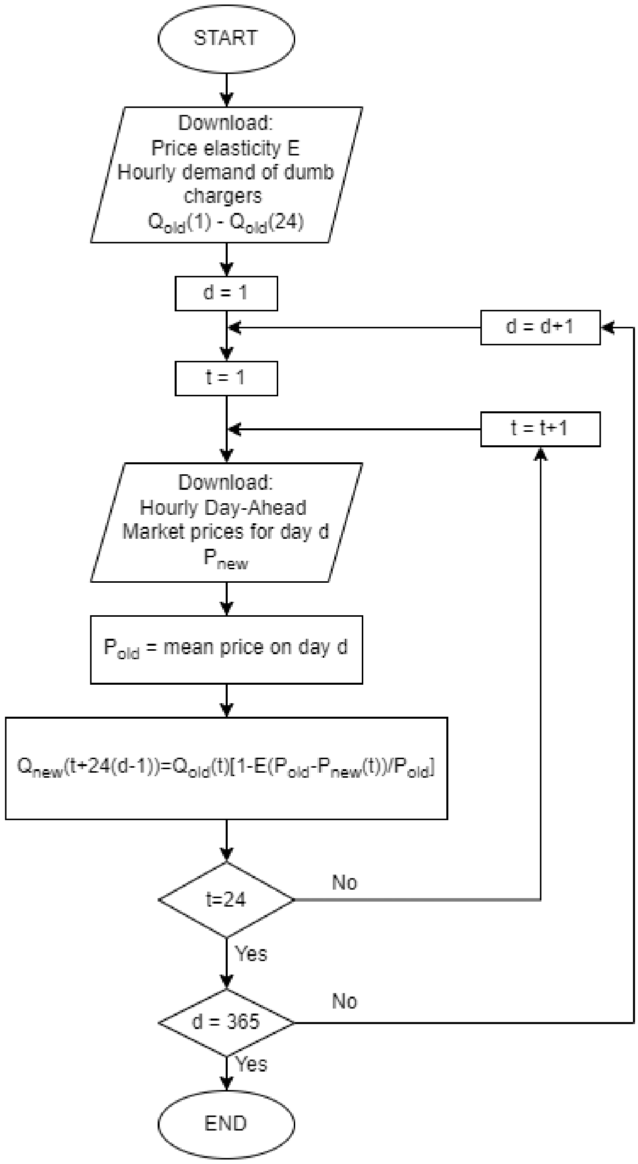

Figure 3.6: Flowchart showing the algorithm used to calculate the energy demand after implementing Flex Settlement

There will be however one major change to the algorithm compared to ToU tariff users. Algorithms used to calculate the demand every day, after implementation of Flex Settlement is presented in the Figure 3.6. The price P_{old} in formula (3.5) will be the mean Day-Ahead Market price in the considered day instead of the flat tariff price that is paid for dumb charging scheme. It is justified by the assumption that the number of drivers charging their cars every day can't be higher than the number of cars available and considering the fact that Day-Ahead Market prices are lower than the flat tariff of 120.55 øre/kWh for 85% hours of the year, calculating new demand with reference to the flat tariff price would mean making the overall demand higher than it is technically possible [11]. An assumption is made that the owners will not postpone their charging event to the next day, but thanks to the information provided a day before the customer can schedule the charging event to take advantage of the price difference. It will modify the numbers of drivers starting their charging event shown in Figure 3.2, according to the formula (3.5).

3.1.4 Smart charging scheme

Smart charging is a scheme in which the aggregator can remotely control the charging process and consumed power over time, provided that the car is plugged in to the smart charger of course. [23]

There can be many different frameworks of smart charging schemes. For the project and its first simulation, the aggregator will define hours in which the EV should be plugged in and later aggregator using an optimization algorithm will determine how the car should be charged over time to utilize the hours with the lowest energy prices and minimize the cost of charging.

Knowing that most cars choosing this scheme will be plugged in during certain hours and knowing the prices from Day-Ahead market, the aggregator can schedule the energy consumption during that time in a way that would minimize the cost of purchasing energy. It will be assumed that aggregator does not have enough market power to influence the prices on electricity markets and purchases the energy at the prices obtained during the trading session on the day-ahead market. However provided with knowledge about the settled prices, detailed hourly schedule can be made. Technically it is also possible for the aggregator to use the cars to take part in balancing market, but it will not be simulated in this project.

This leads to an optimization problem, with a cost function and a few constraints. Provided that cars will be plugged in to the charger for n hours starting at m_{th} hour of the year the optimization problem is developed, where p represents the price for the Elspot market at a given time and q the purchased volume at the same time. [29]

$$\begin{aligned}
\underset{q_m, q_{m+1}, \ldots, q_{m+n}}{\text{Minimize}} \quad & C(q_m, q_{m+1}, \ldots, q_{m+n}) = \sum_{i=m}^{m+n} p_i q_i \\
\text{subject to} \quad & h\left(q_m, q_{m+1}, \cdots, q_{m+n}\right) = \sum_{i=m}^{m+n} q_i - Q_{max} = 0 \\
& g_1\left(q_m, q_{m+1}, \cdots, q_{m+n}\right) = \forall q_i - Q_{ch} \leq 0 \\
& g_2\left(q_m, q_{m+1}, \cdots, q_{m+n}\right) = -\forall q_i \leq 0
\end{aligned} \tag{3.6}$$

The objective of the optimization algorithm is to minimize the cost of energy purchase, while making sure that cars are fully charged and avoiding V2G operation and exceeding charger's maximum capacity.

First constraint **h** will be called *full charge constraint*. It is used to charge the EV battery to the full capacity. It is based on an assumption that the car owner wants to fully charge the car when he plugs it in to the charger overnight. Q_{max} is the remaining capacity that a car has after being driven a day before, taken from third column of Table 3.2, different for each of the five types of drivers. Full charge constraint is an equality constraint.

Constraint $\mathbf{g}_1$ will be called *charger constraint*. It ensures that over each hour during charging event, the EV will not be charged with a higher power than the maximum capacity of a charger. If a charger works with full power for 1h, the car is charged with Q_{ch} [kWh] of energy. Therefore any q_i must not exceed this value. Charger constraint is an inequality constraint. It should be noted that the algorithm does not take into account grid constraints and potential bottlenecks related to the distribution capacities. It is assumed that the grid is technically suitable for all calculated loads and related currents.

Last constraint $\mathbf{g}_2$ is also an inequality constraint which ensures that volume of energy charged each hour must be non-negative - V2G operation is not considered.

Solution to the optimization problem is the consumption of energy that is divided into 1h intervals that provides minimum cost of purchase. Optimization algorithm in MatLab has been created in a way that period of connection (to be considered for prices), charger capacity and maximum available battery storage capacity are the input values and algorithms will work for any of those.

Optimization problem is solved using linear programming method, in particular the LINPROG function, from MatLab's Optimization Toolbox. Using this method of solving an optimization problem is justified, as the objective function is a linear function of multiple variables $\mathbf{q}$=$[q_m, q_{m+1}, \cdots, q_{m+n}]$. [29]

Using calculated consumption and knowing the prices in each hour, the cost of purchasing energy from the market can be easily calculated in the same way as with other aggregation schemes.

Aggregator's income depends on the contract he has with end users and the pricing scheme that both sides agree on.

Pricing schemes used for simulation

Smart charging scheme, compared to dumb charging or ToU tariffs, are less comfortable for the end-user, as he is not to decide when exactly the car will be charged. Also what can be uncomfortable for the end-user is the need to connect the car to charger in certain, prior agreed hours to benefit from the algorithm which provides the lower prices. Therefore smart charging scheme to be convincing to the end-users to choose it, has to be more attractive financially than other schemes.

Prices on the Day-Ahead market for over 85% hours in the year are lower than the flat tariff that users pay for energy in the dumb charging scheme, therefore the aggregator or retailer makes big profits on energy sales to them. Pricing mechanism offered to smart chargers must be both profitable to the aggregator, as well as attractive to the final consumer. The latter is ensured by making the final price, that the end-user pays, visibly lower than in other scenarios. It can reflect the market price, as it is usually lower.

In some pricing schemes, the aggregator can earn money from the commission put on the market price and it is the end-user who saves most money thanks to purchasing at a cheap price, while in other, the aggregator takes the risk of purchasing energy at volatile prices and selling it at a constant price - then he may lose if the purchase price is higher. However, such price must be lower than in other pricing schemes.

Proposed schemes can be linked to the Day-Ahead market price, which the end user would pay and a fixed commission that would ensure aggregator's profits. Smart charging algorithm would ensure that EV is charged at the hours with lowest price which can be treated as a service that end-user purchases with the commission. This fee can be either fixed (like 0.05DKK/kWh) or a percentage of the energy price on the market (like 5%). However the maximum price end-user (but not the aggregator) has to pay must not be higher than the flat tariff of 120.55øre/kWh. If market price is above this value, then the retailer sells energy at a loss - this however would occur only in 15% of the hours in a year.

Other solution would be offering the end-user a fixed price for the energy consumed during smart charging event, which would ensure the aggregator's income as well as attractive enough to the consumer by being lower from both dumb charging flat tariff and the lowest ToU tariff. Since ToU tariff during off-peak periods is going to be 80% of the flat tariff (0.96DKK/kWh), therefore the price for energy consumed withing smart charging scheme must be lower than that. For further simulations a price of 0.75DKK/kWh has been chosen - it represents the 74th percentile of energy prices in 2021.

All three aforementioned pricing mechanisms are going to be compared with each other in the next section and the most profitable one will be selected for further analysis.

3.2 Overview and final selection of the optimal pricing mechanisms

Each charging scheme has different characteristics and therefore different pricing mechanisms must be used. They have been introduced in chapter 3.3. In this section they will be compared to each other and the most profitable one will be chosen for further simulations. All simulations were performed for a year 2021 in 1h long time intervals.

3.2.1 Dumb charging with a flat tariff

Dumb charging does not have any factors that can be changed by the aggregator. The flat tariff is going to be profitable to the retailer for 85% of the time. Table 3.3 presents the results of a simulation performed for 1000 EVs, whose owners have chosen dumb charging scheme.

Table 3.3: Dumb charging simulation results for 1000 cars

Number of EVs	Energy consumed [MWh]	Income [kDKK]	Cost of purchase at Elspot [kDKK]	Profit [kDKK]
1000	2509.4	3023.8	1762.5	1261.4

It can be seen that dumb charging is very profitable for the aggregator, as the difference between market price and price paid by the end-users can be large, which makes the profit for the retailer. What is important to note, is the average purchase price being 702.4DKK/MWh, which is the one occurring when end-users are not getting any information about market prices, nor any monetary incentive to shift their consumption to a time with lower market prices. It should be noted that the income and costs are only based on the prices on energy. Fees for distribution and taxes

3.2.2 Time-of-Use tariffs

ToU tariffs can have different implementations in practice. They can differ from each other in two ways - firstly, depending on the price difference between different ToU periods, secondly, the length of different ToU periods can also differ from each other. There is a very large number of combinations that can be implemented, therefore only a selected four will be simulated and compared with each other.

The tested ToU tariff scenarios are as presented in the Figure 3.7. It should be reminded that selection of peak, off-peak and mid-peak hours in each scenario is based on the market prices in 2020 and simulations are performed for 2021

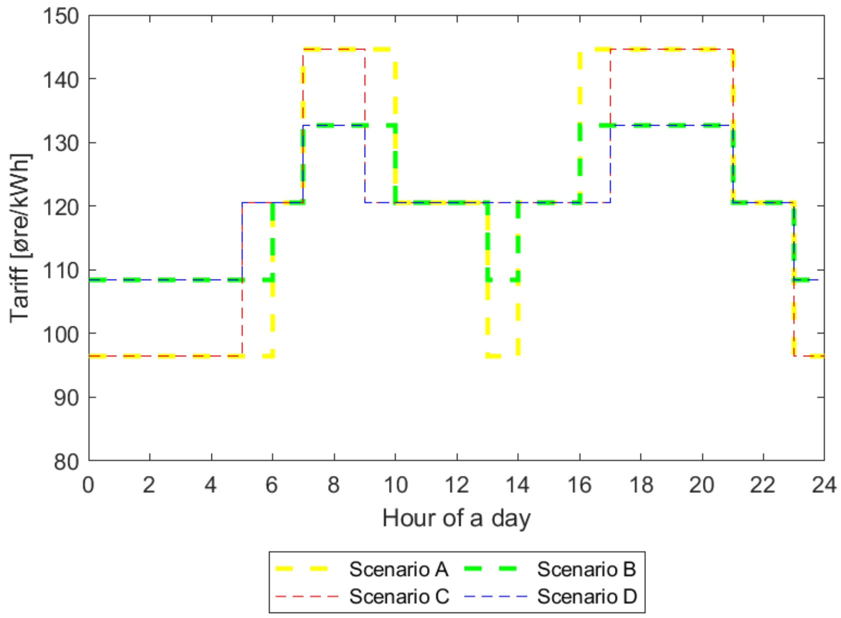

Figure 3.7: Tested ToU-tariff scenarios

Results of the simulations are presented in Table 3.4. All four scenarios were simulated with a set of 1000 EVs.

Table 3.4: Simulation results for 1000 cars for 4 different ToU schemes

Scenario name	Energy consumed [MWh]	Income [kDKK]	Cost of purchase at Elspot [kDKK]	Gross income [kDKK]
A	2365.1	3037.9	1648	1389.8
B	2424.8	3024.5	1696.6	1327.9
C	2390.2	3033.6	1672.2	1361.4
D	2439.7	3021.6	1710.4	1311.2

It can be observed that the total energy consumption in each scenario is different. It occurs based on the theory of price elasticity of demand and formula (3.5). The consumption decrease during peak price period is not fully compensated by the consumption increase during off-peak price period, despite the fact that those two time periods have equal length. This has two reasons, firstly the demand for energy is inelastic (because the price elasticity E is between -1 and 0), secondly a given percentage of a higher value is greater than same percentage of a smaller value.

The most profitable ToU-tariff solution is the one presented as scenario A. Therefore, this one will be used for further simulations.

3.2.3 Flex settlement

Prices for users choosing the flex settlement are highly volatile, as they are directly based on the Day-Ahead market prices. The aggregator's profit is a commission added to the Elspot price. The comission will either be a fixed value of 0.05DKK/kWh or a percentage of the Day-Ahead market price (5% will be simulated). If the market price is negative the end-user receives the energy price after the commission was substracted i.e. 95% of the price. When it comes to the scenario with a commission of 0.05DKK/kWh, the pricing scheme is presented in the flowchart in the Figure 3.8. It is also used for further subsections, where a maximum price is applied.

The two commissions have been compared and the results of the simulations are presented in the Table 3.5.

Table 3.5: Simulation results for 1000 cars for two commissions

Commission	Energy consumed [MWh]	Income [DKK]	Cost of purchase at Elspot [DKK]	Gross income [DKK]
5%	2435.1	1674400	1594100	80299
0.05DKK/kWh	2434.3	1731000	1610000	121070

It can be seen, that average purchase price of energy consumed under Flex Settlement regime is 654.6DKK/MWh and 661.4DKK/MWh for 5% and 0.05DKK/kWh extra commission respectively. These are values over 40DKK/MWh lower, than in the dumb charging scheme. It proves that Flex Settlement is an efficient method to shift the demand to time periods with cheaper energy.

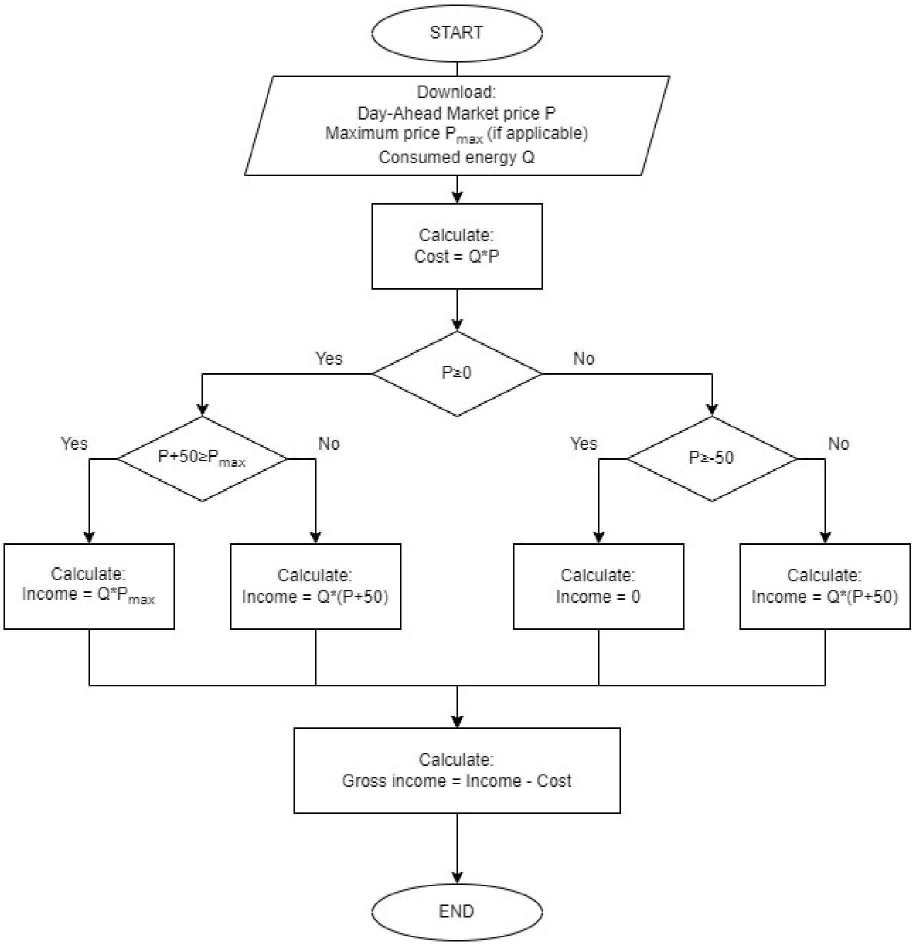

Figure 3.8: Flowchart showing the algorithm used to calculate the income in the 50DKK/MWh commission scenarios

It can be observed that fixed commission of 0.05DKK/kWh brings higher profits to the aggregator, therefore it is chosen for further simulations. This happens due to the fact that 5% of the Elspot price is higher than 0.05DKK/kWh only for 15% of the year.

3.2.4 Smart charging

Smart charging must be more convincing to the end-users than all other charging schemes. Therefore three pricing mechanisms will be considered, simulated and compared. They are as follows:

- Scenario A - commission of 5% of the Day-Ahead market price, with a maximum price of 120.55øre/kWh.

- Scenario B - commission of 0.05DKK/kWh, with a maximum price of 120.55 øre/kWh. In case of negative prices the aggregator receives 50DKK/MWh or less (for prices between 0 and -50DKK/MWh) according to the Figure 3.8
- Scenario C - flat tariff of 0.75DKK/kWh

These pricing scenarios have been graphically shown in Figures 3.9 and 3.10.

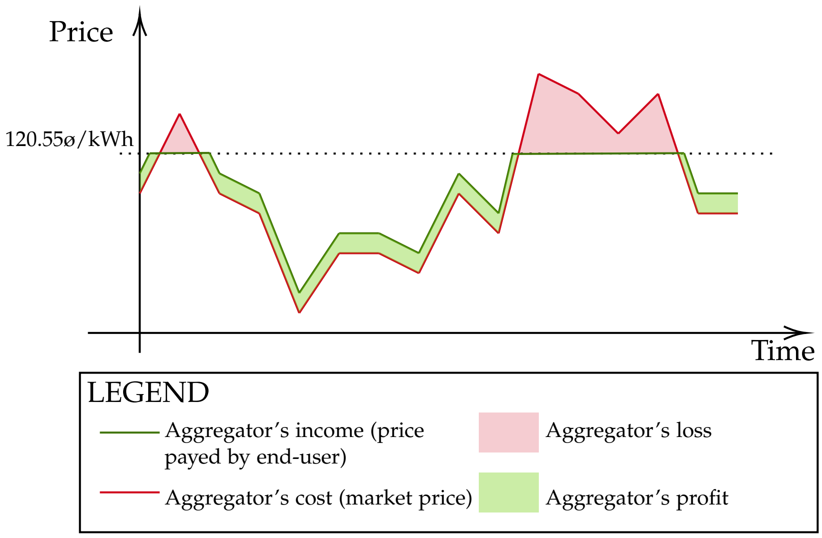

Figure 3.9: Graphical explanation of scenarios A and B

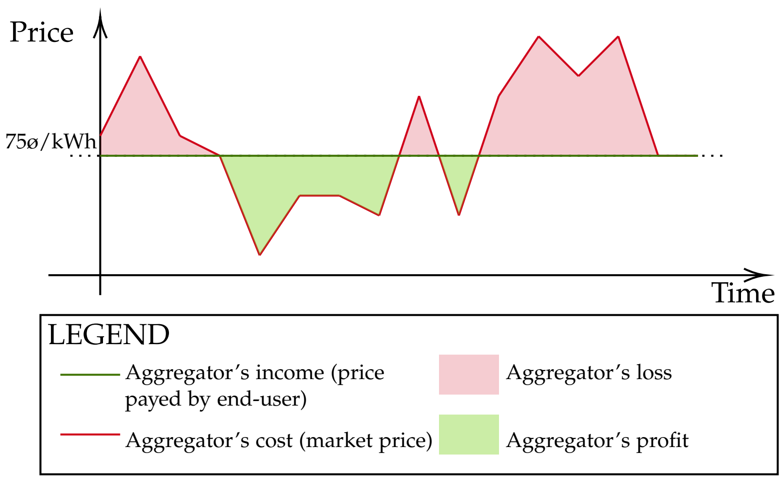

Figure 3.10: Graphical explanation of scenario C

The results of those 3 pricing scenarios are presented in the Table 3.6.

Table 3.6: Smart charging simulation results for 1000 cars and 3 pricing schemes

Scenario name	Energy consumed [MWh]	Income [kDKK]	Cost of purchase at Elspot [kDKK]	Gross income [kDKK]
A	2492.2	1209.5	1175.4	34.154
B	2492.2	1276	1175.4	100.64
C	2492.2	1869.2	1175.4	693.79

It can be seen that the biggest profits are obtained with a flat tariff. Using the optimization algorithm helps to purchase the energy at the lowest possible prices and therefore the cost of purchase is successfully minimized. This occurs no matter of the chosen pricing scheme and thanks to smart charging, the average purchase price of 471.6DKK/MWh is achieved. The tested flat tariff that consumer pays is both profitable for the aggregator, as well as attractive for the end-user, since it is lower than any other tariff (apart from Flex Settlement in the cheapest time periods. Yet, it should be noticed that any flat tariff higher than aforementioned 471.6DKK/MWh would be profitable for the aggregator and therefore could be offered.

Relatively lower profits for scenarios A and B are also justified by implementation of a maximum price. For 10% of the time in a year, the energy is sold at a loss, due to those.

Based on the performed simulations, the flat tariff of 0.75DKK/kWh has been chosen as the pricing scheme for the EV owners choosing smart charging.

Very important remark that should be made about obtained results is that smart charging significantly reduces the cost of purchased energy compared to dumb charging scenario. The average purchase price was lowered by almost 1/3 thanks to implementation of smart charging algorithm.

In the simulation it was assumed that all drivers using smart charging scheme fulfill their obligation to plug in the car during charging hours 10PM-6AM. In the next chapter an uncertainty factor will be included to the simulation. It would influence all three pricing mechanisms simulated above, therefore it did not have to be included when choosing the most profitable one.

3.3 Electric Heat Pumps

HPs are an important component of electricity consumption in many households. Its consumption in winter months fluctuates around 1kW for typical household on a winter day in Denmark and for most houses would reach around 20kWh a day when the average daily temperature falls below 0 degrees [30]. HPs are controllable to a large extent, however unlike EV smart charging schemes, end-users' preferences are much more strict. EV owner choosing to use smart charging algorithm does not mind at what time his car is being charged as long as the battery is full the next morning. Heating needs are different, end-users want to have the indoor temperature in the desired range as soon as they arrive home until the time they leave. This makes the controllable load of a HP less flexible than an EV charger, as the users' constraints for minimum and maximum temperature must be fulfilled.

HPs' flexibility will mostly by used to increase the demand in a period of negative prices to obtain profit. Otherwise the HPs will operate to maintain the indoor temperature which is either desired by the end-user or necessary to prevent thermal stresses to the construction.

Thermodynamic analysis of houses

Indoor temperature can be maintained by delivering thermal energy to the indoor space, which firstly must be heated itself to increase the temperature, secondly the thermal losses that occur due to imperfect thermal isolation must be compensated.

Houses (as a thermal demand) will be simplified to a single volume of air, enclosed by isolating materials. Thermal energy of the enclosed air directly corresponds to the indoor temperature.

$$\Delta E_{VOL} = E_{HP} - E_{LOSS} = \rho \cdot V \cdot C_{p,air} \cdot \Delta T \tag{3.7}$$

$$E_{LOSS} = A \cdot k_c \cdot (T_{out} - T_{in}) \tag{3.8}$$

$$E_{HP} = COP \cdot E_{HP,el} \tag{3.9}$$

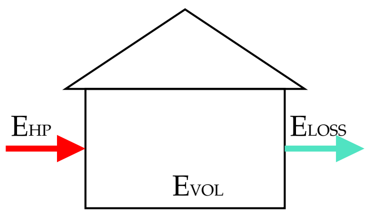

Figure 3.11: Flow of thermal energy

Relationship between the thermal energy of the enclosed volume of air, energy delivered by the HP and the losses to the outside is presented in the Figure 3.11 and formulas (3.7), (3.8) and (3.9) [31].

ΔT_t in equation (3.7) is the difference in temperatures at hour t and hour t-1, while ρ is the air density, $C_{p,air}$ is the specific heat capacity of air and V stands for the volume of the considered enclosed area.

E_{LOSS} is calculated based on the area A of the surfaces through which heat dissipates to the outside and k_c $[\frac{kWh}{m^2 \cdot {}^\circ C}]$ is the heat transfer coefficient of that surface material.

$$COP = 0.078 \cdot T_{out} + 2.791 \tag{3.10}$$

COP in formula (3.9) stands for coefficient of performance, which describes the relationship between thermal output of the HP and its electricity consumption. It is related to the ambient temperature and can be described by a formula (3.10)

HP will also be used for cooling purposes, in such situation it is assumed that E_{HP} is negative. Similarly, E_{LOSS} is negative when there is heat flowing into the inside of the building. However, for obvious reasons, when HP is used for cooling it consumes electricity, therefore for calculating the electricity consumption and further the expenses for electricity purchase, absolute value of E_{HP} will be used.

$$\begin{aligned}
\underset{E_{HP,el}}{\text{Minimize}} \quad & C_t(E_{HP,el}) = |E_{HP,el}| \cdot P_t \\
\text{subject to} \quad & g_1 : |E_{HP,el}| \leq E_{HP,el,max} \\
& g_2 : T_{in,t} \leq T_{in,max} \\
& g_3 : T_{in,t} \geq T_{in,min}
\end{aligned} \tag{3.11}$$

Initial simulation of HP electricity consumption will therefore be based on solving an optimization problem described in equation (3.11). Optimization function that will be used in the MatLab algorithm is going to be FMINCON, as the problem is non-linear and linear programming methods are not suitable.

$$\begin{aligned}
\underset{E_{HP,el}}{\text{Minimize}} \quad & C_t(E_{HP,el}) = |E_{HP,el}| \cdot P_t \\
\text{subject to} \quad & g_1(E_{HP,el}) = |E_{HP,el}| - E_{HP,el,max} \leq 0 \\
& g_2(E_{HP,el}) = \frac{COP \cdot E_{HP,el} + \rho \cdot V \cdot C_{p,air} \cdot T_{in,t-1} + T_{out,t} \cdot \sum(A \cdot k_c)}{\rho \cdot V \cdot C_{p,air} - \sum(A \cdot k_c)} - T_{max,in} \leq 0 \\
& g_3(E_{HP,el}) = T_{min,in} - \frac{COP \cdot E_{HP,el} + \rho \cdot V \cdot C_{p,air} \cdot T_{in,t-1} + T_{out,t} \cdot \sum(A \cdot k_c)}{\rho \cdot V \cdot C_{p,air} - \sum(A \cdot k_c)} \leq 0
\end{aligned} \tag{3.12}$$

Equation (3.12) presents the same optimization problem, but written in the standard form.

First constraint is the maximum capacity constraint - it prevents the solution to the optimization problem to be higher than the installed capacity of the HP. Second constraint maintains the indoor temperature below the maximum allowed value. This constraint will especially play a role during a period with negative energy prices in colder days or during the warmer days. Third constraint prevents the indoor temperature to fall below allowed minimum temperature - especially when negative prices occur in warmer days and during the colder ones.

Data used for simulation

Data required to calculate the electrical consumption of a HP is the outdoor temperature. Data that will be used for this purpose is taken from Danish Meteorological Institute (DMI) and specifically the outdoor temperature measured in Stenhøj weather station in Fredrikshavn Kommune.

Another important input data are the maximum and minimum allowed indoor temperatures. The maximum temperature that is allowed is at any time 28°C and the minimum varies over the day. The minimum indoor temperature chosen for the simulations is 20°.

Apart from that the algorithm must be provided with input data about the buildings that are to be heated. Model of the house used in the simulations is presented in the Figure 3.12. House has an area of 120m^2 and considering it to be a bungalow 3m high, it has a volume of 360m^3. Heat transfer coefficients used for the simulations are 0.18 $\left[\frac{W}{m^2 \cdot K}\right]$ for the roof and 0.23$\left[\frac{W}{m^2 \cdot K}\right]$ for the building's walls.

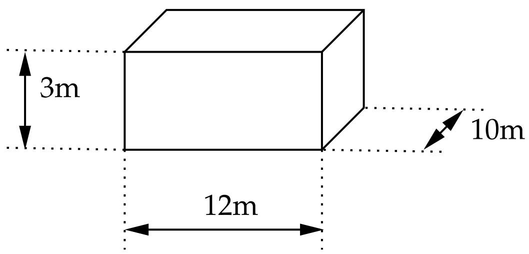

Figure 3.12: House model dimensions used in the simulations.

Economic calculation of HPs

For electricity consumption of HPs a pricing mechanism must be chosen. The cost of electricity purchase is based on Day-Ahead Market price in each hour and the optimal consumption calculated using equations (3.12).

Heating needs are fulfilled differently than EV charging. Charging is to large extent a method of energy storage and once battery is charged, the car is ready to convert the stored electrical energy into kinetic energy. HP converts the electrical energy into thermal energy which dissipates due to thermal losses of the buildings, therefore it does not act as an effective storage. Also heating needs being fulfilled means keeping the indoor temperature in the required range at all time, while EV battery (considering smart charging) should be fully charged at a given time in the morning and it does not matter how the charging looked over time during the hours of connection. Therefore heating is a less flexible need than EV charging.

Selection of pricing mechanism for HP consumption

Aggregator's income, which is the money paid by the end-users, can be modelled similarly to the pricing mechanism used for EV smart charging scheme, which is the Day-Ahead Market price, plus a fee of 0.05DKK/kWh or 5% of the market price. Different solution can be an application of a flat tariff of 0.95DKK/kWh. As heating is less flexible than EV charging it can't be optimized as successfully as smart charging, due to maximum and minimum temperature constraints. Therefore the pricing schemes can be less attractive financially than the ones considered for smart charging - this leads to a higher flat tariff and no maximum price for commission based mechanisms. All pricing schemes will be compared and the most profitable one will be used for further analysis.

Considered pricing scenarios are listed below:

- Scenario A - end-user pays the Day-Ahead Market price plus 5% commission. In case of negative price, the aggregator and end user receive 5% and 95% respectively of the negative market price.
- Scenario B - end-user pays the Day-Ahead Market price plus 0.05DKK/kWh commission. In case of negative price the aggregator receives 0.05DKK/kWh (or less for Elspot prices between -0.05 and 0) and end-user earns the rest of the negative price, as presented in the Figure 3.8.
- Scenario C - flat tariff of 0.95DKK/kWh

Those three scenarios have been simulated for 1000 HPs used to heat houses described in section 3.3. The results are presented in the Table 3.7.

Table 3.7: Heat pump simulation results for 1000 HPs and 3 considered pricing scenarios

Scenario name	**Energy consumed [GWh]**	**Income [kDKK]**	**Cost of purchase at Elspot [kDKK]**	**Gross income [kDKK]**
A	1754.9	1204.1	1146.6	57.567
B	1754.9	1233.8	1146.6	87.183
C	1754.9	1684.7	1146.6	538.12

It can be observed that scenario C with a flat tariff is the most profitable one. This happens due to the fact, that thanks to the algorithm described in equations (3.12) the average purchase price is 653 DKK/MWh, which is visibly lower than the flat tariff which was simulated. Price of 0.96DKK/kWh represents the 84th percentile of the Day-Ahead Market prices in 2020.

3.4 Conclusion

Based on the models of controllable loads of HPs and EV chargers different simulations have been performed in order to predict consumers' behaviour under different pricing mechanisms and different charging schemes. Those have been compared assuming ideal behaviour of the users, in particular the ones choosing smart charging.

It has been proven that implementing different pricing mechanisms than stable flat tariff over whole year and providing a price incentive to end-users to shift their demand to a periods with cheaper energy is a successful method to consume energy in a more efficient way, based on the signals coming from electricity markets.

Based on the information obtained in this chapter more advanced aggregation scenarios will be examined in the next chapter to build a realistic model of different approaches to aggregating large number of consumers that are to choose various charging schemes and also owning other distributed grid assets like PV panels.

Simulations in this chapter did not take into account random events that may disrupt the process of aggregation and make it look different than components modelled so far. In the next chapter, such events will be included to some extent.

Pricing mechanisms for each type of flexible load, that have been selected and will be used in further simulations in Chapter 4 are presented in Table 3.8.

Table 3.8: Pricing mechanisms chosen for further simulations

<table>
<tr><th colspan="2">Load type</th><th colspan="2">Price</th></tr>
<tr><td rowspan="6">EV</td><td>Dumb charging</td><td colspan="2">120.55ore/kWh</td></tr>
<tr><td rowspan="3">ToU tariffs</td><td>144.66ore/kWh</td><td>7-10AM
4-9PM</td></tr>
<tr><td>120.55ore/kWh</td><td>6-7AM
10AM-1PM
2-4PM
9-11PM</td></tr>
<tr><td>96.44ore/kWh</td><td>11PM-6AM
1-2PM</td></tr>
<tr><td>Flex Settlement</td><td colspan="2">Market price + 5ore/kWh</td></tr>
<tr><td>Smart charging</td><td colspan="2">75ore/kWh</td></tr>
<tr><td colspan="2">HP</td><td colspan="2">96ore/kWh</td></tr>
</table>

Chapter 4

Aggregation of distributed grid assets involving local generation

In this chapter, models of different distributed assets that have been introduced in the previous chapter will be aggregated and different aggregation scenarios will be introduced and compared. The idealistic behaviour shown in the models in chapter 3 will be complemented with stochastic events that may occur randomly in real life applications. Renewable distributed generation will also be considered for optimization of consumption and minimizing the cost of purchasing energy from the national grid.

4.1 Introduction

Chapter 3 introduced the techniques used to model the distributed grid assets separately, in particular the controllable loads - EVs and HPs. Apart from the assets themselves, also different levels of price-based demand side management were introduced.

Energy transition away from fossil fuels into energy efficiency and renewable energy sources has moved the electricity generation physically closer to the end-users. Many RES are connected to the distribution grid, not to transmission grid like large central power plants. Many smaller generating installations are owned by the end-users and connected to the national grid through the same point of connection, as the consumption. Good example of those, would be PV panels installed on rooftops. The most desired (and cheapest) method to utilize those generating units is to locally consume the locally produced renewable energy. It is not profitable to feed the generated energy into the national grid and import the energy. DSOs want to avoid reverse power flows, as the grid in residential, commercial and many industrial areas was initially designed and constructed to deliver energy from substations to the end-user and not the opposite. For this reason DSOs and lawmakers introduce policies that discourage the prosumers from doing so.

Those policies have included solutions like forcing prosumers to sell locally generated energy at (typically low) market prices and to buy at (higher) regulated price or offering "grid storage" i.e. 70-80% and not all of the energy fed-in to the grid can be consumed later free of charge [32].

Therefore, apart from optimizing the energy consumption based only on the Day-Ahead Market prices it would be clever to consider also the availability of the locally generated energy, as consuming it is cheaper than importing and exporting the energy from and into the national grid.

In this chapter a concept of energy cluster will be introduced and different solutions will be tested in terms of aggregating the flexible loads.

4.2 Energy clusters and solar generation

Energy cluster is a broad term used for agreements between instutional and non-institutional parties, that has a goal of generating and balancing energy supply using distributed (especially renewable) energy sources and/or energy storage. It includes legal ownership of the assets and administration of the energy generation, supply and management by the members of the local community [33]. Obviously they can outsource some of this activity to an external party like an aggregator, which is the case considered in this project.

It is a similar concept to a microgrid, which is more of a technical term describing remote or isolated grids that are able to operate correctly without significant support from the stiff, national grid. Ideally a microgrid is able to be disconnected from it and maintain security of supply while being islanded. To achieve it, a microgrid must contain of distributed generation and therefore it is such a close concept to an energy cluster (which is more of a legal term).

Energy clusters operate typically within a specific geographic area and have clear borders. Their sizes may be different and maximum area is usually specified by law and differs from country to country.

Energy clusters are a very important component for energy transition we are facing right now. Successful implementation of a self-sufficient microgrid can increase the utilization of RES, but unlike large wind farms it does not negatively impact the national grid in terms of typical problems occurring due to fast diffusion of energy generation that is stochastic, such as high flexibility needed to be provided by conventional blocks when renewable generation changes quickly over time. Changes in the generation output and especially fast changes in conventional power plants lead to higher failure rate of installations in steam units, which is undesired. [34]

The energy cluster considered in the next part of the project will contain EVs with EV chargers and HPs that will be simulated as described in chapter 3. Additional to that the cluster will have also PV panels that generate renewable energy.

Power output of those will be simulated based on the hourly power system data provided by Fraunhofer Institute for Solar Energy Systems and installed PV capacity in Denmark. [35, 36]

It is assumed that capacity factor of the simulated PV panels is the same as for entire Denmark. For example if solar panels at a given time generate 0.65GW and 1.3GW is their installed capacity, then it is assumed, that in the simulated microgrid local PV panels also generate 50% of their installed capacity.

Energy cluster and its components that will be simulated are presented in the Figure 4.1. Different shares of the presented components will be used in different aggregation scenarios in order to find the most efficient solutions in terms of economic performance and best utilization of locally generated energy.

It should be noted that in case of no storage installed, the excess energy that was generated and could not be fully consumed, must be fed into the grid. It is not desired, as the DSOs and lawmakers introduce policies that discourage to do so. [32]

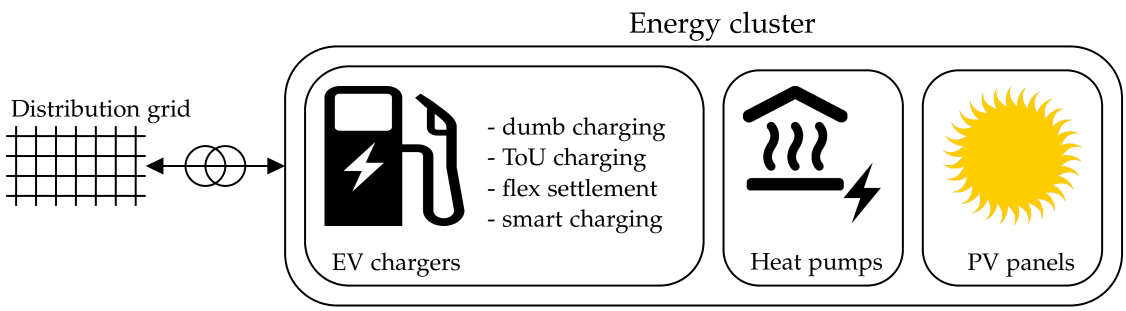

Figure 4.1: Energy cluster and its components

In terms of energy trading, the energy that the aggregator purchases from the power exchange and local prosumers at market prices is his cost. It is later sold to the end-users, which makes for the aggregator's income according to the tariffs shown in chapter 3 and chosen based on the simulation results in chapter 3.2. If generation largely exceeds the needs of a cluster and grid is fully capable of handling larger exports, then a cluster may take part in the energy market as both buyer and seller. It may also start a direct supply contract with an entity with large consumption levels, such as an energy-intensive business, another energy cluster or another aggregator. Connection to the national grid still has to be maintained to fully utilize the assets within the cluster by reacting to the signals that may come from national power system like large increase in generation from offshore wind farms.

4.3 Distributed generation within the microgrid

The main goal of an aggregator in case of a significant renewable energy generation is to utilize as much of that locally generated energy as possible in order to minimize the cost of energy that must be purchased from the national grid. In case of negative energy price, similarly the aggregator wants to avoid the cost of feeding the energy into the grid in order to sell it at negative prices. It is compliant with the main principle of an energy cluster, which is increasing the energy independence of the community from import from the national grid and self-consuming the self-produced energy. The business model of DSO should not be however influenced when reaching those goals, as the DSO still owns and operates the network within the cluster, as well as the connections to the national grid which still must be maintained considering current grid codes [37].

For this reason the optimization algorithms had to be adjusted and generation from the PV panels must be integrated to them. The algorithms implemented are visibly different from the ones used when entire energy is purchased from the grid. The algorithms are to control all HPs and all smart chargers within the cluster, based on the market price signal and PV generation signal.

Smart charging algorithm with included PV generation

Unlike algorithm shown in equation (3.6), the new one uses the data aggregated from the entire microgrid. It does not work separately for each individual end-user. This is due to the fact that not all EV owners have also PV panels and vice versa, therefore from the aggregator's point of view it is more desired to let the locally generated energy be consumed by someone else in the community (other than the asset owner), as exporting to the national grid is undesirable by DSOs and is less profitable than utilizing within the cluster.

$$
\begin{aligned}
\underset{q_m, q_{m+1}, \dots, q_{m+n}}{\text{Minimize}} \quad & C(q_m, q_{m+1}, \dots, q_{m+n}) = \sum_{i=m}^{m+n} [p_i \cdot (q_i - E_{PV,i})] \\
\text{subject to} \quad & h\left(q_m, q_{m+1}, \cdots, q_{m+n}\right) = \sum_{i=m}^{m+n} q_i - Q_{max} = 0 \\
& g_1\left(q_m, q_{m+1}, \cdots, q_{m+n}\right) = \forall q_i - N_{cars} \cdot Q_{ch} \leq 0 \\
& g_2\left(q_m, q_{m+1}, \cdots, q_{m+n}\right) = -\forall q_i \leq 0
\end{aligned}
\tag{4.1}
$$

For this reason, in the the local generation from PV is included here, and algorithm including it is presented in equations (4.1), $E_{PV,i}$ stands for the energy that is generated locally in i-th hour of the charging period starting in m-th hour of the year and lasting n hours. It is a value that stands for energy generated from all PV panels in the entire cluster. Similarly q_i stands for the energy consumed in the entire cluster, not by individual consumer.

The cost function in this case must be adjusted, as the cost of energy purchased depends on the energy generated locally. The more energy is generated locally, the lower the cost (or higher if the prices are negative - then the algorithm maximizes the consumption to avoid paying the negative price for feeding the energy into grid).

The constraints are similar to the ones in equations (3.6). Q_{max} in the first constraint, that stands for the remaining battery capacity in all EVs that has been summed up. In the second constraint, the charger maximum capacity Q_{ch} is multiplied by the number of cars being charged.

The algorithm has an assumption that once the charging event starts, there is information available about forecasted weather conditions until the end of the charging event, which allows to accurately predict the generation output that can be used to optimize the power consumption.

Impact of PV on HP dispatch algorithm

Similarly the algorithm for heat pumps is adjusted to take into account another input value, which is the amount of locally generated energy at a given time. The cost of energy purchased from the grid is therefore not only depending on the electricity consumed, but on the difference between consumption and generation that must be supplied by the national grid.

$$
\begin{aligned}
\underset{E_{HP,el}}{\text{Minimize}} \quad & C_t(E_{HP,el}) = (|E_{HP,el}| - E_{PV}) \cdot p \\
\text{subject to} \quad & g_1(E_{HP,el}) = |E_{HP,el}| - N_{house} \cdot E_{HP,el,max} \leq 0 \\
& g_2(E_{HP,el}) = \frac{COP \cdot E_{HP,el} + \rho \cdot N_{house} \cdot V \cdot C_{p,air} \cdot T_{in,t-1} + T_{out,t} \cdot N_{house} \cdot \sum(A \cdot k_c)}{\rho \cdot N_{house} \cdot V \cdot C_{p,air} - N_{house} \cdot \sum(A \cdot k_c)} - T_{max,in} \leq 0 \\
& g_3(E_{HP,el}) = T_{min,in} - \frac{COP \cdot E_{HP,el} + \rho \cdot N_{house} \cdot V \cdot C_{p,air} \cdot T_{in,t-1} + T_{out,t} \cdot N_{house} \cdot \sum(A \cdot k_c)}{\rho \cdot N_{house} \cdot V \cdot C_{p,air} - N_{house} \cdot \sum(A \cdot k_c)} \leq 0
\end{aligned}
\tag{4.2}
$$

Constraints remain the same as in algorithm used initially, shown in equation (3.12), except for multiplying the energy losses by the number of houses, as the consumption and generation is now aggregated from all individual end-users.

It should be noted that optimization algorithms shown in equations (4.1) and (4.2) do not impact each other at current stage i.e. the consumption of EV chargers is not taken into account when determining the HP electricity consumption and vice versa.

4.4 Components of the tested microgrid

Microgrid that will be tested will initially consist of the following components:

- 10 000 electric HPs suppling 120 m^2 houses as explained in chapter 3.3. Each HP has a maximum power of 1.8kW_{el} and can be used for both heating and cooling.
- 8000 EV chargers of 3.7kW maximum power supplying cars with characteristics similar to popular models mentioned in chapter 2.3.1 and driving patterns shown in chapter 3.1.1.
- 6000 - 60% of the houses are equipped with PV panels. Each has part of the roof covered with PV panels, each having 180W_{peak}/m^2 [38]. In Denmark the vast majority of PV installations (approx. 95%) are represented by residential roof-top PV systems with power levels below 6 kW [39]. Therefore, it will be assumed that those 6000 houses have PV panels with installed capacities of 5kW_{peak} in each. Which makes up 30MW_{peak} combined.

It is presented in the Figure 4.2.

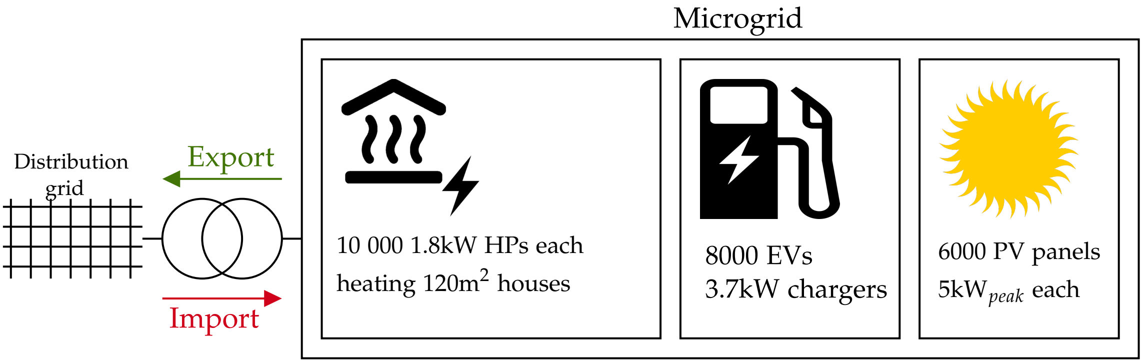

Figure 4.2: Tested microgrid and its components

Firstly, a microgrid consisting only of these assets will be simulated and potential changes will not require installations of new devices. The non-controllable loads like most of other domestic installations will not be included in the simulations. Main goal of the aggregation will be to maximize the utilization of locally generated renewable energy and economic profit will be a secondary matter. Further, additional resources will be proposed that would however require major investments.

Several scenarios will be taken into account in terms of different charging schemes and the number and share of end-users choosing each of them among all aggregated loads. The charging schemes to be aggregated have been presented in details in chapter 3.2 and the ones that have been selected were presented in Table 3.8.

In each scenario, the number of EV owners choosing all aforementioned charging schemes will be different. Scenarios that will be simulated are as presented in the Figure 4.3. HPs in all scenarios are using the same scheme - flat tariff of 0.95DKK/kWh with a smart dispatch algorithm presented in formula (4.2).

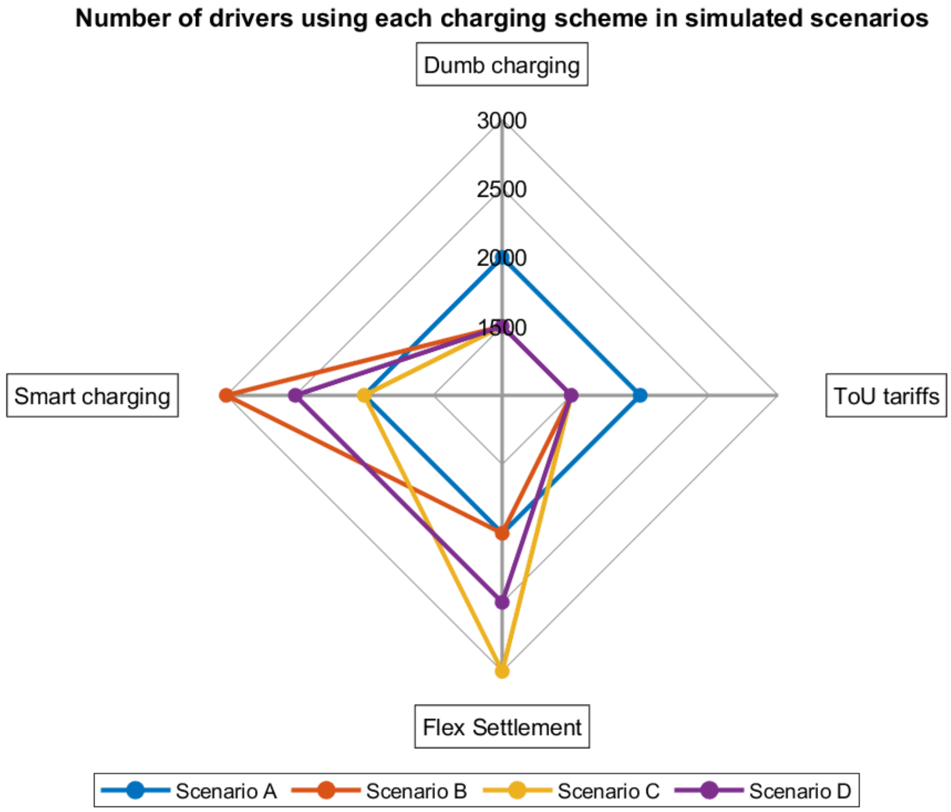

Figure 4.3: Graphical presentation of the simulated aggregation scenarios

These scenarios will be compared with regard to economic profit and utilization of locally generated energy. Scenario A is the most neutral one, where equal number of drivers use each charging scheme. In scenario B the smart charging is prioritized over dumb charging and ToU tariff users, therefore 500 drivers are moved from each of those to the smart charging scheme and number of drivers using flex settlement remains the same. Scenario C prioritized flex settlement in the same way and leaves number of smart chargers same as in scenario A. Last scenario prioritizes flex settlement and smart charging equally over dumb charging and ToU tariffs.

In the simulations 10% of users choosing smart charging will be treated as uncertainty factor. These drivers will not have their cars plugged-in to the charger in the charging hours, but will start their charging event randomly. Simulation in chapter 3 was assuming an ideal behaviour of all end-users plugging-in their chargers during the charging hours.

In real-life application it may happen that end-users are unable to plug-in the car to the charger and an assumption is made that it occurs to 10% of drivers daily. Aggregator should think of a framework that would discourage the drivers from doing so, like setting a limit to the number of days each month when driver is allowed to do so and applying some penalties when the limit is exceeded.

Those drivers that have chosen smart charging scheme, but failed to fulfill their part of the contract are assumed to charge their EVs like dumb chargers and will be distributed over time randomly. They will also pay the same flat tariff as the dumb chargers do.

Profit calculation will not be influenced by the generation from the PV panels. An assumption is made that the aggregator buys energy from the PV owners on the same Day-Ahead Market price as he buys energy that is delivered from the distribution grid and later sells it to the end-users at the price agreed in the contract, just as if no PV panels were included.

Energy that is generated, but not consumed and must be fed-in to the external distribution grid is not included in the aggregator's income. It is assumed that the owners of the PV panels will directly benefit from it, without the middle-man.

4.5 Results of the simulated scenarios

Scenarios presented in the previous section will be compared using different values to assess which aggregation technique is the best in terms of economic profits, utilization of locally generated energy and energy independence. Those values are:

- energy generated
- energy consumed
- energy imported
- energy exported
- profit

It is desired that energy import and export should be as small as possible, and profit should be as high as possible. It can happen that imported and exported energy values are better in terms of utilization of local generation and energy independence (lower), but profits are also lower than in other scenarios. In such situations, higher priority is given to the first indicators.

Simulation results for the scenarios presented in Figure 4.3 are presented in the Table 4.1. It sums up simulations performed for year 2021 with 1h long intervals.

Table 4.1: Results of four aggregation scenarios

Scenario name	**Energy consumed [GWh]**	**Energy generated [GWh]**	**Energy imported [GWh]**	**Energy exported [GWh]**	**Profit [MM DKK]**
A	37.089	32.460	26.399	21.770	12.418
B	37.167	32.460	27.142	22.434	11.864
C	37.109	32.460	26.365	21.716	11.224
D	37.138	32.460	26.745	22.067	11.545

It can be observed that best results in terms of energy import and export were obtained in scenario C, where the strongest focus was given to flex settlement. Therefore it can be said that this pricing scheme is the most successful in informing the end-users about the availability of cheap energy and shaping their demand curve in the way, that helps to utilize the local generation in the most efficient way. However, it should be noted that this scenario brings the smallest economic profits.

On the other hand, the worst results were obtained in scenario B, where the highest number of drivers was using smart charging. The reason of that is the fact that smart charging is happening between 10 PM and 6 AM, when generation from PV panels is low or none. Therefore it can be said that smart charging algorithm, that was developed in this project is a useful tool for optimization of energy purchase and making most profits from the volatile market prices, but not for utilization of locally generated renewable energy. When there is no generation and smart chargers consume energy, then it must be imported. At the same time, scenario B moves drivers from dumb charging and ToU tariff charging to smart charging, as most of the first two groups of drivers start their charging events in late afternoon, when local generation from PV panels is still high. This consumption is moved to the night hours, when smart charging occurs and therefore export is increased.

Biggest profits were obtained in scenario A. This happens due to the largest number of drivers using dumb charging scheme and scheme with ToU tariffs. In these two pricing schemes, the prices payed by end-users are the highest compared to average prices occurring with flex-settlement and to low flat tariff payed by smart chargers.

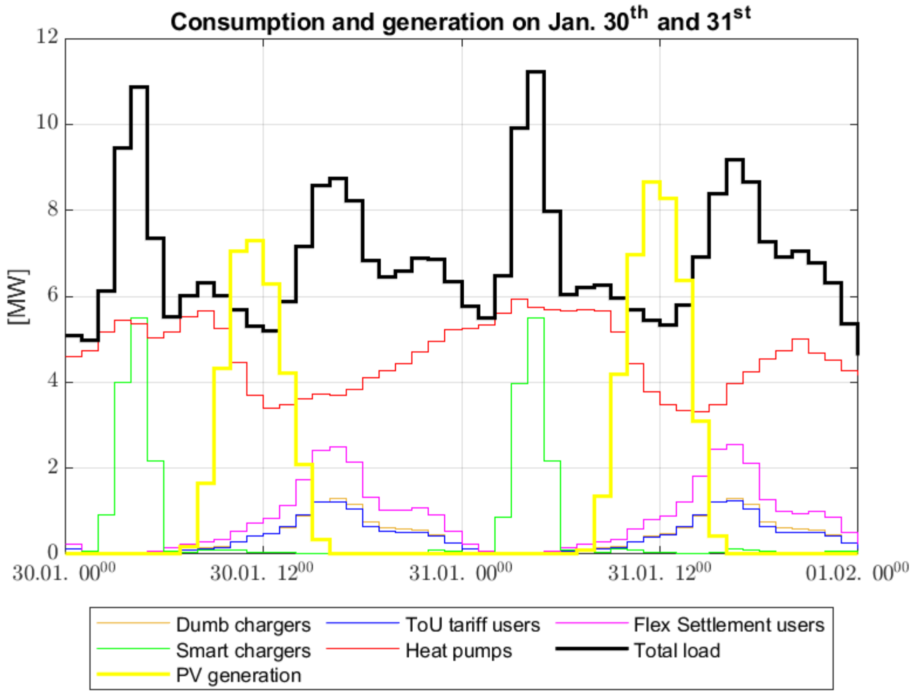

Figure 4.4: Influence of 100MWh battery storage in winter

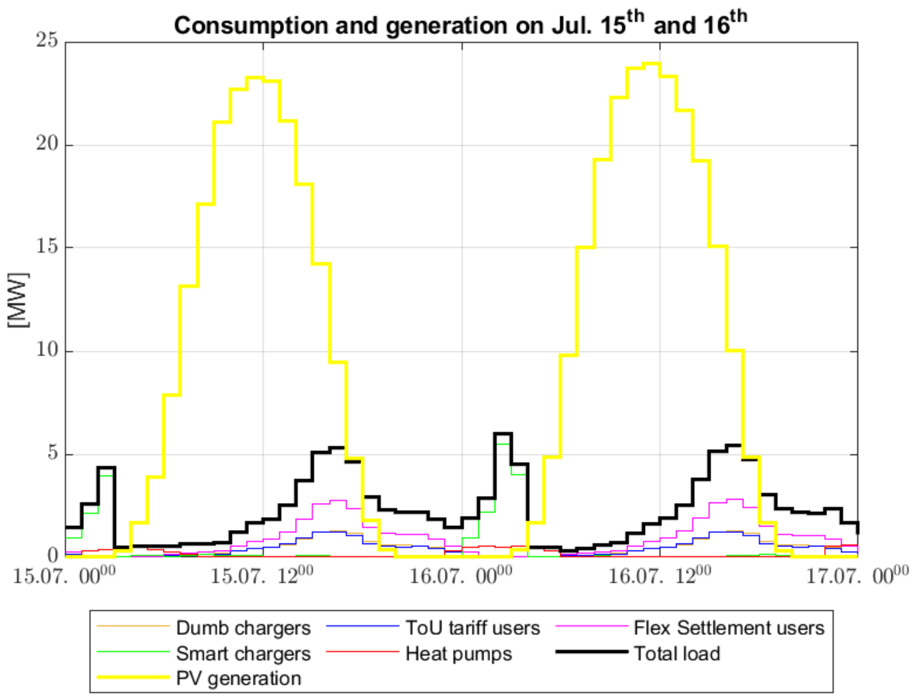

Figure 4.5: Influence of 100MWh battery storage in summer

Negative impact of smart chargers on import and export indicators is also visible in scenario D, where those indicators are second worst after scenario B. It can be seen that negative impact of increased number of smart chargers (compared to scenario A) is not compensated by increased number of flex settlement users.

Scenario C has been chosen for next simulations, that will measure the impact of additional resources.

How smart charging moves consumption from hours with high PV generation can be clearly seen in Figures 4.4 and 4.5, where large spikes in the consumption curve are observed shortly after midnight. It can also be clearly seen how the consumption of heat pumps varies over the year. In winter days it was always above 3MW, while in summer it did not exceed 1MW. Overall monthly consumption, generation and resulting needs to import or export energy is presented in Figure 4.6.

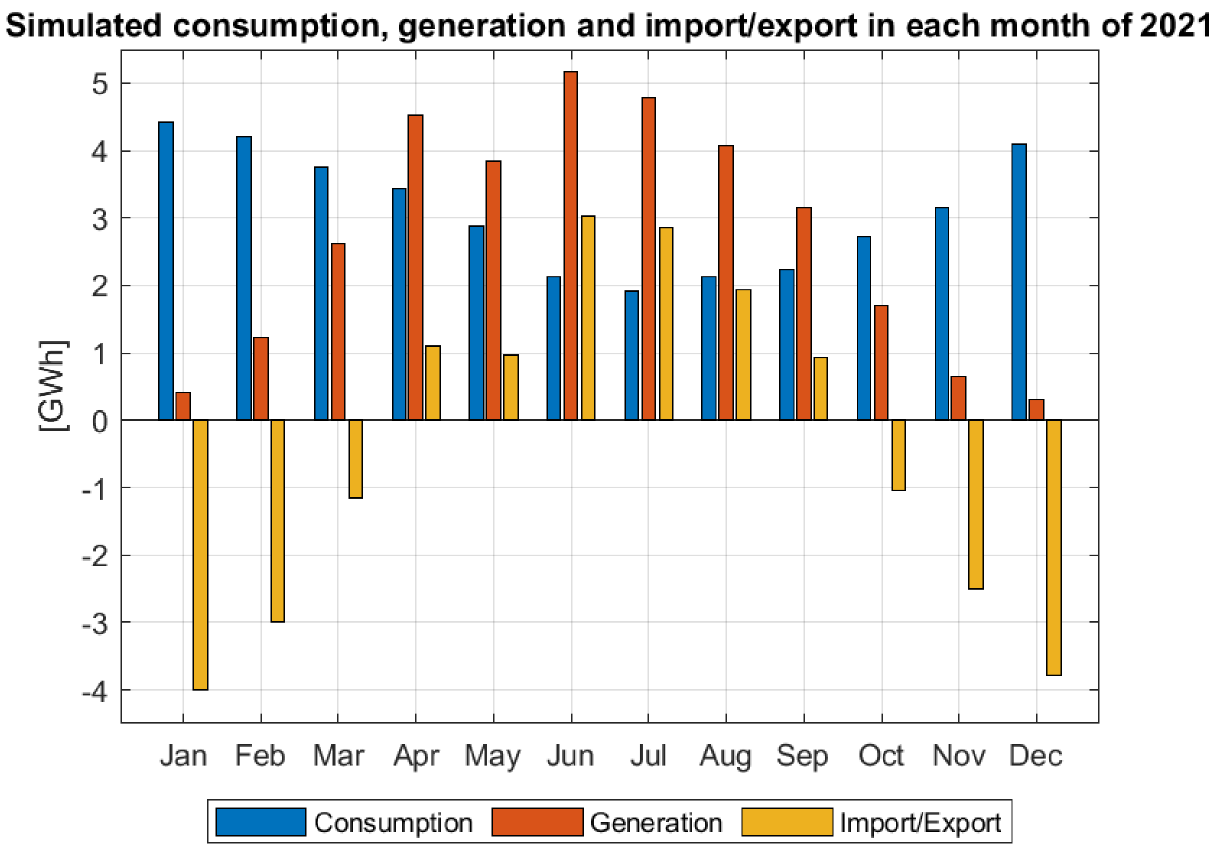

Figure 4.6: Monthly consumption, generation and exchange with the distribution grid

It can clearly be seen that HPs visibly increase the demand for electricity in winter months, which is not met by much smaller generation from PV panels.

4.6 Additional grid-side resources

In this section the resources listed in chapter 4.5 will be complemented with additional resources that can improve the utilization of locally generated energy and energy independence of the microgrid. The number of EVs and HPs will remain the same, as before and the distribution of pricing schemes among drivers will be as in scenario C from Figure 4.3.

4.6.1 Additional PV panels

First solution for improvement of the aggregation and performance of a microgrid, that will be simulated, is the increase of the generation capacities. As can be seen in Table 4.1, the generation was about 10% smaller than the consumption. For this reason, the generation capacities will be increased by 10%, 20% and 30%. The results of such improvements will be presented in the Table 4.2.

Table 4.2: Results of the simulation before and after increasing PV capacity

PV capacity	Energy consumed [GWh]	Energy generated [GWh]	Energy imported [GWh]	Energy exported [GWh]	Profit [MM DKK]
$30MW_{peak}$	37.109	32.46	26.37	21.72	11.224
$33MW_{peak}$	37.109	35.705	26.071	24.668	11.223
$36MW_{peak}$	37.109	38.951	25.807	27.65	11.224
$39MW_{peak}$	37.109	42.197	25.568	30.656	11.224

After adding new capacities the annual generation obviously increase at a rate of c.a. 3.245GWh/year for every $3MW_{peak}$ being added. Considering those values, the average capacity factor is 12.3% for the PV panels in Denmark. From the results it can be seen that most of the increase in generation is being exported at the end, while import decreases in a much smaller range. For each $3MW_{peak}$ extra being installed, the import decreases by no more than 300MWh/a and export increases by over 2.9GWh/year. Therefore it can be said that adding new PV panels is not very efficient in terms of improving utilization of locally generated energy as most of it can't be self-consumed within the microgrid and ends up being fed-in to the external, distribution network.

For this reason it has been chosen not to include extra PV panels in further simulations, where another solutions for improvements will be tested.

4.6.2 Energy storage

With fast progress in storage technologies like fuel cells or lithium-ion batteries and their growing capacities and availability it is becoming possible and more accessible to store electrical energy on the local level, among residential end-users who are connected to the low-voltage distribution grid. During most of the history of electrification, it was possible mainly in large pump-storage hydro power plants with (dis)charging capacities of up to gigawatts.

Today, more and more domestic PV installations are equipped with a battery, as feeding the generated energy in to the distribution grid is undesired by the DSOs and they are discouraging the PV owners from doing so. They use a low buying tariff or different mechanisms to achieve so.

Therefore, second solution for improving the performance of aggregated resources in a microgrid will be adding batteries acting as energy storage - not only (like in EVs) to be utilized for transport.

Batteries will be added to the resources listed in chapter 4.4 in scenario C. There will be five battery sizes compared with each other including a control scenario without any battery. They are presented in the Table 4.3. Maximum charging speed is chosen to be 0.1C, which means that a battery is fully charged 0-100% in 10h. Faster charging is technically possible, but should be avoided, as it may increase the battery wear [40].

Table 4.3: Information about the scenarios with different battery sizes

Scenario name	**Battery capacity [MWh]**	**Maximum (dis)charging speed [MWh/h]**
I	0	0
II	100	10
III	150	15
IV	200	20
V	250	25

Influence of the battery is simulated using an algorithm shown in the flowchart in the Figure 4.7.

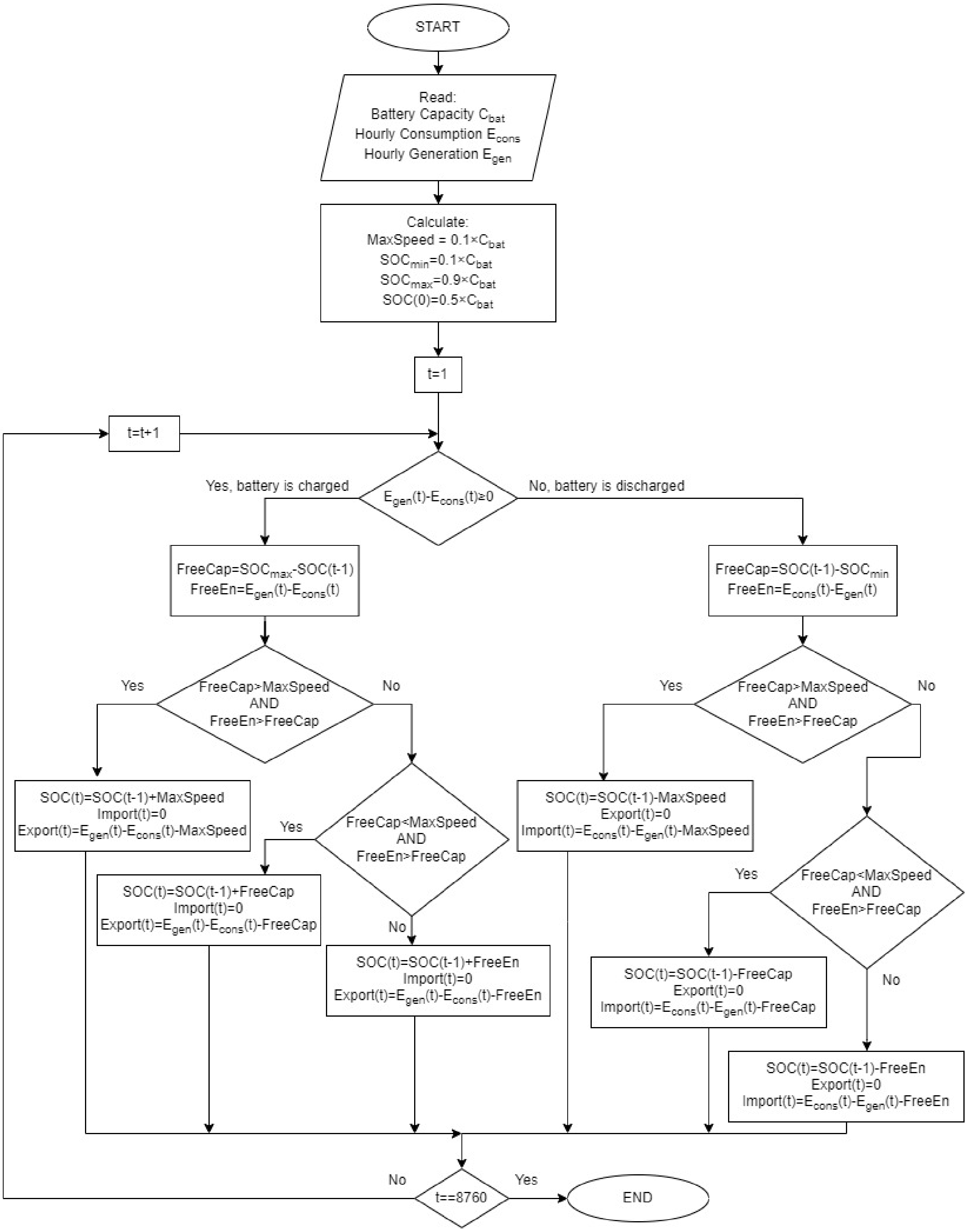

Figure 4.7: Flowchart showing the (dis)charging algorithm

The results of the simulated scenarios are presented in the Table 4.4. It should be noted that adding the battery does not impact the overall consumption and generation.

Table 4.4: Results of the simulated battery scenarios

Scenario name	Energy consumed [GWh]	Energy generated [GWh]	Energy import [GWh]	Energy export [GWh]
I			26.373	21.723
II			16.05	11.44
III	37.109	32.46	15.671	11.082
IV			15.487	10.917
V			15.366	10.816

It can be observed that adding a battery very strongly influences the export and import compared to a control scenario without any battery. By adding batteries with a combined capacity of 100 MWh, the import is decreased by about 40% and export by about 46%. What should be noted, is that adding further battery capacities has much smaller impact on considered indicators. Clearly it can be seen that while first 100MWh in storage decreases both annual import and export by c.a. 10000MWh, while second 100MWh (scenario IV) further decreases those values by only c.a. 500MWh. Considering high cost of installing batteries (209$/kWh), it can be said that the smallest battery size out of the considered ones should be suitable and brings acceptable results. [41]

Adding the 100MWh battery helped to increase the share of locally generated renewable energy in the overall consumption from 29% to 57%, which is a very significant increase. At the same time it decreased the export from 67% of the generated energy to only 35%. Battery's influence can be clearly seen in short time frame on two selected days in winter and in summer, which is presented in Figures 4.8 and 4.9 respectively.

It can be seen that in summer battery charges to the maximum allowed level in the morning which prevents the energy being exported to the external grid and in the evening, when the sun is set it, the battery discharges to fulfill the demand from arriving EVs. The amount of stored energy is large enough to fully supply the needs and no import is necessary. In winter however the generation was small and even though for 3-4h it was exceeding the demand, the amount that could be stored was used in 2h.

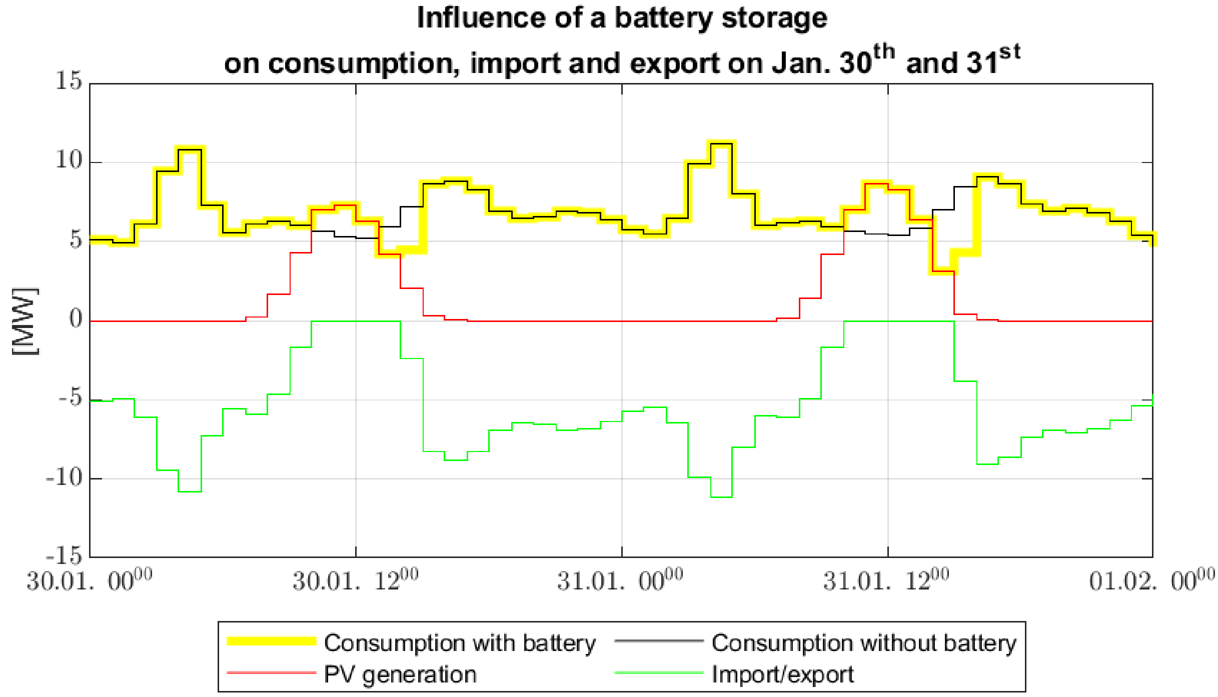

Figure 4.8: Influence of 100MWh battery storage in winter

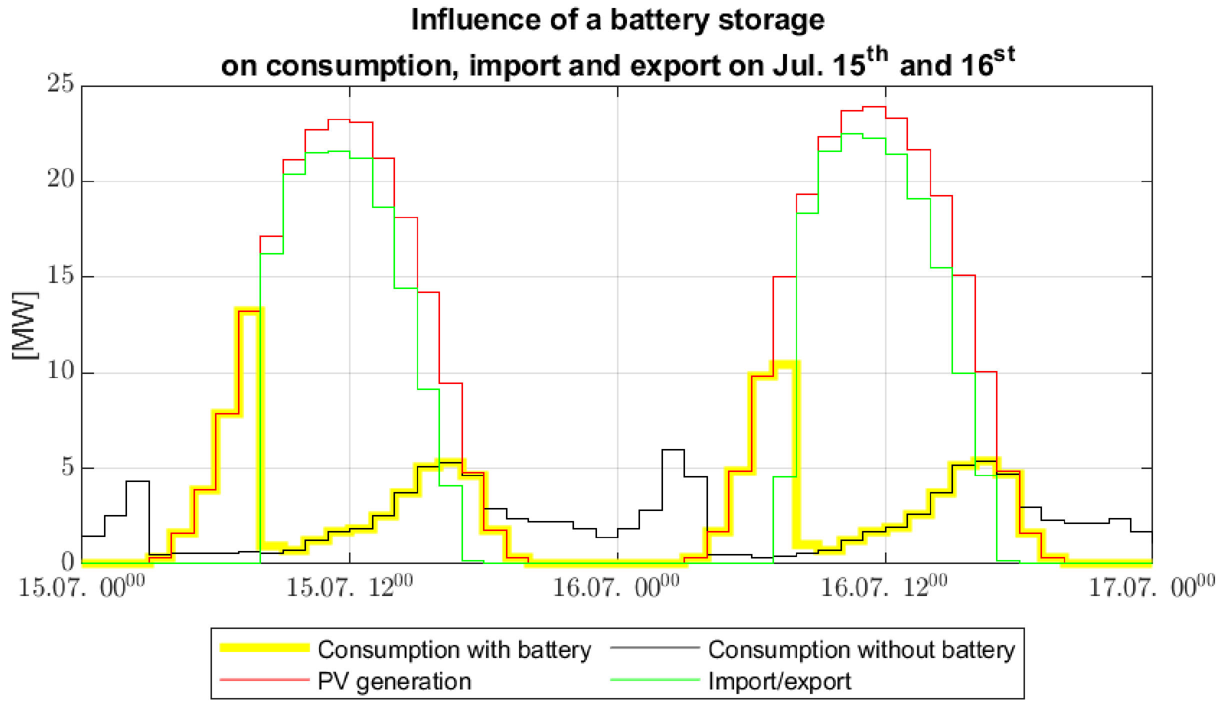

Figure 4.9: Influence of 100MWh battery storage in summer

How the battery changes the results obtained by differences in the selection of pricing schemes among the EV owners is shown in Appendix B.

4.7 Conclusion

In this chapter, several simulations were conducted to measure the performance of different aggregation techniques and various grid-side resources. Initially, it has been proven that the best performance (in terms of decreasing export and import) was obtained with increased number of drivers using flex settlement. Smart charging wasn't the most efficient tool to fulfill the same objective, as it was happening overnight and local generation was happening during the day. Therefore in case of no battery installed, the aggregator should try to increase the number of flex settlement users in his portfolio.

Second important part of this chapter was a simulation of extension of the aggregated grid-side resources i.e. adding new PV panels and adding a battery storage. The simulations showed that increasing PV capacities has poor results, as import is decreased to a very small extent and export increases much larger, which is undesired. Better results were obtained with adding a battery. However it should be noted that increasing the battery capacity has larger impact with the first storage capacities installed and proportionally increasing it, does not result in a proportional improvements of energy import and export numbers. Therefore, considering the costs of battery purchase and installation, the most optimal size should be chosen.

Battery almost completely neutralizes the impact of different pricing schemes on import and export. However, even though, pricing mechanisms have a major impact on obtained profits. Therefore, when large storage capacities are installed, aggregator may focus only on increasing the profits, as energy independence and utilization of local generation goals can be fulfilled.

Chapter 5

Discussion

In this chapter, the results obtained in previous chapters will be discussed and conclusions about different aggregation techniques will be drawn.

5.1 Pricing mechanisms

Different pricing mechanisms for EV charging were simulated. Those were:

- dumb charging with a flat tariff
- dumb charging with ToU tariffs
- dumb charging with Flex Settlement - market price plus a commission
- smart charging

Smart charging has proven to be the most cost-efficient method of charging EVs. The algorithm which was used, has decreased the average purchase price to 471.6DKK/MWh, which is 33% lower than the average purchase price of 702.4DKK/MWh which occurs "naturally", when no price signal was provided to the end-users that would have influenced their behaviour.

When looking at pricing schemes with such price signals, Flex Settlement has proven to be much more efficient in decreasing the purchase cost than ToU tariffs. Flex Settlement reduced the average purchase price by about 40DKK/MWh, while the tested ToU tariffs did not reduce this value by more than 5DKK/MWh.

Flex Settlement prices, unlike ToU tariffs, reflect the market prices much more precisely, as they are updated every day and demand is shaped by them directly. ToU tariffs must be agreed on at the beginning of each billing period, based on the prices in the previous one (in the project it was based on the year 2020 for year 2021). It may happen that in the period with high market prices, when a decrease in demand would be desired, the ToU tariff would provide an incentive to the end-users to do the opposite and increase the demand, because in the previous year this hour of a day was one of the "cheap" ones.

Constant tariffs bring highest profits to the aggregator, as they are visibly higher than the average market prices for which energy is purchased. Obviously, the aggregator takes a risk of a loss, when he buys energy on the market and sells it at a constant price. What should be however noted, is the fact that market price was rarely higher than the simulated flat or ToU tariffs. Similar observation was made with HPs, where a flat tariff has proven to be more profitable than a commission.

Techniques that have been used are all associated with Demand Side Management (DSM). It means such operation of the grid resources that the demand curve is being shaped to match the non-flexible generation better, instead of controlling the generation to follow the load. Price incentives that have been simulated in the project can be a useful tool to do so. Type of DSM is Demand Response (DR), which stands for active control over the dispatch of different loads not only by the actual end-user, but also by other parties. Smart charging and HP dispatch based on Day-Ahead market price signal can be an example of such, as especially the time of charging the EV was chosen based on the information coming from the market. Similar algorithms could be developed, that use renewable or overall energy generation in the system as input value to a control algorithm.

5.2 Aggregated resources in energy clusters

Aggregation of loads and local generation has brought quite different results than expected by looking at each pricing scheme individually. After installing PV panels all aggregated resources were also treated within a microgrid, which is interested in increasing its independence from external grid and in utilizing the locally generated renewable energy sources to the largest extent possible.

When solar generation was included, the best results in decreasing the import and export of energy to and from the microgrid, were obtained with a larger number of Flex Settlement users compared to other charging and pricing schemes. Least successful at fulfilling those goals was smart charging, as it was mainly consuming energy at night, when there was no solar generation.

It could be however improved in a more advanced implementation of smart charging, in which end-users would be able to utilize the smart charging algorithm also in other times of the day if they want to. If the end-user is planning to use his car in the evening and does not want to use it during the day, then he may be interested in a smart charging scheme that would perform the charging event during day hours. Weekends and holidays would be a popular time to fully charge a car, especially in warmer months when PV generation is highest around 12PM. Also, businesses may be interested in such schemes with smart charging being stretched over time during working hours of their employees. When smart charging is scheduled to be performed overnight it is logical that it would not be able to utilize the solar generation that happens in the middle of the day.

After adding batteries to the microgrid, the impact of various charging schemes and differences between them was almost completely removed. Therefore it can be said that the aggregated resources themselves play a much larger role than how they are utilized in terms of their flexibility.

A battery storage is much more flexible than the EVs as it may be utilized at any time and to a much larger extent than EV batteries, as V2G operation is not intended to be used. Also a battery storage can be even more flexible than it was simulated. In the project it was used only to store energy generated within the microgrid, while it is also technically feasible to use it as a tool for speculation in the energy market, for example to buy energy at a low price, store it and utilize it during a period of high prices to avoid paying them, when buying energy on the market to be delivered using distribution grid.

5.3 Potential for improvement of optimization algorithms

What has not been included in the simulations is the consumption of loads other than HPs and EVs. It is an important factor, as the demand curve for non-flexible and non-controllable loads varies during the day. Including it would have a major impact on the results as it could be included in the HP and smart charging algorithm, just like non-flexible and non-controllable generation from PV panels was. Aggregation of those however would not directly contribute to increasing the power system flexibility, but indirectly could do so, if being integrated to the optimization algorithms in HP and smart charging control algorithms. In a real-life application, all charging schemes should also take into account any considerable constraints about voltage level, transformers and cable maximum capacities.

$$
\begin{aligned}
\underset{q_{EV,m},E_{HP,m},\ldots,q_{EV,m+n},E_{HP,m+n}}{\text{Minimize}} \quad & C(q_{EV,m}, E_{HP,m}, \ldots, q_{EV,m+n}, E_{HP,m+n}) = \sum_{i=m}^{m+n} p_i \left(q_{EV,i} + |E_{HP,i}| + q_{NC,i} - E_{PV,i}\right) \\
\text{subject to} \quad & h\left(q_{EV,m}, \ldots, q_{EV,m+n}\right) = \sum_{i=m}^{m+n} q_{EV,i} - Q_{max} = 0 \\
& g_1\left(q_{EV,m}, \ldots, q_{EV,m+n}\right) = \forall q_{EV,i} - Q_{ch} \leq 0 \\
& g_2\left(q_{EV,m}, \ldots, q_{EV,m+n}\right) = -\forall q_{EV,i} \leq 0 \\
& g_3\left(E_{HP,t}\right) = \forall \left|E_{HP,t}\right| - N_{house} \cdot E_{HP,max} \leq 0 \\
& g_4\left(E_{HP,t}\right) = T_{in,t} - T_{in,max} \leq 0 \\
& g_5\left(E_{HP,t}\right) = T_{in,min} - T_{in,t} \leq 0
\end{aligned}
\tag{5.1}
$$

Smart charging and HP dispatch algorithms that have been simulated were not integrated with each other. They were operating those loads based on either market price signal and local generation signal or market price signal only. In this way, they could be offered to a larger group of end-users as both algorithms require only HP or EV charger as controlled system, even outside of aggregated microgrid that requires integration of all assets to balance consumption and generation within it. To improve the performance of all assets, they can be integrated as shown in equations (5.1). The cost function to be minimized includes not only the PV generation E_{PV} like it did in Chapter 4, but also the non-controllable loads that were not included in the project at all. $q_{EV,t}$, $E_{HP,t}$ and $q_{NC,t}$ stand for energy consumption at time t of EVs, HPs and non-controllable loads respectively.

5.4 Interests of different parties to be considered

In the project only two parties were looked at, when it came to their economic profits - the aggregator and the end-users (sometimes forming an energy cluster). There are however different entities that are important players in energy sector that haven't been analysed deeply in this project. Those are network operators - DSOs and TSOs. These players can be influenced by the diffusion of renewable generation and by increasing number of energy communities. Energy clusters tend to increase the utilization of local generation to reduce the energy that must be imported or exported to and from cluster. This could negatively influence the business model of grid operators, however it is not very likely at current stage, as such communities are firstly, far from being able to completely balance the consumption and generation without aid from the national grid and secondly, according to current grid codes such communities must still be connected to the national grid [37].

Grids within the microgrid and connections to the national grid would still have to be operated and since they are owned by the DSO, his revenue from providing operation and maintenance of it should be secured. It should be however noted, that diffusion of loads like EVs or HPs (which have larger needs than most household appliances) and desire to optimally shape their consumption in an optimal way can require reinforcements to the existing grid and other investments like larger transformers. Different aggregation scenarios can influence these issues to some extent and even help avoid those costs.

One of the solutions for DSOs to operate in the ongoing process of diffusion of distributed RES is local marginal pricing based on congestions occurring in distribution grid. It would be a similar solution to what is already implemented in many countries on a transmission level, where there are many price zones, with potential for market coupling between them when there aren't any congestions.

Another solution, would be DSOs buying flexibility from different units who could provide them (those would be mainly gas turbines in most of Europe) and later take a fee for congestion management in the energy costs.

Ancillary services and balancing market

DSOs and TSOs should also not be worried about loosing customers, as connection to the national grid can open up a new business opportunity to the aggregator and the end-users within the microgrid. First one of those is taking part in balancing market and other intraday trading, where large flexibility is crucial to take part in. Second source of extra revenue would be offering ancillary services like frequency control or voltage control. Assets like EV batteries and battery storage can be used for this purpose very efficiently, when optimally scheduled and aggregated. Such services rely on compensating short timescale (seconds and shorter) fluctuations. For this reason it wasn't included in the simulations, but an aggregator should consider adding such service to its portfolio.

5.5 Evaluation of objective fulfillment

It has been observed that tested aggregation techniques have proven successful at decreasing the costs of energy supply. In dumb charging scenario, where end-users were not provided with any price signal to change their consumer behaviour the resulting price was 702.4DKK/MWh and by implementation of smart charging and Flex Settlement, it dropped by over 200DKK/MWh and 40DKK/MWh respectively for users choosing these schemes.

Looking only at the loads and generation considered, the results in maximizing the utilization of locally generated renewable energy were largely improved by adding a battery storage of 100MWh. Without it, most of locally generated energy ended up being exported to the national power system instead of being consumed within the energy cluster. It can be said that the success of optimal aggregation is much more dependent on the number, proportions and types of aggregated assets, rather than on selection of pricing mechanisms, simulations shown in Appendix B have shown that as well.

Chapter 6

Conclusion and future work

6.1 Conclusions

Different techniques can be used for aggregation of grid-side resources. Apart from the resources themselves like distributed generation or large flexible, controllable loads, aggregator (unlike a conventional retailer) can take a more active approach in shaping the demand curve by implementing different pricing mechanisms that influence the consumption due to price elasticity of demand. Aggregator may also implement a form of demand response which is using optimization algorithms to dispatch HPs and EV chargers in a most efficient way.

The project has shown how the theory of economics can be used to influence the behaviour of consumers and shape the demand curve in a way that is desirable by any concerned party which in this project was an aggregator and to a large extent the community of energy cluster as well. Methods that have been tested in this project, after relevant extensions and developments can be used by DSOs, TSOs and system operators to prevent and mitigate different undesired situations like grid congestions or large mismatch between generation and consumption in the energy system that requires increasing the exchange at interconnectors.

It has also been shown which pricing schemes bring highest profits. Generally the ones with flat tariffs and ToU tariffs were the most profitable, as they were visibly higher than the average purchase prices in each EV charging scheme and in HP dispatch scheme. In pricing schemes with a fixed commission the risk of selling energy to the end-user at a loss is removed, but the potential profits are much lower.

Additional resources that have been tested were extra PV panels and battery storage. Increasing PV capacity did not bring large improvements in decreasing exchange with external grid and most of the energy generated thanks to that, had to be exported.

6.2 Future work

Despite the simulations and their results that have been presented in the project report there are some tasks that could be carried out to optimize the aggregation and improve the results.

Including residential loads

In the thesis, many loads were not included in the simulations, like residential loads related to household appliances or street lights. They are less flexible than loads simulated in the thesis, but a real-life aggregator should take them into account, as he will probably serve them as well. Including consumption from different sources could be integrated to the smart charging and HP algorithms to make them even more efficient in minimizing the cost of energy purchase.

Increasing the number of offered schemes

Smart charging that has been simulated was to be happening at night, between 10PM and 6AM. Therefore such scheme would be most likely offered to homeowners that would like to charge their EVs for the lowest price between coming home and leaving it for daily commute to work. Similar charging algorithm could be easily utilized by other end-users like businesses. They would rather like to charge the EVs during the working hours during the day and still be able to utilize the smart charging algorithm and consume energy at the lowest prices available during the charging window other than the one at night.

Simulating other distributed resources

In the thesis only EVs, HPs, PV panels and battery storage were simulated. Apart from aforementioned residential loads, there are other resources that may be included to build an energy cluster. Those are for example wind turbines or biogas facilities that are often located in rural areas. The latter is a popular method for utilizing agricultural wastes which is also an attractive technology in terms of decreasing the environmental impact of food industry. Agricultural biogas power plants usually have small installed capacity and are very flexible. It could strongly influence the objectives of energy cluster, as it could be an important backup for distributed RES which generate energy stochastically. Also unlike battery storage, it generates energy, not only stores it.

References

1. Pachauri, R. *et al. Climate change 2014 synthesis report. contribution of working groups I, II, and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* English. ISBN: 9789291691432 (IPCC, 2014).
2. Pahle, M., Schill, W.-P., Gambardella, C. & Tietjen, O. Renewable Energy Support, Negative Prices, and Real-time Pricing. eng. *The Energy journal (Cambridge, Mass.)* **37,** 147–169. ISSN: 0195-6574 (2016).
3. Van der Veen, A., van der Laan, M., de Heer, H., Klaasen, H. & van den Reek, W. *Flexibility value chain* 2018. `https://www.usef.energy/app/uploads/2018/11/USEF-White-paper-Flexibility-Value-Chain-2018-version-1.0_Oct18.pdf`.
4. Kirschen, D. S. & Strbac, G. *Fundamentals of Power System Economics* 1. Edition. ISBN: 0470845724 (Wiley, New York, 2004).
5. *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (Text with EEA relevance.)* 2018.
6. Danish Energy Agency. *Market Model 3.0. The electricity market as the key to a climate neutral society* `https://ens.dk/sites/ens.dk/files/El/market_model.pdf`.
7. *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (Text with EEA relevance.)* 2019.
8. Stephen, T. British Experience of Electricity Liberalisation: A Model for India? *Economic and Political Weekly* **40,** 5260–5268. ISSN: 00129976, 23498846. `http://www.jstor.org/stable/4417518` (2005).
9. ENTSOE-E. *The Harmonised Electricity Market Role Model* Downloaded: 18-03-2022. `https://docstore.entsoe.eu/Documents/EDI/Library/HRM/Harmonised_Role_Model_2018-01.pdf`.

10. Cludius, J., Hermann, H., Matthes, F. C. & Graichen, V. The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: Estimation and distributional implications. *Energy Economics* **44,** 302–313. ISSN: 0140-9883. https://www.sciencedirect.com/science/article/pii/S0140988314001042 (2014).
11. Nord Pool Group. *Day-ahead market* https://www.nordpoolgroup.com/the-power-market/Day-ahead-market/.
12. Folketinget (The Danish Parliament). *Welcome to Nord Pool Spot* Downloaded: 18-03-2022. https://www.ft.dk/samling/20091/almdel/EPU/bilag/354/882165.pdf.
13. EPEX Spot. *Basics of the power market* https://www.epexspot.com/en/basicspowermarket#day-ahead-and-intraday-the-backbone-of-the-european-spot-market.
14. Nord-Pool A/S. *Intraday trading* Downloaded: 18-03-2022. https://www.nordpoolgroup.com/trading/intraday-trading/.
15. Intercontinental Exchange, Inc. *Nordic Power Financial Base Daily Futures* Downloaded: 21-03-2022. https://www.theice.com/products/57609939/Nordic-Power-Financial-Base-Daily-Futures.
16. Kircher, K., Aderibole, A., Norford, L. K. & Leeb, S. Distributed Peak Shaving for Small Aggregations of Cyclic Loads. *IEEE Transactions on Power Delivery,* 1–1. https://ieeexplore.ieee.org/document/9707884 (2022).
17. Lotus Cars. *The Lotus Evija* Downloaded: 18-03-2022. www.lotuscars.com/en-GB/model/evija/.
18. Electric Vehicle Database. *Nissan Leaf* Downloaded: 05-04-2022. https://ev-database.org/car/1106/Nissan-Leaf.
19. Electric Vehicle Database. *Renault Zoe ZE50 R135* Downloaded: 05-04-2022. https://ev-database.org/car/1205/Renault-Zoe-ZE50-R135.
20. US Energy Information Agency. *How much electricity does an American home use?* Downloaded: 18-03-2022. https://www.eia.gov/tools/faqs/faq.php?id=97&t=3.
21. FDEL (Forenede Danske Elbilister). *Hvor lang tid tager det at lade?* Downloaded: 22-03-2022. https://fdel.dk/guides/ladning/hvor-lang-tid-tager-det-at-lade/.
22. Sinha, R., Bak-Jensen, B. & Pillai, J. R. Operational flexibility of electrified transport and thermal units in distribution grid. *International Journal of Electrical Power Energy Systems* **121,** 106029. ISSN: 0142-0615. https://www.sciencedirect.com/science/article/pii/S014206151932633X (2020).

23. Bessa, R. & Matos, M. *The role of an aggregator agent for EV in the electricity market* in *7th Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2010)* (IET, Stevenage, 2010), 126–. ISBN: 9781849193191.

24. Danish Energy Agency. *Data, tables, statistics and maps. Energy Statistics 2020* Downloaded: 21-03-2022. `https://ens.dk/sites/ens.dk/files/Statistik/energy_statistics_2020.pdf`.

25. SEAS-NVE Strømmen A/S. *BasisEnergi – få en variabel elpris* Downloaded: 20-03-2022. `https://seas-nve.dk/sel/basisenergi/`.

26. Mendaza, I. D. d. C., Pigazo, A., Bak-Jensen, B. & Chen, Z. *Generation of domestic hot water, space heating and driving pattern profiles for integration analysis of active loads in low voltage grids* in *IEEE PES ISGT Europe 2013* (2013), 1–5. `https://ieeexplore.ieee.org/document/6695288`.

27. *The Nordic energy markets and environment* eng. ISBN: 92-893-1625-X (Nordic Council of Ministers, Copenhagen, 2008).

28. Energinet. *SPØRGSMÅL OG SVAR OM FLEXAFREGNING AF KUNDERS ELFORBRUG* `https://energinet.dk/El/Private-husstande-og-virksomheder/Flexafregning`.

29. Arora, J. *Introduction to Optimum Design* eng. ISBN: 0120641550 (Elsevier Science Technology, Burlington, 2004).

30. Kouzelis, K., Tan, Z. H., Bak-Jensen, B., Pillai, J. R. & Ritchie, E. Estimation of Residential Heat Pump Consumption for Flexibility Market Applications. *IEEE Transactions on Smart Grid* **6,** 1852–1864. `https://ieeexplore.ieee.org/document/7079500` (2015).

31. Bhattarai, B. P., Bak-Jensen, B., Pillai, J. R. & Maier, M. *Demand flexibility from residential heat pump* in *2014 IEEE PES General Meeting | Conference Exposition* (2014), 1–5. `https://ieeexplore.ieee.org/document/6939348`.

32. Trela, M. & Dubel, A. Net-Metering vs. Net-Billing from the Investors Perspective—Impacts of Changes in RES Financing in Poland on the Profitability of a Joint Photovoltaic Panels and Heat Pump System. English. *Energies* **15,** 227. `https://www.proquest.com/scholarly-journals/net-metering-vs-billing-investors-perspective/docview/2618220867/se-2` (2022).

33. Hoicka, C. E., Lowitzsch, J., Brisbois, M. C., Kumar, A. & Ramirez Camargo, L. Implementing a just renewable energy transition: Policy advice for transposing the new European rules for renewable energy communities. *Energy Policy* **156,** 112435. ISSN: 0301-4215. `https://www.sciencedirect.com/science/article/pii/S0301421521003050` (2021).

34. Ceran, B. The concept of use of PV/WT/FC hybrid power generation system for smoothing the energy profile of the consumer. *Energy* **167,** 853–865. ISSN: 0360-5442. https://www.sciencedirect.com/science/article/pii/S0360544218322321 (2019).

35. Fraunhofer Institute for Solar Energy Systems ISE. *Energy Charts* Downloaded: 25-04-2022. https://energy-charts.info/index.html?l=en&c=DK.

36. PV Magazine. *Denmark launches third renewables tender* Downloaded: 26-04-2022. https://www.pv-magazine.com/2021/06/28/denmark-launches-third-renewables-tender/.

37. Dansk Energi. *Guide for connection of power generating plants to the medium and high-voltage grid (>1 kV). Type B, C and D* Downloaded: 08-03-2021 (https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2019-04/Guide%20for%20connection%20of%20power-generating%20plants%20MV%20and%20HV.pdf, 2019).

38. Viridian Solar Ltd. *PV Panel Performance* Downloaded: 03-05-2022. https://www.viridiansolar.co.uk/resources-4-4-performance-of-pv-solar-panels.html.

39. Stroe, D.-I., Zaharof, A. & Iov, F. Power and Energy Management with Battery Storage for a Hybrid Residential PV-Wind System: A Case Study for Denmark. English. *Energy Procedia* **155,** 464–477. ISSN: 1876-6102 (Nov. 2018).

40. Tomaszewska, A. *et al.* Lithium-ion battery fast charging: A review. *eTransportation* **1,** 100011. ISSN: 2590-1168. https://www.sciencedirect.com/science/article/pii/S2590116819300116 (2019).

41. WysokieNapiecie.pl. *OZE oraz inteligentne sieci energetyczne sprzyjają rozwojowi magazynów energii. (Polish) [RES and smart grids help the development of energy storage]* Downloaded: 15-05-2022. https://wysokienapiecie.pl/14061-oze-oraz-inteligentne-sieci-energetyczne-sprzyjaja-rozwojowi-magazynow-energii/.

Appendix A

Types of markets

There are several market types that energy can be traded on, which are similar to different products that are traded on financial markets. In this appendix those types of markets will be explained based on theory of markets and book [4]. Energy will be compared to simple and intuitive examples, which however explain well the differences between these market types.

Spot market

Spot market is the most basic and the oldest type of market. Its characteristic is that the delivery of the traded good happens at the moment of trade. Most simple example of spot market is a farmers market located in most cities. Suppliers (farmers) offer their fruit and vegetables while buyers want to get it. Immediately after both sides agree on the price and volume of the trade, the goods change their owner and they may be consumed or stored for later use. On a spot market the seller can sell the entire amount of the goods he has available and buyer can buy as much as he needs (of course if the needed amount does not exceed the entire supply). Prices on such market may be very volatile as any change in demand or supply will influence them. [4]

Forward market

Waiting with the purchase of any good until the time of delivery can be risky, due to high volatility of spot market. Sellers may be afraid of a large drop in price and buyers of the opposite. Both buyers and sellers can be interested in agreeing on the price in advance to be able to plan their production and know better how their income from selling or cost of buying will look like. For example a steakhouse owner and cattle farmer would like to reduce their business risk connected to spot prices of beef. Therefore they sign what is called a *forward contract* in which they specify the date of delivery of the good, date of payment and obviously the price and volume of the trade. Such contract would be legally binding and failing to comply to it (like delivering less goods than the traded volume) will result in some punishment that was agreed in a contract. It is likely that the price for the goods in the spot market will differ from the one agreed in the forward contract and such situation will lead to a loss or profit for the sides of the contract, as they sold and bought a good for a better or worse price than they could. When there is more sellers and buyers willing to sign such contracts for the future delivery a market will be formed which is what we call a forward market. Day-ahead electricity market is a type of forward market. [4]

Futures market

Futures market is a secondary market for forward market. Forward contracts are traditionally signed between producer of a certain good and its consumer, both sides of such contract do not want to take a risk of volatile spot prices. However there are players who would like to take part in trading on such market of future delivery of goods, but are unable to produce or collect the traded good physically. They typically are willing to take a higher risk than actual (physical) producers and consumers and act as middle-man between them. Futures market is not officially separated from the forward market, it is just specified to the market participants that are unable to perform the physical delivery of the good from both sides of the trade. [4]

Options

Futures and forwards contracts are unconditional - when signed, they have to be executed at the time of delivery, no matter the spot price. If a seller is unable to deliver the agreed volume, he must buy the rest on the spot market and if a buyer can’t take an entire delivery, he has to sell it on the spot market as well. Some participants would like to have a possibility to buy some goods at a given time in the future for an agreed price, but if a spot market price is better for them, they would like not to be obliged to buy the good or sell it on the spot market for a lower price than they bought it. Therefore, there is a demand for forward contracts with a conditional delivery, when the buyer or seller decides if he wants the delivery and purchase to be executed, yet still holding the right to buy or sell the good for a previously agreed price. Such contracts are called options. Execution of the contract depends on the spot prices and if the holder decides not to execute it, then the seller of the option receives a fee from the holder. [4]

Contracts for differences

Some goods must be traded on a centralized market like an exchange. Sometimes they may not be able to sign forward, futures or options contracts and therefore they would be exposed to risky and highly volatile spot prices. In such situations both buyers and sellers may sign a contract for differences - they agree on a given price (strike price), given volume, take part in the spot market and if the spot market price is different than the agreed one, the side profiting from the price difference pays it to the other side on the agreed volume. [4]

Appendix B

Aggregation scenarios with a battery storage

Simulations in Chapter 4.5 have proven that smart charging is not very efficient in terms of utilizing local generation, as it happens at night when PV panels do not produce energy. However, those simulations did not include a battery, which was simulated in Chapter 4.6.2. In this chapter four aggregation scenarios from Figure 4.3 will be simulated again, but including a battery with a storage capacity of 100MWh and 10MW maximum (dis)charging capacity. Results are presented in the Table B.1.

Table B.1: Results of four aggregation scenarios with an added battery

Scenario name	Energy consumed [MWh]	Energy generated [MWh]	Energy imported [MWh]	Energy exported [MWh]	Profit [DKK]
A	37090	32460	16073	11484	12417000
B	37167	32460	16155	11487	11863000
C	37109	32460	16048	11439	11223000
D	37138	32460	16100	11461	11545000

It can be observed that once the battery was installed, the exchange with the external distribution grid was very similar in each scenario, which means that large storage capacities make a much stronger difference on the analysed indicators than selection of users (according to their chosen charging scheme) does. When an energy cluster is equipped with large storage capacity, it does not play a major role, how the demand is shaped using different pricing schemes.

Major differences between scenarios were observed in the obtained profits. The highest profit has been achieved in scenario A, with the highest number of dumb chargers with flat and ToU tariffs, which was the same case as observed previously.

Considering those facts, the most desirable type of chargers, from the aggregator's point of view, are those two types, as they bring the highest incomes and provided the battery, don't impact the other objectives of an energy cluster in a negative way.