Aggregators’ business models for flexibility from electricity consumers

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Dissertation

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Living is no laughing matter:
you must live with great seriousness
like a squirrel, for example–
I mean without looking for something beyond and above living,
I mean living must be your whole occupation.
Living is no laughing matter:
you must take it seriously,
so much so and to such a degree that,
for example, your hands tied behind your back,
your back to the wall,
or else in a laboratory
in your white coat and safety glasses,
you can die for people–
even for people whose faces you've never seen,
even though you know living
is the most real, the most beautiful thing.
I mean, you must take living so seriously that
even at seventy, for example, you'll plant olive trees–
and not for your children, either,
but because although you fear death, you don't believe it,
because living, I mean, weighs heavier.

Nazım Hikmet Ran, 1947

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Summary

Introduction and problem statement

Fossil fuels for energy generation contribute to greenhouse gas emission, and increase the risks of climate change. In order to limit the amount of greenhouse gas emission, transitioning to renewable energy sources (RES) is critical. However, integrating RES in the existing power system is not straightforward since these sources possess different characteristics from fossil fuels. RES are variable, i.e., fluctuate over time and can be controlled only to a limited extent, and uncertain, i.e., cannot be forecast with high accuracy. Due to these characteristics, as the penetration of RES increases, maintaining the balance between electricity demand and generation becomes more challenging. Therefore, to deal with variability and uncertainty of RES, the power system needs to become more flexible.

Flexibility can be deployed at different stages of the power system, for example at the demand side. Flexibility from the demand side is acquired by modifying the electricity demand of the consumers' assets, such as appliances and battery energy storage systems (BESSs). This flexibility can be traded at electricity markets to help maintain the system balance. Nevertheless, the electricity demand and generation of individual consumers in residential and service sectors is too small to participate in these electricity markets, and to contribute substantially to flexibility. To overcome this, these consumers can be represented by *aggregators*. The aggregators can trade flexibility obtained from the consumers' assets by participating in various electricity markets on behalf of them. To trade flexibility and make profit from it, the aggregator can choose between different *business models* and strategies to implement these.

To make a business model viable in the long run, it should be feasible in a multi-actor context, i.e., for the aggregator, the consumers and the power system. It should contribute to the aggregator's profit and it should reduce consumers' cost, the *economic feasibility*. Moreover, it should provide flexibility to the power system to maintain the system balance, and should operate the consumers' assets in a suitable way, the *operational feasibility*. The main research question addressed in this thesis was:

What is the operational and economic feasibility of aggregator's business models in residential and service sectors in a multi-actor context?

This question was answered by first giving an overview of the possible business models and the extent to which they differ in terms of the operational and economic aspects. After that, the economic and operational feasibility of these business models, the economic relation between the aggregator and the consumers, and the combination of different business models were studied.

Strategies for the aggregator's business models

A literature review on aggregator's business models was conducted to obtain an overview of the business models and of the ways they differ with respect to the operational and economic aspects. A framework was defined in order to analyze the selected papers in a structured way. This framework distinguishes the following aspects:

1. *Operational aspects*: which consumers' assets are operated, who operates them, for what purpose, and how they are operated.

2. *Economic aspects*: how the aggregator makes profit and how consumers' cost is reduced.

From this literature review, five different business models were determined, shortly noted as: trading flexibility in the day-ahead market (DAM), trading flexibility in the intra-day market, providing power reserves by pooling, balancing portfolio internally (also known as internal balancing), and managing congestion. Based on the literature review and the framework analysis, different operational and economic strategies were determined for each of these business models. Furthermore, several knowledge gaps were identified:

1. Business models involving internal balancing, and Frequency Containment Reserve (FCR) need more attention.

2. Economic relations between the aggregator and the electricity markets, and between the aggregator and the consumers need to be both incorporated while assessing the economic feasibility of business models. In line with that, more emphasis should be put into determining the financial rewards aggregators should offer to the consumers in the aggregator's portfolio.

3. Combining business models involving BESSs should be studied.

These knowledge gaps were addressed in this thesis. To do that, we used different optimization models and case studies from Dutch residential and service sector consumers who possess their own solar panels.

Internal balancing

The business model *balancing portfolio internally*, also known as internal balancing, was underexposed in the literature. We analyzed the operational and economic feasibility of this business model for the aggregator. For this purpose, a comprehensive Model Predictive Control (MPC) model was presented that determines how the consumers' appliances should be operated to reduce the aggregator's imbalances, caused by uncertainties in solar generation. This model was applied to a case study using data from Dutch residential and service sectors.

We showed in this case study that the MPC model was successful in reducing the aggregator's individual imbalances up to 30%. However, the aggregator's imbalance costs remained almost equal with or without internal balancing. This means that from the power system's point of view, internal balancing by aggregators can help maintain the system balance. However, from the aggregator's point of view, it does not provide any financial benefits to implement it. We also discussed which factors can impact the results, to make the results more robust. Based on the insights from the case study, we concluded that internal balancing is not an economically feasible business model. Therefore, if policymakers or TSOs wish to stimulate an active role of aggregators in implementing internal balancing, it is required to introduce external incentives and subsidies.

Financial reward mechanisms between the aggregator and the consumers
While assessing the economic feasibility of the aggregator's business models, it is important to also take into account the economic relation between the aggregator and the consumers in the portfolio. So far, the aggregator's business models have been primarily studied without this relation. We analyzed the economic feasibility of *trading flexibility in the DAM* from the perspectives of both the aggregator and the consumers. To this end, the optimal financial reward mechanisms that the aggregator should offer to the consumers were determined for two different cases: using consumers' appliances, and using consumers' batteries.

For the appliance case, we determined flat-rate retail prices the aggregator can offer to the consumers that make *trading flexibility in the DAM* economically feasible for both actors. To achieve this, an optimization model was presented which minimizes the consumers' costs by shifting the electricity demand of the appliances within two-hour time intervals, and applied to a case study from the Netherlands.

The results showed that there is only a small range of retail prices where the business model becomes profitable for both actors simultaneously. Besides, the decrease in the cost values was even then rather low. Therefore, the economic feasibility of the business model *trading flexibility in the DAM* with appliances and flat-rate retail prices is found to be very limited. We also explored the influence of different factors on the economic feasibility. The insights from this analysis indicated that limited economic feasibility is caused by insufficient revenue gained from the DAM, which is restricted by the shifting time of appliances, as well as by the current DAM prices.

Because of this limited feasibility, we also analyzed the economic feasibility of *trading flexibility in the DAM* with battery energy storage systems (BESSs), comparing the scenario with no BESS (S1), with two scenarios with BESS, i.e., one with individual BESSs (S2), and one with a shared BESS (S3). For these three scenarios, various financial reward mechanisms were studied: (1) FR1: flat-rate retail and flat-rate feed-in tariff, (2) FR2: time of use retail and flat-rate feed-in tariff, and (3) FR3: time of use retail and time of export feed-in tariff. Optimization models were presented to determine how to charge and discharge the BESS in order to minimize the consumers' costs in the BESS scenarios (S2) and (S3), which were applied to a Dutch case study. Based on the optimization results, the aggregator's cost, the consumers' operational cost, and the consumers' total cost including the BESS investment cost were calculated.

Both with the individual and shared BESS, the lowest consumers' operational cost is attained with time of use retail and time of export feed-in tariffs (FR3). When comparing the individual and shared BESS, the consumers' operational cost

is lower with the shared BESS, since the shared BESS can be used more effectively. Nonetheless, even for the shared BESS, when the investment cost of the BESS are included, the consumers' total cost becomes higher than without BESS. This showed that the business model *trading flexibility in the DAM* is not economically feasible for the consumers, and that currently they are not interested in investing in individual or shared BESS. Also, it is not economically feasible for the aggregator.

Combining business models with Frequency Containment Reserve
We explored the impact of combining business models on economic feasibility for both the aggregator and the consumers. We considered an additional scenario with individual BESSs where *trading flexibility in the DAM* was combined with *providing power reserves*, more specifically providing Frequency Containment Reserve (FCR). Only individual BESSs were used for this purpose, since the operation of shared BESS for two business models might conflict with each other. Yet, this can be resolved with individual BESSs by pooling them. An optimization model was formulated to find the optimal share of the individual BESSs reserved for FCR purposes, in addition to how to charge and discharge the BESSs, in order to minimize the consumers' costs.

We found that combining these two business models leads to a bigger decrease in the consumers' operational costs, compared to the scenario with only *trading flexibility in the DAM*. Furthermore, the aggregator is able to make a significant profit, which is gained mostly by providing FCR. However, the consumers' total cost reduction is still not sufficient to make investing in the BESS financially attractive. Another option would be that the aggregator invests in the individual BESSs. This is a feasible scenario in a multi-actor context: (1) economic feasibility: it is economically feasible for both the aggregator and the consumers, (2) operational feasibility: it helps with the system balance.

Conclusions
This thesis analyzes *the operational and economic feasibility of the aggregator's business models in a multi-actor context.* Several optimization models are formulated to optimally operate the consumers' assets to achieve operational and economic feasibility for different business models. Results showed that it is challenging to attain operational and economic feasibility simultaneously in a multi-actor context. Successful implementations require external incentives or aggregator's initiative to invest in the BESSs. When operational and economic feasibility is accomplished, flexibility through the aggregator's business models can contribute to integrating RES in the power system, and by that can support the energy transition.

Samenvatting

Inleiding en probleemstelling

Om de klimaatverandering te beperken en de verdere opwarming van de aarde te voorkomen is het nodig om over te stappen van fossiele brandstoffen op duurzame energiebronnen, zoals zon en wind. De integratie van deze hernieuwbare energiebronnen in het bestaande energiesysteem is echter niet eenvoudig, omdat deze bronnen andere karakteristieken hebben dan fossiele brandstoffen. Ten eerste zijn hernieuwbare energiebronnen zijn variabel, met ander woorden ze fluctueren in de tijd en ze kunnen slecht gestuurd worden. Ten tweede zijn ze onzeker, d.w.z. ze kunnen niet met hoge accuratesse voorspeld worden. Een toename van deze duurzame energiebronnen betekent dus ook een toename in complexiteit van de systeemoperatie en van het behoud van systeemstabiliteit.

Om met deze variabiliteit en onzekerheid van hernieuwbare energiebronnen om te kunnen gaan, moet het energiesysteem flexibeler worden. Flexibiliteit kan gecreëerd worden door, bijvoorbeeld, de energievraag van huishoudelijke apparaten te veranderen en energieopslagsystemen met batterijen te gebruiken. Deze flexibiliteit kan dan verhandeld worden op elektriciteitsmarkten om uiteindelijk bij te dragen aan het behoud van de systeembalans. De elektriciteitsvraag en het -aanbod van individuele prosumers in residentiële en servicesectoren zijn echter te klein om te participeren in deze markten, en te klein om substantieel bij te kunnen dragen aan de benodigde flexibiliteit. Dit kan worden opgelost door deze prosumers te laten representeren door een aggregator, die deze flexibiliteit verzamelt bij de huishoudens en bedrijven om deze vervolgens aan te bieden op een van elektriciteitsmarkten. Om flexibiliteit te verhandelen en er winst mee te maken kan de aggregator tussen verschillende businessmodellen en implementatiestrategieën kiezen. Om een businessmodel rendabel te maken op de lange termijn, dient het uitvoerbaar te zijn in een multi-actor context, d.w.z. zowel voor de aggregator zelf, als voor de consumenten en voor het energiesysteem. Een businessmodel dat niet alleen bijdraagt aan de winst van de aggregator maar ook aan kostenreductie van de consumenten is economisch haalbaar. Als een businessmodel voor flexibiliteit bijdraagt aan de systeemstabiliteit en er op deze wijze voor zorgt dat de energieconsumenten op gepaste wijze bediend worden, dan is het ook operationeel haalbaar. De centrale vraag die in deze thesis wordt beantwoord is:

Wat is de operationele en economische haalbaarheid van bedrijfsmodellen voor aggregatoren in residentiële en servicesectoren in een multi-actor context?

Deze vraag is beantwoord door in de eerste instantie een overzicht te geven van de verschillende businessmodellen en de mate waarin zij van elkaar verschillen op operationeel en economisch vlak. Daarna is de economische en operationele

haalbaarheid van deze modellen onderzocht en is de economische relatie tussen de aggregator en de consumenten in verschillende combinaties van businessmodellen bestudeerd.

Strategieën voor bedrijfsmodellen van aggregatoren
Om de verschillen in operationele en economische aspecten van businessmodellen voor een aggregator in de literatuur te analyseren is een raamwerk ontwikkeld dat de volgende aspecten onderscheidt:

1. *Operationele aspecten*: welke consumentenapparaten worden gebruikt, door wie, met welk doel, en op welke wijze.

2. *Economische aspecten*: hoe maakt de aggregator winst en in hoeverre worden de kosten van de consument gereduceerd.

Op basis van een literatuurstudie werden vijf verschillende businessmodellen voor het verhandelen van flexibiliteit voor de verdere analyse gekozen: de day ahead markt (DAM), de intra-day markt, de levering van energiereserves door pooling, portfolio intern balanceren (ook bekend als intern balanceren), congestiebeheer.

De literatuurstudie en verdere analyse van deze modellen met behulp van het ontwikkelde raamwerk heeft de volgende aandachtsgebieden opgeleverd:

1. Businessmodellen die met intern balanceren werken, en tegelijkertijd bijdragen aan zogenaamde Frequency Containment Reserve (FCR) zijn niet voldoende onderzocht.

2. Economische relaties tussen de aggregator en de elektriciteitsmarkten, en tussen de aggregator en de consumenten, moeten beide worden meegenomen bij het beoordelen van de economische haalbaarheid van businessmodellen. In lijn daarmee moet er meer nadruk komen te liggen op het bepalen van de financiële beloningen die een aggregator moet bieden aan de consumenten in haar portfolio.

3. Het combineren van businessmodellen met gebruik van batterijen voor energieopslag dienen nader bestudeerd te worden.

Deze aandachtsgebieden zijn uitgebreid behandeld in dit proefschrift door verschillende optimalisatiemodellen te analyseren en casestudies uit te voeren met prosumers met eigen zonnepanelen uit de Nederlandse residentiële en servicesectoren.

Intern balanceren
Het businessmodel *portfolio voor het intern balanceren*, of kortweg *intern balanceren*, is onderbelicht in de literatuur. Voor de analyse van de operationele en economische haalbaarheid van dit businessmodel is een *Model Predictive Control (MPC)* model ontwikkeld dat bepaalt hoe de apparaten van de consumenten ingezet moeten worden door de aggregator om de onzekerheden die gepaard gaan met de zonne-energie te minimaliseren. Dit MPC model, toegepast in casestudies met

consumenten uit de Nederlandse residentiële en servicesector resulteerde in een reductie van bijna 30% van de individuele onbalans van de aggregator. Echter, de onbalanskosten voor de aggregator bleven ongeveer gelijk, met of zonder intern balanceren. Dit betekent dat vanuit het gezichtspunt van het energiesysteem intern balanceren door een aggregator kan helpen om de systeembalans te handhaven, maar dat de aggregator geen financieel voordeel heeft om dit te implementeren. Verdere analyse met verschillende factoren verandert niets aan deze conclusie. Intern balanceren is geen economisch haalbaar businessmodel. Derhalve, als beleidsmakers of TSO's een aggregator wensen te stimuleren om een actieve rol te spelen in het implementeren van intern balanceren, dan is het nodig om externe prikkels en subsidies te introduceren.

Financiële beloningssystemen tussen de aggregator en de consumenten
In het beoordelen van de economische haalbaarheid van businessmodellen van de aggregator is het belangrijk om ook rekening te houden met de financiële relatie tussen de aggregator en de consumenten in haar portfolio. In de literatuur zijn de businessmodellen van een aggregator vooral bestudeerd zonder met deze relatie rekening te houden. In dit proefschrift is de economische haalbaarheid van het *verhandelen van flexibiliteit op de DAM* vanuit het perspectief van zowel de aggregator als de consument bestudeerd. Hiertoe werden de optimale financiële beloningssystemen die de aggregator zou moeten aanbieden aan de consumenten voor twee situaties bepaald: ten eerste voor het gebruik van consumentenapparaten, en ten tweede voor het gebruik van batterijen van de consumenten.

In het eerste geval van de elektrische consumentenapparaten zijn de forfaitaire tarieven bepaald die de aggregator kan aanbieden aan de consumenten en die het *verhandelen van flexibiliteit op de DAM* economisch haalbaar moet maken voor beide partijen. Om dit te bereiken werd een optimalisatiemodel geïntroduceerd dat energiekosten van de consument minimaliseert door de elektriciteitsvraag van apparaten te verschuiven binnen een tijdsvak van twee uur. De resultaten tonen aan dat er slechts een klein gebied te vinden is waarvoor het businessmodel winstgevend wordt voor beide partijen tegelijk. De kostenvermindering voor de consument is echter erg laag. De economische haalbaarheid van het businessmodel *flexibiliteit verhandelen op de DAM* met consumentenapparaten en met forfaitaire tarieven is derhalve erg beperkt. We onderzochten ook de invloed van verschillende factoren op de economische haalbaarheid. De inzichten uit deze analyse toonden aan dat de beperkte economische haalbaarheid veroorzaakt wordt doordat er onvoldoende omzet behaald kan worden uit de DAM wat gelimiteerd wordt door de tijd waarin schuiven van de elektriciteitsvraag van de apparaten mogelijk was, alsook door de huidige DAM prijzen.

Vanwege deze beperkte haalbaarheid is ook de economische haalbaarheid van *flexibiliteit verhandelen op de DAM* met batterijen als energieopslagsystemen (BESS's) onderzocht. Hierin zijn drie scenario's meegenomen:

- Basisscenario (S1) met geen BESS
- Scenario (S2) met individuele BESS's
- Scenario (S3) met een gedeelde BESS.

Voor deze drie scenario's werden verscheidene financiële beloningssystemen bestudeerd:

- FR1: flat-rate retail en flat-rate feed-in tarief
- FR2: time-of-use retail en flat-rate feed-in tarief
- FR3: time-of-use retail en time-of-export feed-in tarief.

Optimalisatiemodellen werden ontwikkeld om te bepalen hoe de BESS's opgeladen en ontladen dienen te worden om de energiekosten van de consument te minimaliseren in de scenario's (S2) and (S3). Gebaseerd op deze resultaten zijn de aggregatorkosten, alsmede de operationele kosten van de consument, en de totale kosten van de consument, inclusief de BESS-investeringskosten berekend.

Voor zowel de individuele als de gedeelde BESS's zijn de laagste operationele kosten voor de consumenten gevonden met het tarief FR3. Als de individuele en gedeelde BESS's vergeleken worden, dan blijken de operationele kosten van de consumenten lager bij deze laatste, mits de gedeelde BESS's efficiënter gebruikt kunnen worden. Niettemin is het zelfs voor de gedeelde BESS's zo dat als de investeringskosten meegeteld worden, de totale kosten voor de consumenten hoger zijn dan zonder BESS. Dit toont aan dat het businessmodel *flexibiliteit verhandelen op de DAM* niet economisch haalbaar is voor consumenten, en dat zij derhalve momenteel niet geïnteresseerd zullen zijn om in individuele of gedeelde BESS's te investeren. Het investeren in BESS's is ook voor de aggregator economisch niet haalbaar.

Businessmodellen combineren met Frequency Containment Reserve (FCR)

In dit proefschrift is ook de impact op de economische haalbaarheid voor zowel de aggregator als de consumenten onderzocht als businessmodellen gecombineerd worden. We hebben een extra scenario met individuele BESS geïntroduceerd waar *flexibiliteit verhandelen op de DAM* gecombineerd is met het *leveren van reservecapaciteit*, meer specifiek met het leveren van zogenaamde *Frequency Containment Reserve* (FCR). Er kan geconcludeerd worden dat door individuele BESS's met elkaar samen te voegen of te bundelen (poolen) een optimale percentage individuele BESS's gevonden kan worden die gereserveerd moeten worden voor FCR-doeleinden.

We vonden dat het combineren van deze twee businessmodellen tot een grotere reductie van de operationele kosten van de consumenten kan leiden vergeleken met het scenario met enkel flexibiliteit verhandelen op de DAM. Bovendien kan in dat geval de aggregator een significante winst maken, die vooral toegeschreven wordt aan het leveren van FCR. De totale energiekosten van de consumenten zijn echter nog steeds niet voldoende om het investeren in BESS's financieel aantrekkelijk te maken. Een andere optie zou zijn dat de aggregator investeert in individuele BESS's. Dit is een haalbaar scenario in een multi-actor context. Het is (1) economisch haalbaar voor zowel de aggregator als de consumenten, en het is (2) operationeel haalbaar doordat het bijdraagt aan de systeembalans.

Conclusies

Dit proefschrift analyseert *de operationele en economische haalbaarheid van de businessmodellen van aggregatoren in een multi-actor context.* Verschillende optimalisatiemodellen zijn geformuleerd met als doel de consumentenapparaten optimaal in te zetten om tot operationele en economische haalbaarheid voor verschillende businessmodellen te komen. De resultaten tonen aan dat het uitdagend is om operationele en economische haalbaarheid tegelijkertijd te realiseren in een multi-actor context. Succesvolle implementaties vereisen een externe stimulans of investeringen door de aggregator in individuele BESS's. Wanneer operationele en economische haalbaarheid is bereikt, kan de bijbehorende flexibiliteit bijdragen aan het integreren van duurzame energiebronnen in het energiesysteem en daarbij de energietransitie ondersteunen.

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Özge Okur
Delft, January 2021

1
Introduction

In my work I now have the comfortable feeling that
I am so to speak on my own ground and territory
and almost certainly not competing in an anxious race
and that I shall not suddenly read in the literature
that someone else had done it all long ago.
It is really at this point that the pleasure of research begins,
when one is, so to speak, alone with nature
and no longer worries about human opinions, views and demands.
To put it in a way that is more learned than clear:
the philological aspect drops out and only the philosophical remains.

Heinrich Hertz

This chapter provides a general background of the thesis. Then, it introduces the research topic, and defines its objectives and scope. It also gives a general overview of the chapters' content for the rest of the thesis.

1.1. Energy transition

In the traditional power system, electricity is generated mostly by conventional generation units that are based on fossil fuels, such as coal, oil, and gas. However, fossil fuel demand for electricity generation contributes to greenhouse gas emissions significantly, and thus increases the risks and impacts of climate change. In 2014, the European Union (EU) set the targets of attaining at least a 40% reduction in greenhouse gas emissions compared to 1990 levels, and 80% to 95% by 2050 [1]. Ambitious targets such as set by the EU for 2030 and 2050 can only be achieved through an *energy transition*: a switch from fossil fuels to renewable energy sources (RES). For this reason, the power system is transitioning towards a new system where electricity is increasingly produced by RES. Among RES, particularly penetration of solar and wind generation is increasing most rapidly. According to International Energy Agency, the average annual global growth rate of solar photovoltaics (PVs) between 1990 and 2017 was 37%, that of wind turbines 23.4% [2].

The transition to a power system with a high share of RES introduces new sources of *variability* and *uncertainty*. Traditionally, there have been two main sources of uncertainty and variability in the power system: electricity demand and unexpected outages. Electricity demand varies over the days, weeks and seasons, and heavily depends on consumers' behaviors. It is, therefore, rather cumbersome to forecast this accurately, even though an accurate prediction is necessary for power system planning and operation. Outage uncertainties come from malfunctioning power system components, such as generation units and transmission lines [3]. They have a very low probability of occurrence, but a high impact. These uncertainties have been dealt with conventional generation units where electricity is produced by fossil fuels. Nevertheless, with energy transition, the share of these generation units is expected to decrease, whereas share of RES is anticipated to increase. RES differ from conventional generation sources in terms of variability and uncertainty of their output.

Renewable generation variability: Variability of RES means that their generation fluctuates over time, and cannot be dispatched [4].

Renewable generation uncertainty: Uncertainty of RES relates to the difficulty to forecast RES generation with high accuracy. Even though forecasting models help improve the accuracy of renewable generation forecasts, it is still unlikely to be 100% accurate. Hence, the amount actually generated still differs to some extent from the forecast amount.

Figure 1.1 allows to observe both variability and uncertainty characteristics of solar and wind generation. It shows the day-ahead forecast and actual values for solar and wind power generation, for a week in June and a week in December 2018 within the control area of TenneT [1] in Germany. The data is obtained from TenneT website [5].

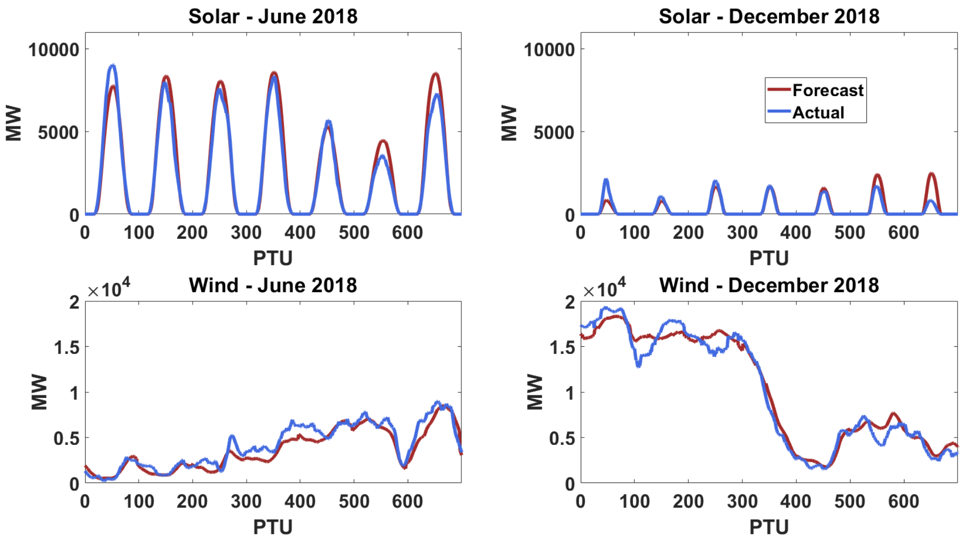

Figure 1.1: The left graphs shows day-ahead forecast and actual solar and wind power generation per Program Time Unit (PTU) for a week in June 2018 within the control area of TenneT controlled area in Germany. The graphs in the right column depict the same for a week in December 2018. PTU is equal to 15 minutes. Forecast values are estimated at 8:00 for the following day. (Note the differences in y-axis.)

The stable operation of the power system relies on a continuous balance between electricity demand and generation. A difference between them leads to a deviation from the nominal system frequency (50 Hz in the Netherlands). The excess generation causes the frequency to increase above 50 Hz, while excess consumption to decrease below 50 Hz. These frequency deviations are tolerated by the power system only to a very limited extent. Larger deviations threaten the security of the power system [6, 7], and can even cause power outages. Transmission System Operators (TSOs) are responsible for maintaining the system balance.

Due to the variable and uncertain characteristics of RES, maintaining the balance between electricity demand and generation becomes more challenging as the penetration of RES increases. Thus, the power system needs to be flexible to cope with this variability and uncertainty of RES.

1.2. Flexibility

Flexibility is defined as the ability of a power system to adapt its operation in response to variability or uncertainty, by modifying electricity demand or generation [8, 9]. Flexibility can be obtained using the following four

[1] TenneT is the Transmission System Operator in the Netherlands and in a large part of Germany.

means: dispatchable power plants, demand response, energy storage, and interconnection [10, 11].

- Flexibility from *dispatchable power plants* is realized by conventional generation sources where production can be ramped up and down easily.
- *Demand response* is defined as "the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." [12, 13]. In other words, consumers' electricity consumption can be turned off, curtailed or shifted to another time period, based on external factors, such as electricity prices. These actions can be taken by either the consumers or by an external party via Home Energy Management Systems (HEMS), which is called automated demand response [14].
- Electrical *Energy storage* (ESS) technology refers to the process of converting energy from one form (mainly electrical energy) to a storable form and reserving it in various mediums; then the stored energy can be converted back into electrical energy when needed [15]. This allows to store electricity and to use it at a later point. By this way, electricity consumption and/or generation can be shifted in time to provide flexibility. ESS technologies can be classified into four major groups: mechanical (pumped hydroelectric storage, compressed air energy storage and flywheels), electrical (capacitors, supercapacitors), thermal (low temperature, high temperature), chemical (batteries, flow batteries, fuel cells). These technologies possess diverse characteristics in terms of energy density, power density, efficiency, energy capacity, volume etc., which make some of them more suitable depending on the application. A comprehensive overview of the energy storage technologies and their potential applications is presented in [16, 17].
- Using cross-border *interconnections* and networks, the electricity can be transported from where it is produced at lowest cost to where it is needed.

This thesis focuses on flexibility coming from the demand side of the power system. Hence, it does not take into account dispatchable power generation and interconnection, but discusses demand response (DR) and energy storage. These means have attracted growing attention to facilitate the integration of RES both in academia, and in industry [18–20].

1.3. Consumers & aggregator

Studies related to the demand side of the power system involve electricity demand from consumers in three different sectors: residential (households), service (offices, shops, schools, etc.) and industrial [21–23]. Between 2000 and 2014 in the EU, electricity consumption in both residential and service sectors increased, by 12%

and 24%, respectively. On the other hand, in the same period, industrial electricity consumption dropped by 6% [24]. Therefore, in this thesis we choose to focus on flexibility coming from consumers in the residential and service sectors.

Consumers in the residential and service sectors might be able to produce their own electricity via RES, which is called prosumers. We assume in this thesis that a certain share of consumers possess their own solar panels since this is already common in the Netherlands. In 2018, the installed capacity of solar panels in the Netherlands grew by 37% (from 1682 MW to 2307 MW) on roofs in the residential sector, and by 46% (from 1131 MW to 1662 MW) on roofs in offices in the service sector [25]. The installed capacity of solar panels is expected to increase in the future as well. Note that the term prosumers is not used in this thesis, despite the fact that consumers may be able to generate their own electricity.

Flexibility from consumers is traded in electricity markets to help maintain system balance. However, the demand and supply of individual residential and service sectors' consumers is too small to individually participate in these electricity markets, and to contribute substantially to flexibility. To overcome this, these consumers' assets can be aggregated and represented by aggregators. Overall, *aggregators* can be considered mediators between the consumers and the electricity markets [26]. They can trade flexibility obtained from their consumers' assets by participating in various electricity markets on behalf of these consumers [27]. This relation is shown in Figure 1.2. Aggregators are relatively new actors in the power system [28], and have received significant attention to enable flexibility from the demand side.

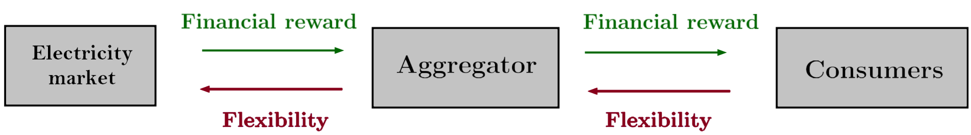

Figure 1.2: Aggregator's relation with the consumers and the electricity markets.

Aggregators can handle electricity market complexities on their consumers' behalf [29]. In this sense, aggregators can also increase the negotiation power of small consumers by representing them as a group to the existing actors in the electricity markets [26]. Furthermore, aggregators can protect the consumers from uncertainty in electricity market prices, and associated risks.

In order to make profit by trading flexibility in different electricity markets, the aggregator implements business models in these electricity markets. A *business model* is a "model of the way in which a company creates and delivers value so as to generate revenue and achieve a sustainable competitive position." [30].

To make the aggregator's business model viable in the long run, it should be feasible in a multi-actor context, i.e., for the aggregator, the consumers and the power system. It should contribute to the aggregator's profit and it should reduce the consumers' cost, the *economic feasibility*. Moreover, it should provide flexibility to the power system to maintain the system balance, and should operate the consumers' assets in a suitable way to provide that flexibility, the *operational feasibility*. A business model can only get implemented if both operational and economic feasibility are achieved.

1.4. Research objective and questions

The aim of this research is to facilitate flexibility from the demand side in residential and service sectors through aggregators' business models. For this purpose, we analyze the operational and economic feasibility of these business models. The following main research question is formulated:

What is the operational and economic feasibility of aggregator's business models in residential and service sectors in a multi-actor context?

To help answer this main research question, the following research sub-question is formulated:

1. *What are the different strategies to implement the aggregator's business models with respect to economic and operational aspects?*

This sub-question is answered through a literature review and application of a framework in Chapter 3. In this chapter, different strategies of aggregators to implement business models are determined, and knowledge gaps are identified. Based on these knowledge gaps, other research sub-questions are formulated, and added in Section 3.6.

1.5. Research method

In this thesis, we mainly employ mathematical optimization models combined with data from residential and service sector samples in the Netherlands. We select to employ optimization models since they allow us to formulate economic feasibility of business models in objective function, while also taking into account operational feasibility in the constraints. Optimization models have been widely used in research on energy transition. The number of articles that use optimization models applied to renewable energy systems between 2001 and 2019 is shown in Figure 1.3. The search is carried out within articles in Scopus database with keywords "optimization" AND "renewable energy". Note that review articles are left out in this search. Additionally, a review of optimization models applied to energy systems with focus on renewable energy can be found in [31, 32]. Various optimization methods and models are used in this thesis and they are elaborated in the subsequent chapters.

1.6. Audience

This thesis addresses audiences both in industry and academia. In industry, the scope of this thesis mainly concerns aggregators. Aggregators or companies that wish to become an aggregator can gain an understanding of which business

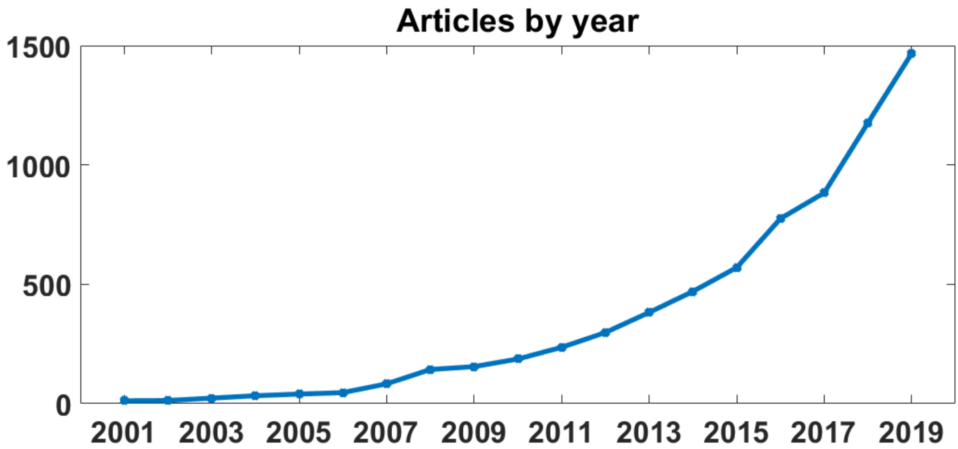

Figure 1.3: The number of articles that use optimization models applied to renewable energy systems between 2001 and 2019.

models can be implemented, using which strategies, whether or not these business models are economically feasible, and when they can become economically feasible. Furthermore, certain chapters in this thesis study how to determine the optimal economic relation between the aggregator and their consumers. For this reason, the results from this thesis can be useful to for residential and service sector consumers as well.

Secondly, the outcomes of this research can be beneficial for policymakers, TSOs, electricity market regulators. The results can assist them on subjects related to flexibility from the demand side of the power system and the aggregators' position in the energy transition. They can gain insights on the impacts of regulations on aggregators' business models, and also what to alter to make these business models more feasible.

This thesis can be of interest for academic researchers with questions about the aggregators, their business models, and flexibility from the demand-side. A multi-actor approach is taken in this thesis to analyze the operational and economic feasibility of the aggregator's business models using a literature review and various optimization models. Exploring these aspects allows to explicitly address the operational and economic feasibility simultaneously and helps to understand whether it is possible to implement the aggregator's business models. It also enables to gain insights on how well we can utilize flexibility through these business models.

1.7. Thesis outline

The rest of this thesis is structured as follows. In Chapter 2, more detailed information on aggregators is given. Chapter 3 includes a structured literature review on the aggregator's business models. Based on this literature review, several knowledge gaps are identified, which are analyzed in Chapters 4-6. Finally,

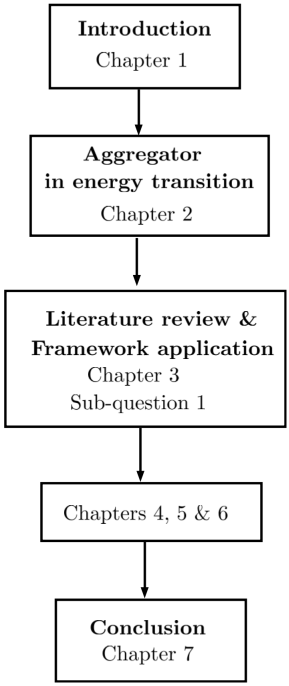

Figure 1.4: Representation of the thesis outline.

Chapter 7 provides a discussion on the results, and finalizes with conclusions and recommendations for further research. Thesis structure is shown in Figure 1.4. Chapters 4, 5, and 6 in this figure will be updated based on the knowledge gaps identified in the literature review.

2

Aggregator in energy transition

We look at the world once, in childhood.
The rest is memory.

Louise Glück

In this chapter, we aim to provide background information on aggregators that is considered helpful for a better understanding of the remainder of this thesis. To this end, we start by describing consumers' assets in residential and service sectors which can be used by the aggregator while implementing their business models. After that, we focus on the companies that we consider to be an aggregator in this thesis. Finally, we explain the aggregators with different roles, and outline which actors in the power system can become an aggregator.

2.1. Aggregator's portfolio in residential and service sectors

The aggregator's portfolio consists of assets owned by the consumers, which the aggregator uses while implementing their business models. These assets can be different types of appliances, storage and generation units, and they can provide different means of flexibility.

2.1.1. Assets for demand response

Assets that can be used to provide flexibility with DR, are the consumers' electric appliances and Electric Vehicles (EVs). Electricity consumption of the appliances can be curtailed, or shifted to other time periods in order to provide DR. Similarly, EVs[1] can be charged at the appropriate moments to provide DR. The consumers' willingness to participate in DR depends to a large extent on the inconvenience caused by DR. This is particularly a problem for the appliances since they tend to impact consumers' comfort more substantially, compared to EVs. Consumers' appliances can be categorized into three types based on the inconvenience they cause when used for DR: non-flexible, semi-flexible and flexible appliances [33, 34], which are explained as follows:

- **Non-flexible appliances:** Their consumption cannot be shifted or curtailed without bringing much inconvenience to the consumers, such as computers, television, and lighting.
- **Semi-flexible appliances:** Their consumption can be shifted or curtailed without bringing much inconvenience to the consumers on condition that consumers are notified in advance, such as washing machines, dryers, and dishwashers.
- **Flexible appliances:** Their consumption can be shifted or curtailed on short notice without bringing inconvenience to the consumers, such as refrigerators, freezers, ventilation, fans and heat pumps.

2.1.2. Assets for energy storage

Among energy storage technologies, highly compact features of *battery energy storage systems* (BESSs) enable them to be better suited for volume-limited applications, such as at the residential and service sectors. Within BESS technologies, a wide range of technologies exist: lead–acid, lithium-ion, sodium–sulfur, nickel–cadmium, and so on [16]. Lithium-ion batteries are widely studied in the literature, owing to their high energy density and energy efficiency [35]. EVs also show similar characteristics to BESSs, when they provide vehicle-to-grid (V2G) power [36]. Fuel cell electric vehicles can also be used for V2G purposes [37].

2.1.3. Generation units

In addition to the appliances and BESSs, the consumers might also possess RES as generation units. We assume in this thesis that a certain share of consumers in the aggregator's portfolio possess their own solar panels since this is already common in the Netherlands. In 2018, the installed capacity of solar panels in the Netherlands grew by 37% (from 1682 MW to 2307 MW) on roofs in the residential sector, and by 46% (from 1131 MW to 1662 MW) on roofs in offices in the service sector [25]. The installed capacity of solar panels is expected to increase in the future as well.

2.2. Aggregator's function

Enhancing flexibility is essential to successfully integrate RES in the current power system. We identify three functions companies can have to assist the power system

[1] In this thesis, the term 'EVs' is used to refer to battery electric vehicles and plug-in electric vehicles.

with the flexibility needs: flexibility developer, flexibility operator/facilitator, and flexibility trader. These functions are explained below.

2.2.1. Flexibility developer

The companies with this function develop products which can be used to obtain flexibility. For instance, these companies can develop software tools that determines the optimal operation of consumers' assets. They can also design and produce BESSs, to be used to obtain flexibility. Besides, designing the tariffs that suppliers can offer to the consumers to change their demand can also be considered part of this function. Companies with this function correspond to the orange region in Figure 2.1. An example of flexibility developer company in the Netherlands is Alfen; they design and sell BESSs in different sizes, and for different purposes [38].

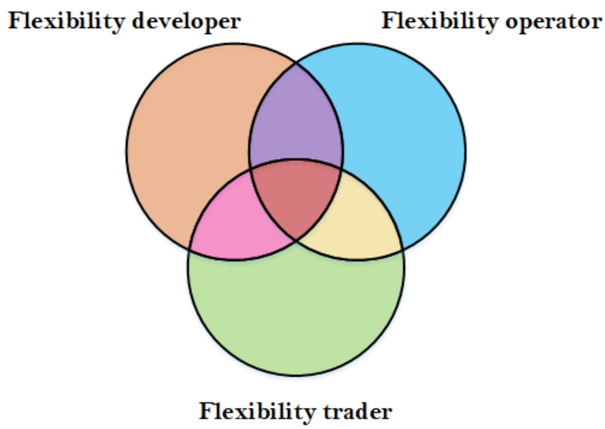

Figure 2.1: Venn diagram of flexibility functions

2.2.2. Flexibility operator/facilitator

The companies with this function are responsible for operating the consumers' assets, without participating in any electricity markets. A company which is responsible for operating the assets in an isolated microgrid or energy community is an example of a flexibility operator. Companies with this function correspond to the blue region in Figure 2.1.

Note that these companies might possess the flexibility developer function as well, which means that they might also develop the product they operate, which is illustrated in purple region in Figure 2.1. An example of flexibility operator company with also developer function in the Netherlands is iWell. iWell develops and sells BESSs to residential buildings to be used for building electricity demand: elevators, lighting in the corridors of the building, etc. [39]. They also provide a software tool to make sure that the BESSs operates correctly.

2.2.3. Flexibility trader

The companies with this function participate and trade flexibility in the electricity markets. In this thesis, we consider companies with flexibility trader function to be aggregators since it is significant that aggregators provide access to the electricity markets.

In addition to having solely trader function, these companies can also take up flexibility developer and/or flexibility operator function as well. Combination of flexibility trader and developer is marked with pink in Figure 2.1. For example, a supplier that offers time-varying tariffs to their consumers, and operates their assets belongs to this region. Combination of flexibility trader and operator is marked with yellow in Figure 2.1. A company that operates BESSs owned by the consumers, yet does not produce or sell BESSs to the consumers is an example of this region. Similarly, a company to represent an energy community[2], to trade in electricity markets on behalf of them is considered an aggregator and also belongs to this region [41]. Moreover, combination of flexibility trader, operator and developer is shown with red in Figure 2.1. In this case, the company possesses all the functions.

2.3. Aggregator with different roles

Existing actors in the power system, such as suppliers, and Balance Responsible Parties (BRPs), can take up flexibility trader function in order to become an aggregator. A supplier is responsible for purchasing and selling electricity for consumers by trading in electricity markets. A BRP is responsible for submitting energy programmes that indicate the net energy that is planned to be taken from/fed into the grid for the next day [42]. Any deviation between the energy planned to be taken from/fed into the grid, and actual energy taken from/fed into the grid, is called the individual imbalance of the BRP. The BRP needs to pay imbalance costs for their individual imbalances.

In addition to suppliers and BRPs, an independent actor, not associated with a supplier or BRP, can also become an aggregator. It should be noted that Distribution System Operators (DSOs) are also discussed to become an aggregator. However, DSOs are heavily regulated, and they are not able to trade flexibility in the electricity markets. Besides, for this reason, based on surveys among European stakeholders in the electricity markets, DSOs are considered least suitable to act as an aggregator [43]. Hence, in this thesis we do not consider DSOs to be an aggregator.

Suppliers, BRPs or independent actors can take up flexibility trader function to become an aggregator. This is depicted in Figure 2.2, where an aggregator can have one of the three roles: (1) supplier's role, (2) BRP's role, and (3) independent aggregator.

The addition of flexibility trader function necessitates new contractual agreements. These requirements for aggregators with different roles are elaborated in the following subsections.

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[2]More information on energy communities can be found in [40].

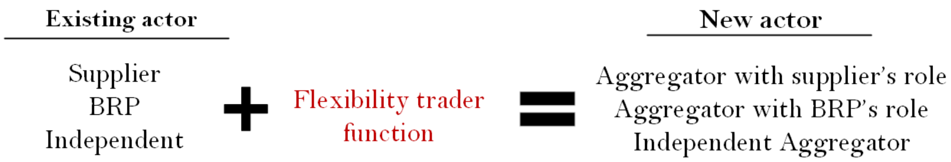

Figure 2.2: An existing actor to become an aggregator

2.3.1. Aggregator with supplier's role

A supplier takes up the flexibility trader function to become an aggregator, demonstrated in Figure 2.3. In this case, the aggregator is responsible for both buying electricity for the consumers, and for trading flexibility obtained from their assets in the electricity markets. It should be noted that it is obligatory for suppliers to be a BRP, or to have a contract with another BRP company, to be allowed to trade in the electricity markets. Thus, every supplier has already contracts with a BRP and their consumers. For this reason, they do not require any new contractual agreements, except for making changes in the existing ones, i.e., offering financial rewards to the consumers to be able to use their assets' to trade flexibility.

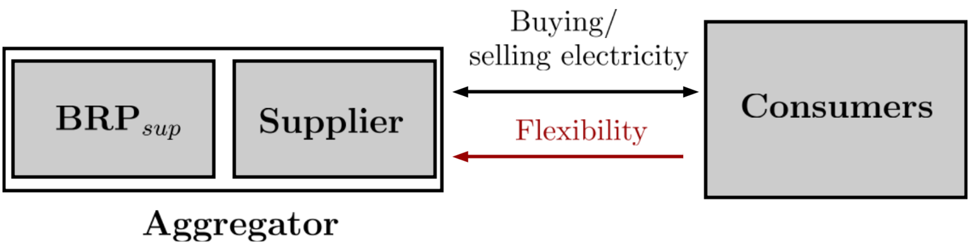

Figure 2.3: Overview of an aggregator with supplier's role

2.3.2. Aggregator with BRP's role

A BRP takes up the flexibility trading function to become an aggregator, displayed in Figure 2.4. This results in two BRPs on the same connection; both the supplier and the aggregator have their own BRPs. Thus, agreements need to be made between the aggregator and BRP$_{sup}$, as the aggregator's actions might influence the imbalance position of BRP$_{sup}$. In other words, aggregator's decisions may result in an imbalance for BRP$_{sup}$. This is explained in more detail in [44].

The aggregator also needs to have contracts with the consumers to be able trade their assets' flexibility in the electricity markets. Furthermore, another contract between the aggregator and the supplier is necessary since the aggregator might change the supplier's plans on when to use consumers' assets.

2.3.3. Independent aggregator

An independent actor which is not affiliated with a supplier or a BRP, when taking up the flexibility trader function, can be defined as an independent aggregator [45].

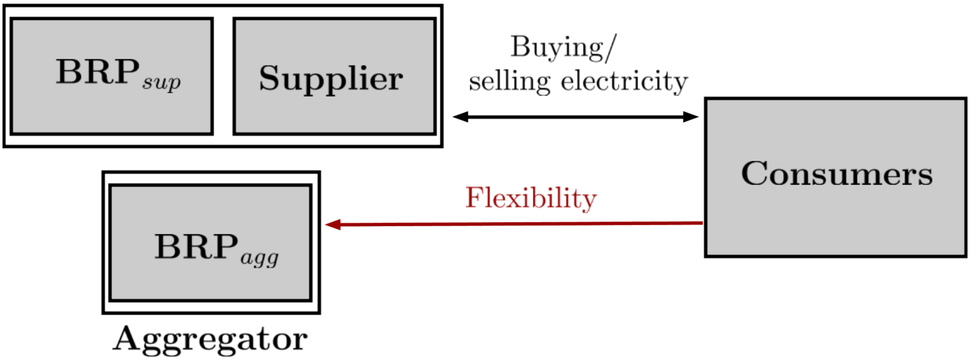

Figure 2.4: Overview of an aggregator with BRP's role

It is obligatory in the Netherlands for independent aggregators to have contracts with a BRP [46]. This means that an explicit agreement with a BRP is required to allow an aggregator to participate in electricity markets. The independent aggregator's agreement with a BRP can be realized in two ways: (1) having a contract with supplier's BRP (BRP$_{sup}$), and (2) having a contract with another BRP (BRP$_{agg}$). These are elaborated below:

Independent aggregator having contract with supplier's BRP:

By having a contract with BRP$_{sup}$, the independent aggregator transfers their balance responsibility to BRP$_{sup}$. This means that there is only one BRP, which is BRP$_{sup}$ at the connection of the consumers. The aggregator also needs to have contracts with the consumers to be able trade their assets' flexibility in the electricity markets.

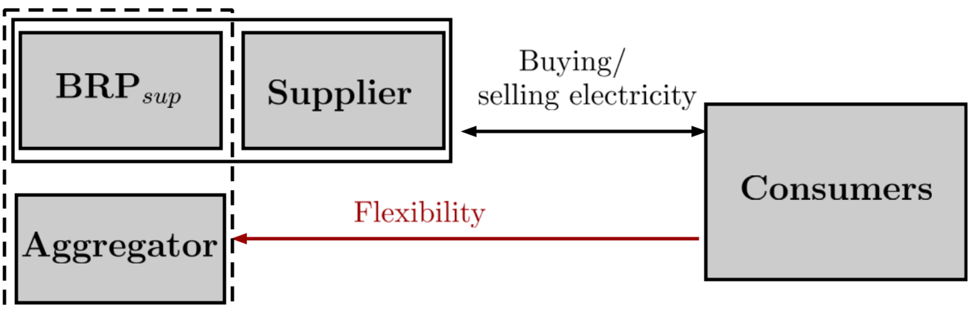

Figure 2.5: Overview of independent aggregator having contract with BRP$_{sup}$

Furthermore, another contract between the aggregator and the supplier is necessary since the aggregator might change the supplier's plans on when to use the consumers' assets, see Figure 2.5, which can lead to a loss for the supplier. Hence, the independent aggregator needs to provide a compensation for the supplier's loss.

Independent aggregator having an agreement with another BRP:

By having a contract with another BRP (BRP$_{agg}$), the independent aggregator transfers their balance responsibility to BRP_{agg}. This results in two BRPs on the same connection, see Figure 2.6. This is similar to the aggregator with BRP's role in terms of contractual agreements, except for the contract between the independent aggregator and BRP_{agg}, as the independent aggregator is not a BRP.

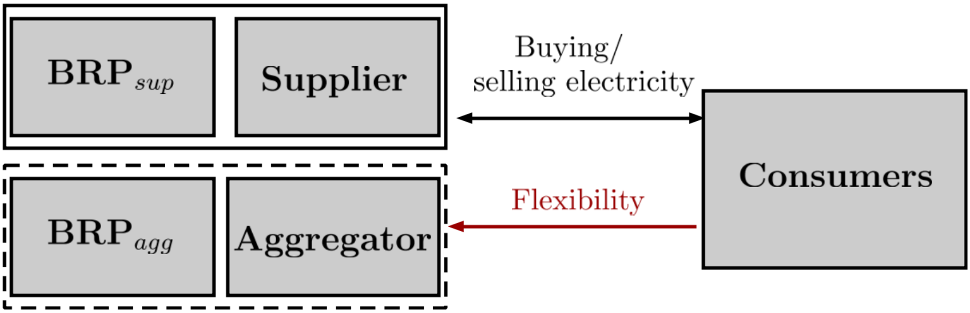

Figure 2.6: Overview of independent aggregator having contract with BRP_{agg}

All the contractual agreements needed for aggregators with different roles are summarized in Table 2.1. Note that the contractual agreements are given for the Dutch context. The contracts for independent aggregators might vary between different countries, depending on their regulations regarding aggregation [46]. Nonetheless, in many countries, the independent aggregators require contracts with other actors. In countries such as Spain and Portugal, since the independent aggregation is not well developed, the regulations to address this have not been introduced yet.

Table 2.1: Contractual agreements for aggregators with different roles. Cells marked with • indicate new contractual agreement is required between the actors, ◇ indicate modifications to existing contracts are required, **x** indicate no new contractual agreement is needed.

	Consumers	**BRP$_{sup}$**	**BRP$_{agg}$**	**Supplier**
Aggregator with supplier's role	◇	x	x	x
Independent aggregator with BRP$_{sup}$	•	•	x	•
Independent aggregator with BRP$_{agg}$	•	•	•	•
Aggregator with BRP's role	•	•	x	•

2.4. Challenges faced by aggregators with different roles

Aggregators with different roles face different challenges while implementing a business model, which are addressed in this section.

2.4.1. Number of contracts

As displayed in Table 2.1, it is easier for aggregators with supplier's role to implement their business models, due to the fewer number of the contractual agreements, as opposed to independent aggregators and aggregators with BRP's role.

2.4.2. Information exchange

As the number of contracts between the aggregator and the other actors increases, information exchange between them also becomes a serious issue. Actors may need information from the aggregator, in order to enable accurate forecasting or calculating consumers' electricity bills. However, some of this information may contain commercial interests. Therefore, it is essential that the actors agree what information will be disclosed.

2.4.3. Financial relations with the other actors

The aggregator is interested in making profit when implementing a business model. Therefore, they need to make sure that the business model is economically feasible. In order to assess whether a business model is economically feasible, it is essential to take into account all the financial relations the aggregator has with the other actors, i.e., the payments the aggregator needs to make to other actors. These financial relations may impact the economic feasibility of the business model. For instance, they may cause the business model to be economically infeasible, meaning that the aggregator would not implement it. Not incorporating these financial relations makes the assessment of economic feasibility incomplete, and might lead to wrong conclusions.

For aggregators with supplier's role, the only financial relation is with the consumers, whereas more financial relations are defined for independent aggregators and aggregators with BRP's role. For example, when independent aggregators with BRP_{sup} evaluate the economic feasibility of a business model, they need to consider how much they need to pay to the consumers, as well as the supplier.

2.4.4. Familiarity with existing actors

Consumers have familiarity with actors with whom they already have contracts. This familiarity provides an advantage to these actors, over actors with whom the consumers need to establish new contracts. This means that the consumers might be more inclined to have their supplier as the aggregator, instead of BRPs or independent actors, since only alterations to existing contracts are required with the suppliers, as shown in Table 2.1.

2.5. Recommendations to deal with challenges

Considering the identified challenges, it can be noticed that it seems to be easier for aggregators with supplier's role to implement a business model, owing to fewer number of contracts, less need for information exchange, option to modify the retail prices, fewer number of financial relations, and the already established contracts with the consumers. Contrarily, independent aggregators and aggregators with BRP's role involve higher complexity. This also coincides with the results from the survey in [43], as the most respondents prefer suppliers to become the aggregator. For this reason, it is assumed throughout this thesis that the aggregator possesses the supplier's role.

This high complexity may cause suppliers to have a more dominating position, and may hinder the participation of BRPs and independent actors as aggregators. As a result, it may prevent a healthy competition in the electricity markets, while it is argued that having independent aggregators is expected to boost competition [46]. Therefore, to facilitate the participation of BRPs and independent actors, the following recommendations can be considered:

2.5.1. Standardization of contracts

The drawbacks of the high complexity can be solved by establishing standardized processes for the contractual agreements. The following needs to be defined in this process:

- **Financial relations between actors:** How much the aggregator needs to pay to the other actors, and how these payments impact the economic feasibility of the business model should be incorporated.
- **Information exchange.** What information will be shared between actors should be clarified.

Standardizing the contractual agreements enables aggregators with different roles to implement their business models more smoothly, and thus fosters competitive electricity markets.

2.5.2. Raising consumer awareness

Raising consumer awareness of the opportunities provided by aggregators with BRP's role and independent aggregators might motivate consumers to engage with actors that they are not familiar with (they do not already have a contract with). For this purpose, offers of these aggregators may be promoted via various mediums such as emails, newsletters, public reports, websites, etc.

2.6. Conclusions

In this chapter, we aim to provide background information on aggregators that is considered helpful for a better understanding of the remainder of this thesis. For this reason, we describe the consumers' assets in the aggregator's portfolio, which companies are considered aggregators, aggregators with different roles, and challenges faced by these different roles. Based on this description, in the following chapter, we explain aggregators' business models in detail.

3

Aggregator's business models: A structured literature review

For there is nothing either good or bad,
but thinking makes it so.

William Shakespeare

After giving information on the aggregator and the consumers' assets in their portfolio, this chapter focuses on the aggregator's business models. The aggregator can implement business models by trading flexibility from their consumers' assets in different electricity markets. As expressed before, it should be feasible in a multi-actor context, i.e., for the aggregator, the consumers and the power system. It should contribute to the aggregator's profit and it should reduce consumers' cost, the *economic feasibility*. Moreover, it should provide flexibility to the power system to maintain the system balance, and should operate the consumers' assets in a suitable way, the *operational feasibility*.

This chapter addresses the first research sub-question: "What are the different strategies for aggregators to implement business models in terms of operational and economic aspects?". The aim of this chapter is to provide an overview of the aggregator's business models in the residential and service sectors, and of the ways they differ with respect to the operational and economic aspects. For this purpose, we conduct a literature review on aggregator's business models. We propose a framework in order to analyze the selected papers in a structured way. Advantages of applying this framework are twofold: (1) we can determine operational and economic strategies the aggregator can implement a business model, and (2) we can identify knowledge gaps in relation with this subject that are worth studying.

This chapter first describes the business models that the aggregator can implement in Section 3.1. The framework used in the analysis of business models are introduced in Section 3.2. In Section 3.3, the business models are analyzed using this framework. The results and knowledge gaps are presented in Section 3.4. Finally, conclusions are drawn in Section 3.5.

3.1. Aggregator's business models in residential and service sectors

The aggregator implements business models by trading flexibility from their consumers' assets in different electricity markets. In this section, we first describe the Dutch electricity markets, and then identify business models of the aggregator, based on the existing literature.

3.1.1. Electricity markets

The aggregator can trade flexibility obtained from consumers' assets in long-term and short-term electricity markets. In long-term markets, the electricity is traded through bilateral contracts on a long-term horizon. Short-term markets allow electricity trading on a short-term basis, and can be classified into three types in the Netherlands: day-ahead market, intra-day market, and balancing market. The first two markets are managed by European Power Exchange (EPEX), whereas the third market is operated by the TSO.

In the *day-ahead market* (DAM), market participants (like the aggregators) submit their hourly buying and selling bids, for the next day [47]. These bids are submitted before the DAM closure time (12:00 noon). After that the DAM is closed, a market clearing price is determined for each hour of the next day [48]. In order to trade electricity in the DAM, it is obligatory for the market participants to have a BRP role, or to have a contract with another party that has a BRP role. Following the clearing of the DAM, each BRP submits energy programmes (e-programs) to the TSO, one for each Program Time Unit (PTU) of the next day, which is equal to 15 minutes in the Netherlands [49]. These e-programs indicate the net energy that is planned to be taken from/fed into the grid per PTU in a day, based on the forecasts of electricity generation and demand [50]. A simplified representation of the timing of electricity markets in the Netherlands is illustrated in Figure 3.1.

In between the submission of e-programs and the actual delivery of electricity, BRPs are able to update their e-programs, by trading in the *intra-day market*. Unlike the DAM, the intra-day market takes place on the day of delivery, and is based on continuous trading in the Netherlands. Continuous trading is possible from 15:00 on the day before delivery, in hourly, half-hourly and 15-minute contracts. The trading closes the 5 minutes before the contract starts [51].

In the *balancing markets*, on the day of delivery, the individual imbalances of BRPs are calculated per PTU. The *individual imbalance* is equal to the difference between the planned energy exchange with the grid on the e-program, and the actual

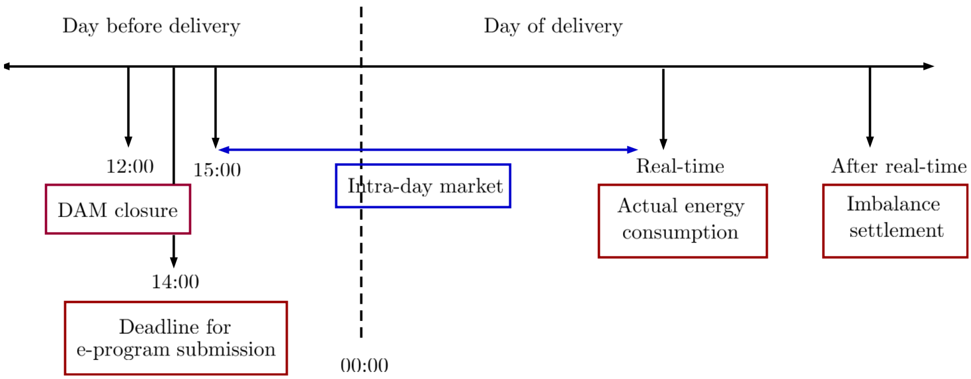

Figure 3.1: Timing of electricity markets in the Netherlands [48].

energy exchange with the grid in real-time [52]. Negative and positive individual imbalances occur when BRPs have a shortage, or a surplus, respectively. BRPs are financially responsible for their individual imbalances [53], which implies that these imbalances are settled by means of imbalance prices in imbalance settlement process. The negative imbalance price is paid for negative imbalances, and the positive imbalance price is earned with positive imbalances [42]. The net sum of all individual imbalance of each BRP is called the *system imbalance*.

When not equal to zero, the system imbalance leads to a deviation from the nominal system frequency, 50 Hertz in Europe. TSO is responsible for eliminating the system imbalance, and for restoring the system frequency back to its nominal value. For this purpose, TSO activates power reserves [1] in case of a system imbalance. If there is a shortage in the system (negative system imbalance), upward reserve is activated, i.e., a generation increase, or a demand decrease. On the other hand, if there is a surplus in the system (positive system imbalance), downward reserve is activated, i.e. a generation decrease, or a demand increase [54]. Parties that provide power reserves are called balancing service providers (BSPs). In the Netherlands, there are mainly three types of power reserves that contribute to the stabilization of the frequency: Frequency Containment Reserve, automatic Frequency Restoration Reserve, and manual Frequency Restoration Reserve [55].

- **Frequency Containment Reserves (FCR):** FCR, also known as primary control, is the first type of reserves to get activated by the Dutch TSO, TenneT. It is used to stabilize the system frequency, and to restrict larger frequency deviations.

- **automatic Frequency Restoration Reserves (aFRR):** aFRR, also known as secondary control, is automatically activated to restore the system frequency to its nominal value.

[1] In this field's terminology, several names are used to refer to power reserves. Other names include "frequency control", "regulation power", "balancing reserve", and "balancing power".

- **manual Frequency Restoration Reserves (mFRR):** mFRR, also known as tertiary control, is used for substantial imbalances that lasts for a long time. TenneT manually activates mFRR if the available capacity of aFRR becomes lower than a certain limit [56]. mFRR is activated, directly as manual Frequency Restoration Reserve direct activated or scheduled as manual Frequency Restoration Reserve scheduled activated.

Auction based markets are organized to obtain these reserves. The TSO acts as a single buyer and acquires necessary reserve capacity and balancing energy through these auctions. When *reserve capacity* (in MW) is acquired, the TSO has the right to activate balancing energy from this capacity in case of system imbalance. The *balancing energy* can be activated by increasing/decreasing generation or demand [57].

Separate markets exist for reserve capacity and balancing energy in the Netherlands. Reserve capacity market results in a reserve capacity price (reservation payment), while balancing energy market leads to a balancing energy price (activation payment). It is mandatory for successful bidders in these markets to provide reserve capacity and/or balancing energy when it is required. Otherwise, they are penalized by the TSO.

The regulatory characteristics of power reserves in the Netherlands are explained as follows:

Minimum bid size: The minimum acceptable bid to participate in the auction. This varies for FCR, aFRR and MFRR as 1,4 and 20 MW, respectively.

Activation method: Whether the bids are activated automatically or manually by the TSO. FCR and aFRR get activated automatically. In contrast, mFRR gets activated manually.

Procurement - capacity and energy: How reserve capacity and balancing energy is procured. In the Netherlands, reserve capacity and balancing energy are procured in separate auctions. Only reserve capacity for FCR is procured, and thus solely reservation payments are given for FCR participation. This means that no activation payment is made since up and downward FCR activations corresponds to very small energy volumes, and are expected to compensate for each other [54].

As opposed to FCR, both capacity reserves and balancing energy are procured by auctions for aFRR and mFRR. Furthermore, for aFRR and mFRR, it is possible to submit bids only for balancing energy, without submitting for reserve capacity. These are called free bids [58]. However, in this case it should be noted that the bidder can only receive the activation payment, but not the reservation payment.

Symmetrical bid - capacity and energy: Whether or not, the bid should offer the same amount in both directions: upward and downward. The capacity bids need to be symmetrical for all three types of reserves, whereas energy bids, in case of aFRR and mFRR are allowed to be asymmetrical.

Auction frequency - capacity and energy: How frequently the auction is carried out. Auction frequency of FCR is changed from weekly to daily auctions as of 1st of July 2019 [59], while it is significantly longer for capacity bids of aFRR and mFRR. Auction frequency for energy bids is every PTU, 15 minutes, for both aFRR and mFRR.

Full activation time: Maximum time allowed to reach from zero to the full capacity. Since FCR is the first reserve to get activated, it needs to respond very quickly, and full capacity needs to be delivered in 30 seconds. Full capacity needs to be achieved in maximum 15 minutes for aFRR and mFRR.

These regulatory characteristics are summarized in Table 3.1 [56, 58, 60–62]. A more comprehensive analysis of power reserves in the Netherlands can be found in [61].

Table 3.1: Regulatory characteristics of power reserves in the Netherlands. N/A signifies not applicable.

	FCR	**aFRR**	**mFRR**
Minimum bid size	1 MW	4 MW	20 MW
Activation method	Automatic	Automatic	Manual
Procurement - capacity	Contracted	Contracted	Contracted
Procurement - energy	N/A	Contracted/Free	Contracted/Free
Symmetrical bid - capacity	Yes	Yes	Yes
Symmetrical bid - energy	N/A	No	No
Frequency - capacity	Daily	Monthly/ Weekly	Quarterly/ Monthly
Frequency - energy	N/A	15 min	15 min
Full activation time	30s	15 min	15 min

3.1.2. Aggregator's business models

The aggregator's business models are described here briefly and explained in more detail in the next sections.

- **Trading flexibility in day-ahead market:** The aggregator can purchase and sell electricity at the convenient periods at the DAM, to reduce their cost [63].
- **Trading flexibility in intra-day market:** The aggregator can update their e-program in the intra-day market, based on recent information close to real-time [64, 65].
- **Providing power reserves:** The aggregator is able to provide power reserves by pooling consumers' assets to help TSOs to eliminate the system imbalance.
- **Balancing portfolio internally:** The aggregator can adjust electricity consumption within their portfolio, based on recent information close to real-time (adapted from [42]).
- **Managing congestion:** The aggregator can offer flexibility to cope with congestion issues in the grid.

3

3.2. Aggregator's business model framework

One of the widely used frameworks to analyze business models is the business model canvas framework [66]. This framework allows companies to describe and structure their business models more easily. The canvas framework consists of four areas of business, and nine blocks within areas: customer (customer segments, customer relationships, channels), offer (value proposition), infrastructure (key activities, key resources, key partners), and financial viability (cost structure, revenue stream). The business model canvas framework is depicted and its blocks are explained in Appendix A. This framework is also employed in the literature to support energy transition [67–69].

In business model canvas framework, even though the economic aspects of business models are addressed by cost structure and revenue stream blocks, the remaining blocks put emphasis on technical aspects (such as key resources and key partners), and social aspects of the business models (such as customer relationships and customer segments), leading to a lack of emphasis on operational aspects. Since both economic and operational aspects have a significant influence on the economic feasibility, a new framework is required to more explicitly integrate operational aspects, and to study the operational and economic aspects simultaneously. In order to analyze the operational and economic aspects of the aggregator's business models, the framework depicted in Figure 3.2 is proposed. This framework is called *aggregator's business model framework*.

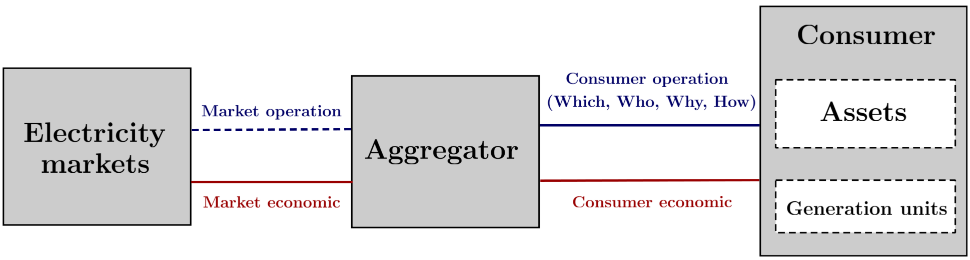

Figure 3.2: Aggregator's business model framework

The aggregator's business model framework includes operational (Market operation and Consumer operation) and economic aspects (Market economic and Consumer economic). Market operation and Consumer operation aspects of the framework deal with the operational relations between the electricity markets and the aggregator, and between the aggregator and the consumers, respectively. Consumer operation involves the following four elements:

- **Which** assets can be operated in the business model. This heavily depends on the regulations of the electricity market involved.
- **Who** is able to operate the assets, the consumer or the aggregator.
- **Why**, i.e., with what objective the assets are operated.

- **How** the assets are operated to achieve this objective.

Market operation represents how the operation of the assets from Consumer operation is translated bids on the electricity markets. Note that a dashed arrow is given for Market operation since bids on the markets are not present for every business model.

Market economic and Consumer economic aspects represent the economic relation between the aggregator and the electricity markets, and the economic relation between the aggregator and the consumer, respectively. Market economic relates to how the aggregator earns money from the electricity market. Consumer economic addresses what kind of financial reward the consumers earn for giving the aggregator permission to use their assets. As mentioned earlier, in this thesis consumers are assumed to be financially motivated, although different consumer motivations are also studied in the literature [70].

Note that the technical and social aspects of the business models are not accounted for in this framework. Yet, it should be remarked that these aspects are also critical for the aggregator while implementing business models. For instance, Information and Communication Technologies (ICT) infrastructures are associated with the technical aspects; the aggregator requires ICT infrastructures, such as Home Energy Management Systems (HEMS), so as to access, monitor, and control consumers' assets [71]. Moreover, the privacy concerns of the consumers, due to having their data monitored, can be considered an important social aspect [72].

3.3. Application of the framework

We review scientific papers and regulation documents on the aggregator's business models in the residential and service sectors. For this purpose, we search three electronic databases (ScienceDirect, Google Scholar, Scopus) for papers published until 1 March 2020. The following keywords are used for searching: Aggregator AND one of the words from {intra-day market, intraday market, congestion, day-ahead market, internal balancing, portfolio balancing, imbalance reduction, battery, electric vehicle, frequency control, primary control, secondary control, tertiary control, frequency containment reserve, frequency restoration reserve}. Forward and backward snowballing are used to select more papers as well.

In this thesis, the electricity market regulations are described for the Netherlands in Section 3.1.1. In Central Western European (CWE) countries, like the Netherlands, Germany, Belgium, France and Austria, these regulations vary to a small extent, even though the differences still exist, particularly for the power reserves [54]. Therefore, studies that involve market regulations are selected if they are applicable to the Dutch markets and do not contradict with the Dutch regulations; these are mainly studies about European markets, including the Dutch. For studies that do not involve market regulations, we do not make a distinction.

After the literature review is carried out, the framework in Figure 3.2 is applied to the selected papers. By applying this framework, the operational and economic aspects of aggregator's business models are analyzed. Based on this analysis, different *strategies* the aggregator can implement a business model are defined. This analysis is discussed in this section, following the list of business models given in Section 3.1.2.

It should be pointed out that due to the slight differences in the market regulations, the identified strategies and the knowledge gaps can also be relevant for the other CWE countries. Nonetheless, the proposed framework can still be applied for other countries, such as North America and Nordic countries. Yet, it might result in different strategies owing to different regulations.

3.3.1. Trading flexibility in DAM

This business model enables the aggregator to decrease their DAM cost for purchasing electricity/to increase their revenue for selling electricity (*Market economic*). The consumers get a financial reward to permit the aggregator to use their assets (*Consumer economic*). The operation of the assets is transformed to bids on the DAM (*Market operation*).

We identify three different strategies for the operation of the consumers' assets to trade in the DAM (*Consumer operation*). Appliances, BESSs and EVs (*Which*) are suitable for trading in the DAM since market-related regulatory requirements do not impose any restrictions. On the other hand, who is operating the assets and for what purpose they are operated differ. In addition, Consumer economic might also differ in these strategies. These three strategies are described:

Strategy 1A: Aggregator operating to minimize the aggregator's DAM cost. The aggregator (*Who*) is given permission to control (turn on/off, shift, curtail) the electricity consumption of the consumers' assets via HEMS, and to operate them according to their own interests, i.e., buying electricity when the DAM prices are low and selling electricity when the DAM prices are high (*Why*). In exchange for operating the assets according to their own interests, the aggregator can offer consumers a financial reward. The consumers might override the aggregator's control, at the expense of losing this reward [73].

In [74], the optimal operation of the appliances in the residential and service sectors is determined to maximize the aggregator's profit in the DAM, taking into account the consumers' comfort. The optimal operation of EVs to minimize the aggregator's DAM cost while also satisfying consumers' demand for EVs is studied with bilevel optimization in [75]. An algorithm to determine the operation of EVs is designed in [76], to minimize the aggregator's cost to purchase electricity either from the DAM, or from long-term contracts.

Other papers also deal with several uncertainties in the power systems: market price, RES generation, electricity consumption from consumers. For instance, the optimal operation of EVs to minimize the aggregator's DAM cost is studied, while also accounting for uncertainties in the market prices and EV driving patterns with stochastic optimization [77]. In [78], a robust optimization model is used to model market price uncertainty with the objective of finding the optimal operation of an aggregator with EVs. Similarly, a robust optimization is employed in [79], while finding the optimal operation of BESSs and thermal storage at the residential level. Moreover, a stochastic robust optimization is proposed for an aggregator with EVs in [80], to deal with market price and EV driving requirements, where both stochastic and robust approaches are used.

In addition to the aggregator's DAM cost, some papers also consider the aggregator's imbalance costs in real-time. A two-stage stochastic optimization model is proposed to minimize the aggregator's DAM cost and imbalance cost, using thermostatically controlled loads (TCLs), EVs, and semi-flexible appliances in [81], and using of BESSs and electric water heaters (EWHs) in [82]. Furthermore, a stochastic optimization model for an aggregator with EVs is given in [83], in which the uncertainties related to EV driving patterns and RES generation are also take into account. The operation of EVs, TCLs, and semi-flexible appliances is studied to minimize the aggregator's DAM cost and imbalance cost in [84] with a clustering-algorithm and a two-stage stochastic optimization. In [85], the DAM cost of an aggregator operating EVs is minimized in an optimization model, based on day-ahead forecasts of EV availability and EV charging requirements. Afterwards, in the real-time, the aggregator's imbalance cost is minimized.

Some papers also consider the financial reward between the aggregator and the consumers, which is the equivalent of Consumer economic in the framework. In [86], the aggregator uses flat-rate prices for buying and selling electricity for charging and discharging EVs. [87] considers two types of financial rewards: (1) the aggregator keeps 20% of total cost reduction contributed by a specific consumer, (2) the aggregator provides the entire cost reduction to the consumer while charging a lower flat fee. In [88], the aggregator offers two types of financial rewards to the consumers, to operate their electric space heating: (1) reward based on consumer inconvenience, and (2) based on provided flexibility. In [89], the aggregator offers load curtailment and load shifting contracts to the consumers for curtailing and shifting their assets. In [90], time-varying rewards for utilizing BESSs are offered to the consumers, together with rewards for load curtailment, load shifting using appliances.

Some papers also aim to find the value of financial reward that should be offered to the consumers. For example, a bilevel optimization is formulated in [91] to find the optimal flat-rate tariff for both aggregator and consumers, where the upper level aims to maximize the profit of an aggregator with EVs, and the lower level aims to minimize the consumers' cost. In [92], a stochastic optimization problem is given to determine how the aggregator needs to operate the consumers' assets to minimize DAM and imbalance cost, as well as the financial rewards given to the consumers for load shifting and load curtailment.

Strategy 1B: Consumers operating to minimize the consumers' electricity cost. The aggregator can offer time-varying tariffs, that are defined based on different prices in different time periods. Thanks to these time-varying tariffs, the consumers (*Who*) are able to react to the prices by decreasing their electricity consumption, or by shifting it to time periods when prices are low (*Why*). This strategy does not entail the aggregator's control over the consumers' assets; the operation of the assets entirely depends on the consumers' decision. The aggregator only provides the time-varying rewards, and the access to the DAM.

Main examples of time-varying tariffs are Time of Use (TOU), Critical Peak Pricing (CPP), and Real Time Pricing (RTP) [18]. TOU tariff establishes two or more daily periods that reflect time periods when the system load is higher (peak) or lower (off-peak), and charge a higher rate during peak periods. The same price values are applied every day with TOU tariff. RTP tariff fluctuates continuously during the day, following the DAM prices. The consumers are typically notified of RTP on a day-ahead or hour-ahead basis. In CPP tariff, higher prices are imposed during high peak periods, compared to TOU tariff. However, CPP is applied only on a relatively small number of critical days where particularly high demand is estimated [93]. The consumers are usually informed of these critical days a day in advance. Additionally, the price difference between peak and off-peak periods is higher in CPP, than in TOU. A more comprehensive explanation on DR programs and time-varying electricity tariffs can be found in [18, 94, 95].

However, it should be noted that time-varying tariffs require relatively high efforts and active participation from the consumers, which might discourage the consumers to engage in DR. DR research and pricing research from other fields show that many consumers prefer simple pricing schemes, despite possible financial disadvantage [96, 97]. For example, an online survey in the UK indicates that the consumers choose to switch to a direct load control program with a lower flat-rate tariff with override ability, over TOU and RTP tariff [98]. Similarly, RTP tariff is shown to be not attractive for the consumers, due to the complexity to react to fluctuating electricity prices [98, 99], even though the effectiveness of RTP in reducing the peak demand is found to be high [95].

Strategy 1C: Aggregator operating to minimize the consumers' electricity cost. The aggregator (*Who*) is given permission to control the consumers' assets via HEMS, and operate them to minimize consumers' costs (*Why*). This could reduce the consumers' burden for active participation. According to the survey in [98], having automated DR causes people to express significantly greater intention to use RTP tariffs.

This is mostly studied with time-varying tariffs in the literature, although it is also possible with flat-rate retail prices. The optimal schedule of residential appliances and BESSs to minimize the consumers' cost is determined in [100], via an aggregator. TOU, CPP and RTP tariffs are incorporated in this paper. Both stochastic and robust optimization models are applied in [101], to study the operation of appliances with RTP to minimize the consumers' cost. Autonomous scheduling algorithm for RTP is proposed to minimize the electricity costs and to regulate the peak demand for appliances in [102], and for both appliances and BESSs in [103].

In addition to time-varying tariffs, some papers also include extra payments. A two-stage optimization model is presented in [104]. The first stage optimization schedules storage space heating in residential sector to minimize the consumers' electricity cost with day-ahead hourly prices, while the second stage schedules the same assets to maximize extra fixed payment given by the aggregator in exchange for reducing the imbalances in real-time. In [105], an optimization model to schedule appliances is proposed with TOU tariff, as well as an extra time-varying payment, given by the aggregator.

3.3.2. Trading flexibility in intra-day market

We identify two strategies in which the intra-day market trading can be performed. In both these strategies, Market operation and Consumer economic are the same. The operation decisions of the assets are transformed to buying or selling bids in the intra-day market (*Market operation*). The consumers get a financial reward from the aggregator for being able to use their assets (*Consumer economic*).

Also, the operation of consumers' assets is almost the same in these two strategies (*Consumer operation*). Appliances, BESSs and EVs (*Which*) are suitable for trading in the intra-day market, and are mainly operated by the aggregator (*Who*), not by the consumers themselves. Nevertheless, for what purpose (*Why*) the consumers' assets are operated differs in these two strategies, as well as how the aggregator is expected to earn money (*Market economic*). The detailed descriptions of these strategies are outlined as follows:

Strategy 2A: Aggregator operating to minimize aggregator's imbalance cost. The intra-day market allows the aggregator to decrease their imbalance costs by updating their e-program, based on more recent information, obtained close to the real-time. In this way, the aggregator aims to reduce the imbalance costs that they would face in the balancing markets without updating their e-program in the intra-day market.

In [106], aggregator's optimal bidding to the DAM and the intra-day market is determined to minimize aggregator's DAM and imbalance costs, using BESSs, semi-flexible and flexible appliances, and taking into account uncertainties caused by RES, electricity consumption, and market prices. In addition, a two-stage stochastic model for EV charging is presented in [107]. In the first stage, electricity is traded on the DAM based on forecasts of EV driving patterns. In the second stage, deviations from the forecasts are handled by trading on the intra-day market.

Strategy 2B: Aggregator operating to arbitrage. In this strategy, the consumers' assets are operated by the aggregator to arbitrage, i.e., buy more energy when intra-day market prices are low, and less when high. In [108] and [109], residential TCLs are employed to arbitrage intra-day market prices via load control. Moreover, a simulation-based study is presented in [110] to utilize DR from space heating of residential buildings in both DAM and intra-day market trading with lowest operational cost.

3.3.3. Providing power reserves

The aggregator can offer power reserves to the TSO, to help eliminate the system imbalance, in exchange for reservation and/or activation payments by the TSO *(Market economic)*. The operation decisions of the assets become bids in the FCR, aFRR or mFRR markets (*Market operation*). A financial reward is given to the consumers by the aggregator to get their permission to use their assets (*Consumer economic*). In this business model, the consumers' assets are operated by the aggregator (*Who*) as the activation of power reserves need to be rather fast, even as fast as 30 seconds (*Consumer operation*). Mostly EVs, BESSs and flexible appliances (*Which*) are used for providing power reserves. The objective (*Why*) is to increase the aggregator's profit by participating in FCR, aFRR, and mFRR markets.

In [111], the optimal bid size on the Dutch FCR market is determined using an aggregator's portfolio of heat pumps. The potential economic benefits of providing aFRR with EVs for EV users are assessed in the Netherlands in [112] and [113]. A multi-objective optimization is proposed in [114] to find the optimal operation of EVs that satisfies the driving demand of EV owners and maximizes the aggregator's profits from providing aFRR.

Several optimization models are presented to minimize the cost of an aggregator participating in the DAM and providing aFRR with EVs [115–119]. The operation of EVs and TCLs to minimize the aggregator's DAM cost in the DAM and aFRR market is studied in [120] with Model Predictive Control (MPC), and in [121] with two-stage stochastic optimization. Moreover, EVs and a single BESS is combined by an aggregator to provide aFRR in [122]. Optimal operation in the DAM and aFRR markets is analyzed with BESSs in [123], and HVAC systems in office buildings in [124]. In addition to the aggregator's cost from the DAM and aFRR, the imbalance costs are also incorporated in a two-stage stochastic programming model in [125].

The aggregator's operation is studied to minimize the cost of buying and selling energy in the DAM, and to maximize the revenue from providing mFRR, using both an optimization model and algorithms with EVs in [126], and using a two-stage stochastic optimization with EVs and TCLs in [127]. A heuristic approach is studied in [128], where the aggregator's revenue from mFRR is maximized by operating TCLs.

Some papers also consider the economic relation between the aggregator and the consumers while providing power reserves. An optimal bidding strategy for the aggregator with EVs is proposed in [129], to maximize their profits from participating in the DAM and aFRR markets, while compensating the consumers for degradation. In [130], the aggregator's revenue is maximized when operating EVs in the DAM and aFRR market, while simultaneously considering the consumers' cost. In [131], the financial reward the aggregator offers to the consumers is calculated in an algorithm, to use their EVs in the DAM and aFRR market.

3.3.4. Balancing portfolio internally

The purpose of balancing portfolio internally, also known as internal balancing, is to minimize the aggregator's imbalance cost, by preventing deviations from the aggregator's e-program, i.e., by reducing aggregator's individual imbalances. For this purpose, the electricity consumption of the consumers' assets is changed, using updated forecast data closer to real-time [57] (*Market economic*). The consumers are rewarded to allow the aggregator to use their assets (*Consumer economic*). This business model is performed entirely internally, and does not involve any interaction with the electricity markets. For this reason, the operation of the consumers' assets does not get transformed to bids (*Market operation*).

The consumers' assets are operated, to minimize the aggregator's imbalance costs (*Why*) by reducing their individual imbalances (*Consumer operation*). Since internal balancing takes place close to real-time (which could be as close as 15 minutes), automatized operation by the aggregator (*Who*) is most suitable for internal balancing. Moreover, as it is carried out internally within the aggregator's portfolio, market-related regulatory requirements do not exist for this business model and appliances, BESSs and EVs (*Which*) are suited. In [132], algorithm-based simulations are studied to distribute the charging of plug-in hybrid EVs (PHEVs) over imbalances in different PTUs, with the objective of decreasing the individual imbalances.

Note that there is a special form of internal balancing, called passive balancing, where the aggregator intentionally deviates from the e-program within their portfolio, in order to make profit from imbalance settlement [3, 57]. This means that the aggregator creates intentional individual imbalance, contrary to internal balancing. This is not considered in this thesis. More information on passive balancing can be found in [54, 57, 64].

3.3.5. Managing congestion

The term congestion in the distribution grid refers to a situation in which the power imported from/sent to the grid exceeds the transfer capability of the grid. Especially with the high penetration of RES, congestion becomes a challenging operation issue. Congestion management refers to avoiding or relieving congestion in the distribution grid. Conventionally, congestion issues are managed by Distribution System Operators (DSOs) by reinforcing the grid, e.g. increasing the capacity of cables, transformers etc. [133]. However, this approach is usually not economically efficient since it requires an expensive investment [134]. Flexibility from demand side can offer an alternative solution for congestion issues.

With this business model, the aggregator aims to help the distribution grid to avoid congestion issues. This can be realized by means of three strategies. In these strategies, all Market operation, Consumer operation and Market economic, Consumer economic might differ. The only common element seems to be the consumers' assets; appliances, BESSs and EVs (*Which*) are suitable for congestion management. The detailed descriptions of these strategies are given as follows:

Strategy 5A: Consumer tariffs. The peak of electricity demand can be reduced by shifting the consumers' demand to an off-peak period, or curtailing it (*How*). This can be done by the consumers (*Who*) with time-varying financial rewards, to the consumers, such as TOU, CPP, or RTP. The impacts of time-varying tariffs on peak-shaving are discussed, based on data from pilot projects conducted in North America in [93]. The results show that CPP tariff with automatic curtailment is able to achieve a peak reduction of 30%, while TOU tariff can reach 5%.

Moreover, this can also be done by the aggregator (*Who*), who is given permission to control the consumers' assets via HEMS. For example, scheduling of consumers' appliances and EVs is studied with RTP and extra time-varying payment in [135] to minimize consumers' cost, and to mitigate the peaks. However, these financial rewards can also be fixed payments. In [136], a reward based DR scheme is proposed for residential consumers to shave peak loads. Rewards are calculated once a day and fixed throughout the day. The operation of consumers' assets in this strategy is similar to strategies in trading flexibility in the DAM. Hence, this strategy can be implemented as a part of trading flexibility in the DAM.

Strategy 5B: Tariffs from DSOs. Market mechanisms between DSO and the aggregator are proposed in the literature for congestion management. In this strategy, the aggregator (*Who*) interacts with DSO through tariffs to help with congestion management (*How*). A market-based mechanism is proposed in [137], where DSO offers daily dynamic prices to the aggregator to manage congestions, caused by EVs and heat pumps. A day-ahead tariff is proposed in [138], which DSO offers to the aggregator before the DAM clearing, with the objective of preventing possible congestions caused by EV charging. Similar market mechanisms are presented in [139–142], where the DSO predicts possible congestions for the next day and publishes prices prior to the clearing of the DAM to mitigate possible congestions.

Strategy 5C: Flexibility markets. Flexibility markets are regarded as a tool to trade flexibility with grid operators [143], to reduce the need for grid reinforcements [144]. Note that flexibility markets can also help with system balancing, although they are mainly studied and implemented for congestion management. Currently, existing flexibility markets are mostly in pilot phase, such as InterFlex and DYNAMO [145]. More information on flexibility market pilots and the issues related to flexibility markets is given in [144]. In addition, Universal Smart Energy Framework (USEF) proposes a framework that describes the design and structure of flexibility markets [146]. Furthermore, [147, 148] study a new market structure, called Flexibility Clearing House (FLECH). This market enables trading between the aggregator and the DSO, and runs parallel to the existing electricity markets. Similarly, [41] describes a flexibility market that allows the aggregator to sell flexibility for congestion management.

3.4. Main observations and identified knowledge gaps

Tables 3.2, 3.3 and 3.4 present an overview of papers about the aggregator's business models in residential and service sectors, analyzed by the framework. The aggregator's business models and identified strategies are separated by horizontal lines. Note that 'Who' element of Consumer operation of the framework is not given in these tables, as the consumers' assets in the papers are operated by the aggregator, yet with different objectives ('Why'). Similarly, Market operation is also not given since it is always present, except for balancing portfolio internally. Main observations and knowledge gaps identified as a result of this literature review are given in this section.

3.4.1. Common methods

It is observed that optimization models are commonly used in studies related to the aggregator's business models. Various types of optimization models are employed: deterministic optimization models, stochastic programming models, robust optimization models and MPC. The latter three are employed to cope with uncertainties in the power system such as RES generation, electricity consumption of consumers, and electricity market prices. Apart from optimization, algorithms and simulation based models are used in some papers as well.

3.4.2. Lack of studies about intra-day market and internal balancing

It can be noticed that the number of papers that study trading in DAM, and providing power reserves is significantly higher than the rest, especially compared to trading in intra-day market, and to balancing portfolio internally. For trading in intra-day market, this could be explained by the low liquidity of this market in the Netherlands and most of the European countries [149–151]. In fact, it is indicated in [152] that the traded intra-day volumes are equal to 4% of the traded day-ahead volumes in 2017 in the Netherlands. Due to the limited liquidity of the current Dutch intra-day market, the intra-day market is not studied in this thesis.

It is discussed in the literature that the design of current intra-day market should be improved to deal with their low liquidity [153]. By this way, more market participants, like aggregators, can trade closer to real time. For instance, Energy Trading Platform Amsterdam (ETPA) is a recent Dutch trading platform, started in April 2016, which serves as a market place to trade electricity in the short-term markets, focusing on the intra-day market [154]. New platforms and approaches, like ETPA, are expected to enhance the liquidity of the intra-day market.

3.4.3. Lack of studies about FCR

Among papers related to power reserves, the number of papers analyzing FCR is remarkably less than the other two. This could be attributed to the regulatory characteristics of FCR being different. Both capacity and energy bids exist for aFRR and mFRR. Auction frequency for energy bids is every PTU for both aFRR and mFRR. This means that the aggregator can decide to provide aFRR and mFRR energy bids, very close to real-time, with more accurate information on electricity consumption of the consumers and RES generation.

Contrarily, FCR does not allow energy, but only capacity bids. The auction frequency of FCR was previously weekly in the Netherlands, as well as in other CWE countries, like Germany, Belgium and France. Having weekly auctions was difficult for the aggregator to provide FCR with consumers' assets since it is a long time horizon to accurately forecast electricity consumption and RES generation. Besides, it is risky for the aggregator to guarantee FCR capacity for this long time. However, auction frequency of FCR is changed from weekly to daily auctions as of 1st of July 2019 [59]. More frequent auctions might facilitate more participation from the aggregator with consumers' assets, and might thus lead to new opportunities for aggregators.

3.4.4. Economic relations

The majority of the papers only focus on one of the economic relations. If the objective of the paper is to minimize the aggregator's cost, they focus on the aggregator's profit from the market (Market economic), while the financial reward the aggregator needs to pay to the consumers is considered out of scope (Consumer economic). On the other hand, if the objective is to minimize the consumers' cost, they only focus on the decrease in the consumers' cost (Consumer economic), without considering how much the aggregator earns from the market (Market economic).

However, the assessment of economic feasibility of a business model needs to involve both economic relations: how much money the consumers earn from the aggregator (Consumer economic), and how much profit the aggregator makes (Market economic and Consumer economic). Not considering both economic relations might have serious consequences: (1) the aggregator's profit is not calculated completely and realistically, or (2) the consumers might not be motivated to permit the aggregator to use their assets. Hence, this makes the assessment of economic feasibility incomplete and unrealistic, and might lead to wrong conclusions. Both economic relations need to be incorporated when evaluating economic feasibility of a business model.

A few papers consider both economic relations, as presented in Tables 3.2, 3.3, and 3.4. However, it can be noticed that this is mostly studied in DAM trading. This means that it is still not well incorporated in studies related to power reserves, intra-day market, internal balancing, and congestion management. A few papers research the financial rewards the aggregator offers to the consumers in more detail [91, 92, 135]. These papers determine optimal values of these financial rewards so that both the aggregator and the consumers can benefit from the business model in the optimal way. This guarantees that both actors gain the optimal benefit from the business model.

3.4.5. Semi-flexible appliances for providing power reserves

It can be observed that a substantial number of papers study EVs offering power reserves in the literature, along with a number of studies on flexible appliances and BESSs. To the best of our knowledge, there is currently no work focusing on the potential of only semi-flexible appliances in the residential and service sectors, to provide power reserves. In [155], the usefulness of DR from appliances to provide power reserves is studied and found that they have high potential for short term services such as FCR, whereas they have lower potential for aFRR and mFRR. However, this study also involves both semi-flexible and flexible appliances in the residential sector, as well as appliances in the industrial sector.

Considering the regulatory requirements of power reserves, semi-flexible appliances might not be suitable to provide power reserves. Activation of power reserves takes place very close to the real-time, and it cannot be known the day before. Hence, the operation of the appliances cannot be notified to the consumers a day, or an hour in advance, which might cause too much inconvenience to the consumers. Moreover, capacity bids for FCR, aFRR and mFRR need to be symmetrical. This implies that at a certain moment the energy may be taken from the grid, while at another moment it may be sent to the grid, depending on the upward and downward direction. However, semi-flexible appliances are not suitable to turn off during their use [156].

Additionally, the aggregator is penalized by the TSO for not delivering power reserves. This increases the dependency on the consumers' behavior. Even when the assets are operated by the aggregator, the consumers can override the aggregator's decisions, which may lead to penalties for the aggregator. It is also possible that the consumers do not comply with aggregator's operation in other business models, such as DAM trading, peak-shaving etc. However, in these cases, mainly the aggregator's imbalance costs get affected. These costs are considerably less than the penalty in case of a non-delivery of power reserves.[2] Therefore, it is necessary to keep in mind penalties for non-delivery of reserves, when considering providing power reserves only with semi-flexible appliances. Considering all these regulatory restrictions, the operation of semi-flexible appliances for power reserves does not seem promising as a business model for aggregators. Therefore, this is left out for further studying in this thesis.

3.4.6. Consumers' operation to trade flexibility in intra-day market

In the literature, the consumers' assets are mainly operated by the aggregator in the intra-day market. It is not known whether the consumers can operate their own assets for intra-day market trading. In the DAM trading and managing congestions, this is achieved by offering time-varying prices to the consumers. These prices can be offered with day-ahead notification or hours-ahead notification, i.e., consumers are notified on a day-ahead or hours-ahead basis, respectively.

Unlike the DAM, the intra-day market takes place in the day of delivery, and is based on continuous trading in the Netherlands. According to [65], 25% of all trades in the intra-day market are carried out maximum 1:42 hours before the start of the contract. Only 5% of all trades are carried out more than 15:00 hours before the contract starts. This indicates a preference for intra-day trading close to the real-time. Furthermore, the intra-day market prices are very volatile and difficult to predict well in advance [157]. For these reasons, it is rather difficult to offer consumers time-varying prices with day-ahead notification. Nonetheless, it might be possible to offer time-varying prices with hours-ahead notification. However, hours-ahead notification for the intra-day market may not be appealing to the consumers, similar to complex time-varying tariffs [98]. Hence, consumers' operation to trade flexibility in the intra-day market does not seem promising for the business model. In order to gain a better understanding of the consumers' preferences, a survey on consumers' reaction to hours-ahead notification for the intra-day market might be needed. This is not further addressed in this thesis, owing to limited liquidity of the current Dutch intra-day market.

3.4.7. Benefit stacking for BESS

BESSs can reserve its capacity to provide multiple business models, which is called benefit stacking [158]. Benefit stacking is considered essential to increase the financial attractiveness of BESSs [159, 160]. Although benefit stacking appears to be financially attractive, it is difficult to satisfy technical and regulatory constraints

[2]More information regarding the calculation of non-delivery penalties for power reserves is given in [111].

while controlling BESSs to provide multiple business models. A couple of papers study the operation of BESSs when combined with FCR or aFRR [161–163]. Yet, the benefit stacking for BESSs seems to be not studied in detail in the literature, although combining multiple business models is well considered for EVs, such as [115–117]. This may lead to new opportunities for business models for the aggregator.

Table 3.2: Papers from business model trading flexibility in the DAM, analyzed by the framework.

		Elec. market	Market economic	Consumer operation: Which	Consumer operation: Why	Consumer operation: How	Consumer economic	Paper
Trading flexibility in the DAM	Strategy 1A	DAM	y	Appliances	Max. agg's profit	LP	x	[74]
		DAM	y	EVs	Min. agg's cost	Bilevel opt.	x	[75]
		DAM	y	EVs	Min. agg's cost	Algorithm	x	[76]
		DAM	y	EVs	Min. agg's cost	Bilevel stoc. prog.	x	[77]
		DAM	y	EVs	Max. agg's profit	Robust opt.	x	[78]
		DAM	y	BESS & thermal storage	Min. agg's cost	Robust opt.	x	[79]
		DAM	y	EVs	Min. agg's cost	Stochastic robust opt.	x	[80]
		DAM & imbalance	y	EVs, TCLs & semi-flexible appliances	Min. agg's cost	Two-stage stoc. prog.	x	[81]
		DAM & imbalance	y	BESS & EWHs	Min. agg's cost	Two-stage stoc. prog.	x	[82]
		DAM & imbalance	y	EVs	Min. agg's cost	Stochastic prog.	x	[83]
		DAM & imbalance	y	EVs, TCLs & semi-flexible appliances	Min. agg's cost	Clustering algorithm & Two-stage stoc. prog.	x	[84]
		DAM & imbalance	y	EVs	Min. agg's cost	LP	x	[85]
		DAM & imbalance	y	EVs	Max. agg's profit	Two-stage stoc. prog.	Flat-rate	[86]
		DAM & imbalance	y	TCLs	Min. agg's cost	Two-stage stoc. prog.	y	[87]
		DAM	y	Electric space heating	Min. agg's cost	Optimization	Flat-rate + Extra	[88]
		DAM	y	BESS & Appliances	Max. agg's profit	MILP	Time-varying	[90]
		DAM & imbalance	y	EVs	Max. agg's profit	Bilevel stoc. prog.	Optimal flat-rate	[91]
		DAM & imbalance	y	Not specified	Max. agg's profit	Stochastic prog.	Optimal time-varying	[92]
	Strategy 1C	DAM	x	BESS & Appliances	Min. cons' cost	MILP	TOU, CPP, RTP	[100]
		DAM	x	Appliances	Min. cons' cost	Stochastic & robust	RTP	[101]
		DAM	x	BESS & Appliances	Min. cons' cost	Algorithm	RTP	[103]
		DAM & imbalance	x	Storage heating	Min. cons' cost	Two LP models	RTP + fixed payment	[104]
		DAM	x	Appliances	Min. cons' cost	MILP	TOU + time-varying	[105]

3

Table 3.3: Papers from business models trading flexibility in the intra-day market (IDM) and providing power reserves, analyzed by the framework.

		Elec. market	Market economic	Consumer operation: Which	Consumer operation: Why	Consumer operation: How	Consumer economic	Paper
Trading flexibility in IDM	Str. 2A	DAM + Intra-day	y	Appliances & BESS	Min. agg's cost	Probabilistic opt.	x	[106]
		DAM + Intra-day + aFRR	y	EVs	Min. agg's cost	Two-stage stoc. prog.	x	[107]
	Str. 2B	Intra-day	y	TCLs	Min. agg's cost	LP	x	[108]
		Intra-day	y	TCLs	Min. agg's imbalance cost	MPC	x	[109]
		DAM + Intra-day	y	Space heating	Min. agg's imbalance cost	MPC & Simulation	x	[110]
Providing power reserves		FCR	y	Heat pumps	Min. agg's cost	Simulation	x	[111]
		aFRR	x	EVs	Min. cons.' cost	Agent-based model	y	[113]
		aFRR	y	EVs	Max. agg's profit	Multi-objective opt.	x	[114]
		DAM & aFRR	y	EVs	Min. agg's cost	Optimization	x	[115],[116]
		DAM & aFRR	y	EVs	Max. agg's profit	Quadratic prog.	x	[117]
		DAM & aFRR	y	EVs	Max. agg's profit	Two-stage stoc. prog.	x	[119]
		DAM & aFRR	y	EVs & TCLs	Min. agg's cost	MPC	x	[120]
		DAM & aFRR	y	EVs & TCLs	Min. agg's cost	Two-stage stoc. prog.	x	[121]
		DAM & aFRR	y	EVs & single BESS	Max. agg's profit	Stochastic prog.	x	[122]
		DAM & aFRR	y	BESS	Max. agg's profit	Optimization	x	[123]
		DAM & aFRR	y	HVAC in offices	Min. agg's cost	MPC	x	[124]
		DAM & imbalance & aFRR	y	EVs	Min. agg's cost	Two-stage stoc. prog.	x	[125]
		DAM & mFRR	y	EVs	Min. agg's cost	Optimization	x	[126]
		DAM & imbalance & mFRR	y	EVs, TCLs & semi-flexible appliances	Min. agg's cost	Two-stage stoc. prog.	x	[127]
		mFRR	y	TCLs	Max. agg's profit	Heuristic approach	x	[128]
		DAM & aFRR	y	EVs	Max. agg's profit	Optimization	Battery degradation compensation	[129]
		DAM & aFRR	y	EVs	Max. agg's profit	Optimization	Flat-rate	[130]
		DAM & imbalance & aFRR	y	EVs	Min. agg's cost	Two-stage stoc. prog.	Optimal flat-rate	[131]

3

Table 3.4: Papers from business models balancing portfolio internally and managing congestion, analyzed by the framework.

		Elec. market	Market economic	Consumer operation Which	Consumer operation Why	Consumer operation How	Consumer economic	Paper
Balancing internally		x	y	PHEVs	Min. agg's imbalances	Algorithm	x	[132]
Managing congestion	Str. 5A	DAM	y	Appliances	Min. agg's cost	MILP	RTP & time-varying	[135]
Managing congestion	Strategy 5C	DAM + DSO tariffs	y	EVs & heat pumps	Max. agg's profit	MILP	Flat-rate	[137]
		DAM + DSO tariffs	y	EVs	Min. agg's cost	LP	x	[138]
		DAM + DSO tariffs	y	Flexible appliances	Min. agg's cost	LP	x	[139]
		DSO tariffs	y	EVs	Min. agg's cost	LP	x	[140]
		DAM + DSO tariffs	y	EVs & heat pumps	Min. agg's cost	Distributed opt.	x	[141]

3

3.5. Conclusions

This chapter provides insights in operational and economic aspects of the aggregator's business models in residential and service sectors. A literature review is carried out, and aggregator's business model framework is presented to analyze the selected papers on operational and economic aspects. Based on this analysis, different strategies to implement these business models are determined. Moreover, several knowledge gaps worth studying are identified: (1) Considering new trading platforms and regulatory changes, business models involving intra-day market, internal balancing, and FCR need more attention. (2) Economic relations between the aggregator and the electricity markets, and between the aggregator and the consumers need to be both incorporated while assessing economic feasibility of business models. In line with that, more emphasis should be put into determining the financial rewards aggregators offer to their consumers. (3) Business models involving BESSs should be combined. Nevertheless, the business model concerning the intra-day market is not studied further in this thesis, owing to their limited liquidity in the Netherlands. The remaining knowledge gaps are converted to research sub-questions in Section 3.6, and addressed in the next chapters.

In a broader perspective, gaining insights in operational and economic aspects of aggregator's business models, and studying the knowledge gaps help enhance the economic feasibility of aggregator's business models. This can be beneficial for aggregators and consumers since they become more interested in business models. Similarly, the power system can also benefit from this since flexibility obtained from consumers through these business models supports the transition to a power system with high penetration of RES.

3.6. Research questions revisited

Following the knowledge gaps identified in this chapter, three additional research sub-questions are added to the sub-question formulated in Section 1.4:

1. *What are the different strategies to implement the aggregator's business models with respect to economic and operational aspects?*
2. *What is the operational and economic feasibility of internal balancing with consumers' appliances?*
3. *What are the financial reward mechanisms between the aggregator and the consumers, to make business models economically feasible for both?*
4. *What is the impact of combining business models on operational and economic feasibility?*

The first sub-question is answered in this chapter through a literature review and application of a framework. The remaining three sub-questions correspond to the knowledge gaps given in the previous section. In order to answer these three sub-questions, in Chapter 4, we first focus on the aggregator implementing internal balancing. In Chapter 5, we explore financial reward mechanisms between the aggregator and the consumers. In Chapter 6, we assess how combining business models affects economic feasibility. In these sub-questions, we utilize several optimization models which are detailed in the next chapters. Based on these sub-questions, the thesis structure is updated and displayed in Figure 3.3.

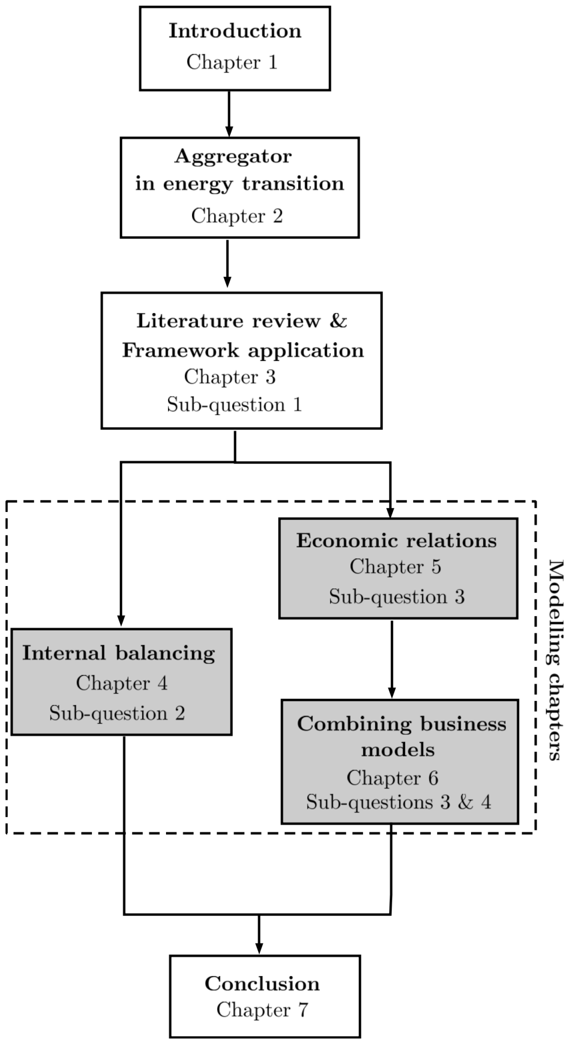

Figure 3.3: Updated representation of the thesis outline.

3.7. Overview of business models considered

Table 3.5 presents the business models and strategies considered in this thesis. In this table, Strategy 3 and 4 are written for providing power reserves and balancing portfolio internally, respectively, since there is only a single strategy determined for these business models. As described previously, the business model trading flexibility in the intra-day market which corresponds to Strategies 2A and 2B, is not studied, due to their limited liquidity in the Netherlands. Strategies 1B is also not studied since these strategies do not entail the aggregator's control over the consumers' assets; the operation of the assets depends on the consumers' reaction. Moreover, managing congestion is also not the main focus of this thesis, although Strategy 5A is briefly discussed. This business model mainly involves new tariffs and flexibility markets. Our focus is not to develop new market structures for the aggregator, but to analyze the aggregator's business models in the existing electricity markets.

Table 3.5: An overview of the aggregator's business models considered in this thesis.

	Strategy	**Deals with**	**Level**
Trading flexibility in the DAM	Strategy 1A	Variability	System
	Strategy 1C	Variability	Portfolio
Providing power reserves	Strategy 3	Uncertainty	System
Balancing portfolio internally	Strategy 4	Uncertainty	Portfolio

Table 3.5 also shows how different strategies help deal with variable and uncertain characteristics of RES, and thereby help with the system balance. We assume in this thesis that a certain part of the consumers possess their own solar panels since this is already common in the Netherlands. Hence, the aggregator helps with the variability and uncertainty of RES either in the power system or in the aggregator's portfolio, depending on the business model and the strategy.

The business model *trading flexibility in the DAM* helps deal with variable characteristics of RES. For instance, in Strategy 1A, the aggregator operates the consumers' assets to minimize their cost in the DAM. The DAM prices are affected by the electricity demand and generation in the power system. By reacting on these DAM prices, the aggregator helps maintain the system balance. The DAM prices are also expected to be affected by the variability of RES. By this way, the aggregator also helps deal with variability of RES in the power system. By reacting on the DAM prices, the aggregator is expected to reduce the electricity exchange with the grid at the moments when the power system has peak electricity demand.

On the other hand, in Strategy 1C, the aggregator operates the consumers' assets to minimize the consumers' costs. Since minimizing consumers' cost means, the aggregator reacts on the solar generation and attempts to utilize more solar generation for electricity demand. By this way, the aggregator deals with variability of RES within the aggregator's portfolio. By using more of renewable generation, electricity exchange with the grid is also expected to decrease at the moments when the power system has peak electricity demand. Note that by dealing with variability within their own portfolio, the aggregator indirectly contributes to the variability of RES in the power system.

The business models *providing power reserves* and *internal balancing* help deal with uncertainty of RES. The aggregator offers power reserves to the TSO to help cope with the system imbalance caused by forecast errors in renewable generation in the power system, while with *internal balancing* the aggregator aims to cope with their own individual imbalance caused by forecast errors in renewable generation in their portfolio. Note that by dealing with uncertainty within their own portfolio, the aggregator indirectly reduces to the uncertainty of RES in the power system.

4

Internal balancing with consumers' appliances

No joy is attained without some difficulty in this world.
All happiness presupposes some effort.

Jules Payot

4.1. Introduction

Internal balancing can be defined as the real-time adjustment of electricity consumption within a portfolio to reduce the aggregator's imbalance costs *by minimizing their individual imbalances*, adapted from [164]. In other words, the aggregator can use flexibility from the assets in their portfolio to reduce the individual imbalances close to the real-time internally, i.e., without participating in any electricity market. By reducing their individual imbalances, the aggregator's goal is to decrease the imbalance costs.

In the literature, a number of authors consider using different types of assets in real-time to reduce imbalance costs. In [165], an aggregator controls a group of storage space heating loads in the DAM and in the balancing market to minimize the imbalance costs. Similarly, [92] studies the aggregator's participation in the DAM and balancing market with the objective of minimizing the aggregator's DAM and imbalance costs. However, these papers focus on the aggregator's participation in electricity markets, not their ability to implement internal balancing. Unlike other papers, [166] aims to minimize the imbalance costs with internal balancing. However, this is done using combined heat and power (CHP) plants where the output of CHP plants is scheduled and no aggregator is taken into account. To the best of our knowledge, little attention has been given to using DR from appliances in residential and service sectors for internal balancing to minimize the aggregator's individual imbalances.

In this chapter, we address the research sub-question: "What is the operational and economic feasibility of internal balancing with consumers' appliances?". The aim of this chapter is to assess to what extent DR from appliances in residential and service sectors can be used for internal balancing to reduce the individual imbalances of the aggregator. Additionally, we aim to gain understanding of whether this is an economically feasible business model for the aggregator. Therefore, consumers' appliances are operated by the aggregator for internal balancing, i.e., to reduce their individual imbalances. For this purpose, a Model Predictive Control model is employed. A case study based on data from the Netherlands is used in the model: electricity demand from consumers in both residential and service sectors, solar generation forecasts at different time scales, and electricity market data.

An overview of the system considered in this chapter is provided in Section 4.2. The model equations are formulated and explained in Section 4.3. Input data and some assumptions regarding the modeling choices are outlined in Section 4.4. The results are described in Section 4.5, and discussed in Section 4.6. Lastly, conclusions are drawn in Section 4.7.

4.2. System description

In the system considered in this chapter, the aggregator has residential and service sector consumers in their portfolio. Some consumers own PVs. The aggregator is assumed to be an entity representing the role of a BRP, and a supplier of electricity to these consumers. Hence, the aggregator participates in the DAM on behalf of the consumers.

4.2.1. Aggregator's DAM participation

The timing of the DAM participation and internal balancing is displayed in Figure 4.1. Even though the DAM participation of the aggregator is not modeled in this chapter, we assume that the aggregator takes part in the DAM by submitting the DAM energy bid before the DAM closure time (12:00 noon). The aggregator can purchase electricity from the DAM on behalf of consumers, and can also sell excess solar generation of consumers in the DAM [121, 167]. After the closure of the DAM, the aggregator sends e-program to the TSO which includes the planned energy exchange with the power grid. It is based on DAM price predictions, consumers' demand predictions and day-ahead solar generation forecast. Day-ahead solar generation forecast is assumed to be received by the aggregator close to the DAM closure time and includes the prediction of solar generation for the day of delivery. Furthermore, the intra-day market is considered out of scope, meaning that it is not possible for the aggregator to update their e-program in the intra-day market.

4.2.2. Internal balancing with shifting appliances

On the day of delivery, once the e-program is submitted, the intermittent characteristics of solar generation cause the aggregator to face deviations from the e-program. These deviations, caused by solar generation forecast errors, are the

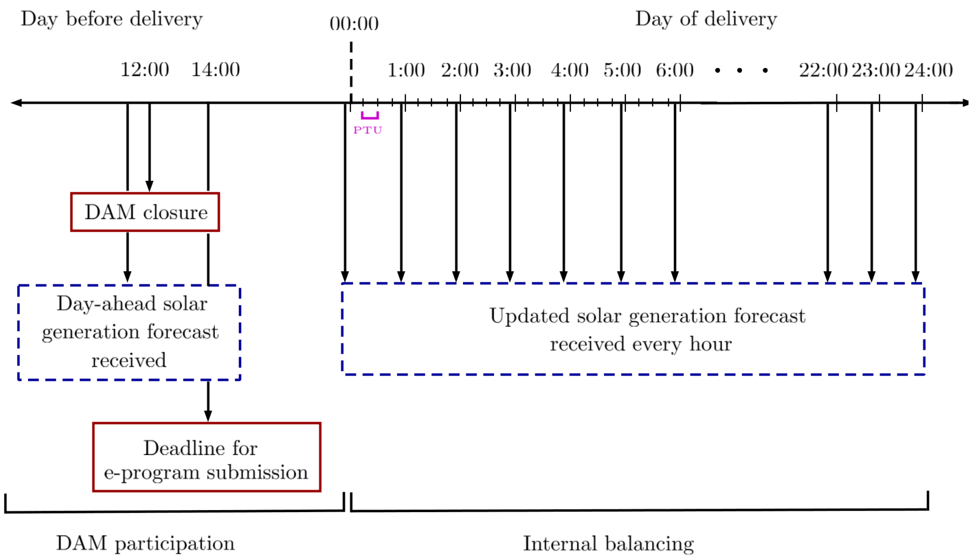

Figure 4.1: Timing of DAM and internal balancing in the Netherlands [48].

aggregator's individual imbalances. Note that, in this chapter, the only cause of individual imbalances is assumed to be solar generation because the main focus is on dealing with the impacts of uncertain production of RES. Consequently, other possible causes of individual imbalances such as demand from consumers, electricity outages etc., are neglected.

The aggregator is assumed to be given permission to use consumers' appliances for DR to implement internal balancing. For this purpose, DR with load shifting is considered in this system, which refers to the shifting of electricity consumption to another time period within pre-specified time limits. Load curtailment is not considered. It is significant to point out that the success of load shifting for internal balancing depends on the consumers' willingness to participate, which is to an important extent determined by the inconvenience caused by the load shifting. Since internal balancing takes place close to the real-time, short notice on shifting time makes flexible appliances more suitable for internal balancing. As a result, in this system we assume that only flexible appliances are available to the aggregator to be used for internal balancing.

The aggregator is assumed to receive updated solar generation forecasts shortly before the beginning of every hour on the day of delivery, starting from 00:00, as illustrated in Figure 4.1. These updated solar generation forecasts become increasingly accurate as the time horizon to real-time shortens [168]. Using a more accurate solar forecast, the aggregator can shift flexible appliances shortly before delivery so as to minimize the imbalances, i.e., implementing internal balancing. As expressed earlier, only flexible appliances are available for shifting for internal balancing due to their controllability characteristics.

As the purpose of internal balancing is to minimize their individual imbalances, the positive and negative imbalances are not differentiated and they both need to be minimized. In this way, the aggregator intends to remain close to their e-program.

4.2.3. Imbalance settlement

After the real-time, the individual imbalances are settled in the imbalance settlement with imbalance prices. Two types of imbalance price mechanism exist: single and dual pricing. In single pricing, the positive and negative imbalance prices are the same, and dependent on the direction of the system imbalance. Namely, if the upward power reserve is activated, both imbalance prices are based on the upward power reserve price (λ^{up}), vice versa for downward power reserve price (λ^{down}). Unlike that, in dual pricing, different imbalance prices are applied for positive and negative imbalances. The upward power reserve price is applied to negative imbalances, while the downward power reserve price is applied to positive imbalances. The imbalance pricing mechanisms in single and dual pricing are illustrated in Table 4.1.

The imbalance pricing mechanism in the Netherlands is applied as a combination of both single and dual pricing. Dual pricing is applied when both upward and downward power reserves are activated by TSO in the same PTU, whereas single pricing is valid when power reserve is activated in only one direction. Yet, majority of the time, single pricing takes place since dual pricing occurred 10% of all PTUs, in 2009 [57]. Note that upward reserve prices are in general higher than DAM prices. Conversely, downward reserve prices are lower than DAM prices [54].

Table 4.1: Imbalance prices under single and dual pricing mechanisms. Negative sign indicates paid, while positive sign indicates received.

			System imbalance	
			Negative	**Positive**
Aggregator's imbalance	**Single pricing**	**Negative**	$-\lambda^{up}$	$-\lambda^{down}$
		Positive	λ^{up}	λ^{down}
	Dual pricing	**Negative**	$-\lambda^{up}$	$-\lambda^{up}$
		Positive	λ^{down}	λ^{down}

4.3. Optimization model

The aggregator uses an optimization model to implement internal balancing with consumers' appliances. For this purpose, a Model Predictive Control (MPC) model is employed in this chapter. The general algorithm for MPC, and its inputs and outputs to the MPC model in this chapter are explained in the first and second subsections, respectively. The third subsection formulates the equations for the MPC model. The fourth subsection explains how to calculate the results for a single day from different runs of the MPC model.

4.3.1. Model Predictive Control algorithm

MPC, also known as receding horizon control, has become an important strategy in order to solve optimization problems over a moving time horizon. It has gained growing attention in fields of energy transition [169, 170].

The basic algorithm for MPC can be summarized as follows:

1. The MPC starts from the current state of the system at the beginning of the time step k. It aims to determine the optimal solution based on objective function, taking into account the constraints. This is done over a certain prediction horizon of T steps.
2. After the optimal solution over the prediction horizon is found, the MPC implements the actions of the first time step of the prediction horizon.
3. At the start of the next time step, the prediction horizon is shifted and now starts at $k+1$, and the MPC uses updated input data. Thus, the MPC operates in a rolling horizon approach.
4. The model goes back to the Step 1, and the procedure is repeated.

More comprehensive information in the matter of MPC can be found in [171, 172].

4.3.2. Model Predictive Control description

MPC is selected as the optimization model in this chapter, owing to its rolling horizon approach and its ability to update the model input. The objective of this model is to minimize the aggregator's total individual imbalances based on input data, some of which get updated between the different runs.

The time resolution of the MPC model is PTUs which is 15 minutes in the Dutch balancing market. Since internal balancing starts at the beginning of the day of delivery (00:00), the MPC model starts at 00:00, and is run at the beginning of each PTU ($T = 96$ times per day in total). The symbol t represents the MPC run, where $t \in \{1, 2, \ldots, T\}$. The symbols t' and t'' denote the PTUs in that run. The inputs of the MPC model for different runs (Runs 1, 2 and 5) are illustrated in Figure 4.2. The non-flexible, semi-flexible, flexible appliance demand from consumers ($P^{nf}_{t'}$, $P^{sf}_{t'}$, $P^{f}_{t,t'}$, respectively), and the planned energy exchange with the power grid on e-program ($P^{da}_{t'}$) are provided as the inputs to the model. In addition these inputs, updated solar generation forecasts ($P^{PVfor,upd}_{t,t'}$) are also inputs to the model. Note that although the MPC model is run at every PTU, we assume that $P^{PVfor,upd}_{t,t'}$ is received by the aggregator at every 4 PTUs. That is to say, the aggregator obtains an updated solar generation forecast shortly before the beginning of every hour.

It should be remarked that $P^{f}_{t,t'}$ gets updated as a result of a MPC run, depending on how the flexible appliances are shifted. Therefore, Figure 4.2 shows that $P^{f}_{t,t'}$ is obtained as the output of the current MPC run, and becomes the input for the next MPC run. Since its values might change between different runs t in the MPC model, the symbol is given as $P^{f}_{t,t'}$. Contrarily, $P^{nf}_{t'}$, $P^{sf}_{t'}$ and $P^{da}_{t'}$ are input data that do not change between different runs; t is omitted in these symbols. Thus, for the inputs and outputs whose values change between different runs t in the MPC model, t is incorporated.

The outputs of the MPC model are also given in Figure 4.2. As a result of every run of the MPC model, the optimal schedule of flexible appliances ($P^{sch,f}_{t,t''}$) which minimizes the total imbalances is acquired. Furthermore, the information regarding imbalances ($\Delta_{t,t'}$), positive imbalances ($\Delta^{+}_{t,t'}$) and negative imbalances ($\Delta^{-}_{t,t'}$) are obtained as well.

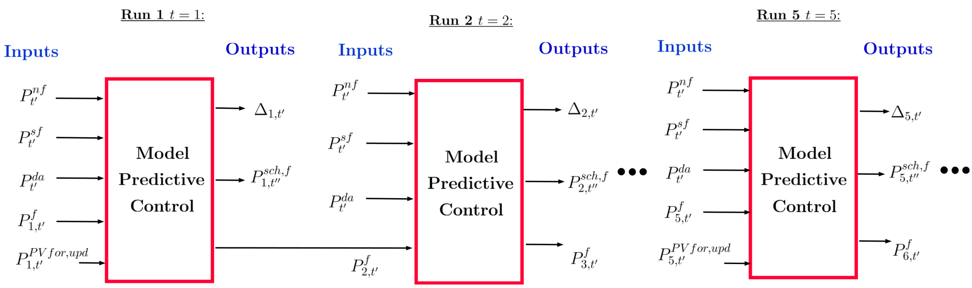

Figure 4.2: The inputs and outputs of the MPC model for different runs (Runs 1, 2 and 5).

4.3.3. Mathematical formulation

The following MPC model is formulated. Nomenclature for this chapter is given in Appendix B.1.

$$\text{Minimize} \quad \sum_{t'=t}^{T} \Delta^{+}_{t,t'} + \Delta^{-}_{t,t'} \tag{4.1}$$

subject to

$$P^{act}_{t,t'} + P^{PV\,for,upd}_{t,t'} = P^{nf}_{t'} + P^{sf}_{t'} + P^{sch,f}_{t,t''} \qquad \forall t', t'' \in \{t, \ldots, T\} \tag{4.2}$$

$$\Delta_{t,t'} = P^{da}_{t'} - P^{act}_{t,t'} \qquad \forall t' \in \{t, \ldots, T\} \tag{4.3}$$

$$\Delta_{t,t'} = \Delta^{+}_{t,t'} - \Delta^{-}_{t,t'} \qquad \forall t' \in \{t, \ldots, T\} \tag{4.4}$$

$$P^{f}_{t,t'} = \sum_{t''=\max(t'-t_{shift},t)}^{\min(t'+t_{shift},T)} P^{shifted}_{t,t',t''} \qquad \forall t' \in \{\max(1, t-t_{shift}), \ldots, T\} \tag{4.5}$$

$$P^{sch,f}_{t,t''} = \sum_{t'=\max(t''-t_{shift},1)}^{\min(t''+t_{shift},T)} P^{shifted}_{t,t',t''} \qquad \forall t'' \in \{t,\dots,T\} \tag{4.6}$$

$$P^{f}_{t+1,t'} = P^{f}_{t,t'} - P^{shifted}_{t,t',t} \qquad \forall t' \in \{\max(1, t - t_{shift}),\dots,T\} \tag{4.7}$$

$$0 \le \Delta^{+}_{t,t'} \le M\, y_{t'} \qquad \forall t' \in \{t,\dots,T\} \tag{4.8}$$

$$0 \le \Delta^{-}_{t,t'} \le M\,(1 - y_{t'}) \qquad \forall t' \in \{t,\dots,T\} \tag{4.9}$$

$$y_{t'} \in \{0,1\} \qquad \forall t' \in \{t,\dots,T\} \tag{4.10}$$

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The objective function in Equation (4.1) aims to minimize both positive and negative imbalances ($\Delta^{+}_{t'}$ and $\Delta^{-}_{t'}$) of the aggregator. Therefore, this equation gives the absolute value of the sum of the positive and negative imbalances. The power balance constraint in Equation (4.2) ensures that the demand from the consumers' non-flexible, semi-flexible and flexible appliances is satisfied by the supply at all times: updated solar generation forecast and the actual energy exchange with the power grid ($P^{act}_{t'}$). Equation (4.3) calculates the total imbalance of the aggregator which equals the actual energy exchange with the power grid, subtracted from the planned energy exchange with the grid one day ahead. In Equation (4.4), the total imbalance is broken down into the sum of the positive and negative imbalances of which at most one can be non-zero in one time step.

Equation (4.5) describes that the flexible appliances can be shifted forward and backward up to maximum shifting time (t_{shift}) in order to limit the discomfort for the consumers. Equation (4.6) calculates the total scheduled appliance at each PTU shifted from other PTUs. Equation (4.7) determines the updated flexible appliance demand for the next runs. The use of Equations (4.5), (4.6), (4.7) is demonstrated with a simplified example in Appendix B.2.

Equation (4.8) and (4.9) make sure that the positive and negative imbalances are greater than or equal to zero and cannot occur at the same time, thanks to the binary variable $y_{t'}$. This binary variable $y_{t'}$ is defined in Equation (4.10) and is equal to 1 if there is a positive imbalance and to 0 if there is a negative imbalance.

It should also be noted that the equations are executed $\forall t' \in \{t,\dots,T\}$ to incorporate the rolling horizon of the MPC model, with the exception of Equations (4.5) and (4.7) as they are used to compute the updated flexible appliance demand which depends on the previous runs. The MPC model is implemented and solved in GAMS using the CPLEX solver.

4.3.4. Calculations of the results for a single day

The MPC optimization model runs 96 times in a day, i.e., for all $t \in \{1,\dots,T\}$. This means that the MPC model gives 96 sets of outputs in total. Due to the rolling horizon fashion of MPC, each next output starts from a later PTU t'. For instance, for the first run, the output $P^{sch,f}_{1,t'}$ has 96 PTUs starting from $t' = 1$, while for the second run, output $P^{sch,f}_{2,t'}$ has 95 PTUs, starting from $t' = 2$. This is illustrated in

Figure 4.3. However, in the MPC model, only the first PTU is implemented after each run. At the end of the model, the first PTU from each run should be taken as the result for a day, marked with red in Figure 4.3. Therefore, the scheduled flexible appliances at the end of the model ($P^{final,f}_{t'}$) are defined in Equation 4.11. The obtained vector is represented by the red rectangle on the right in Figure 4.3.

$$P^{final,f}_{t'} = P^{sch,f}_{t',t'} \qquad \forall t' \in \{1,\ldots,T\} \tag{4.11}$$

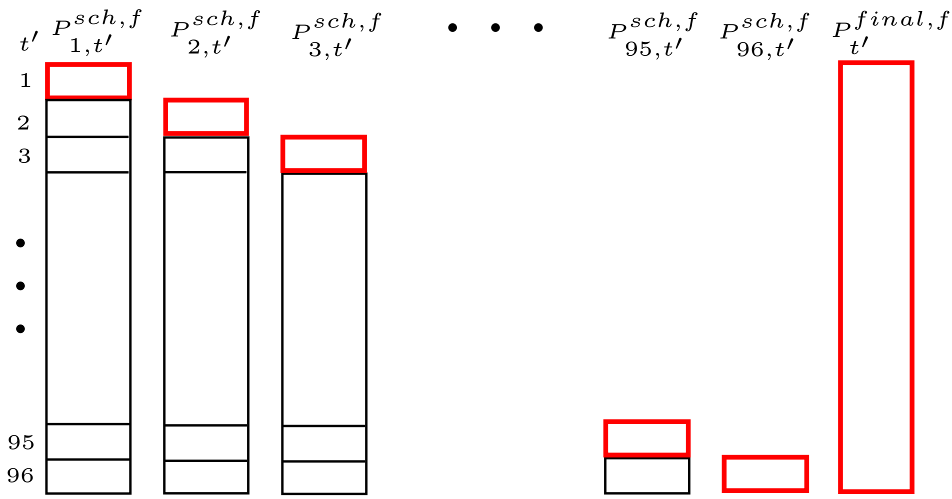

Figure 4.3: Calculation of $P^{final,f}_{t'}$ for a single day

The results for total amount of imbalances and total imbalance costs for a day are calculated from the outputs of each run in a similar manner. These calculations are presented in Equations (4.12) and (4.13). Equation (4.12) describes the total amount of individual imbalances of the aggregator for one day as the absolute value of the sum of positive and negative imbalances. Total amount of individual imbalances is defined as the absolute value of this sum. Equation (4.13) calculates the total imbalance cost of the aggregator for one day which consists of the cost from the multiplication of negative imbalance prices with negative imbalances, and the revenue from the multiplication of positive imbalance prices with positive imbalances.

$$\Delta^{tot} = \sum_{t=1}^{T} \Delta^{+}_{t,t} + \Delta^{-}_{t,t} \tag{4.12}$$

$$C^{tot}_{imb} = \sum_{t=1}^{T} \Delta^{-}_{t,t}\lambda^{-}_{t} - \Delta^{+}_{t,t}\lambda^{+}_{t} \tag{4.13}$$

4.4. Case study 1: Data & assumptions

The MPC model is implemented for a case study involving residential and service sectors in the Netherlands. The input data for the case study, together with the assumptions regarding the modeling choices are described in this section.

4.4.1. Appliance demand

The model is evaluated both for residential and for service sector appliances. Electrification of heat is taken into account for both consumer types by assuming the use of heat pumps for heating. We assume that the aggregator has perfect information on the appliance demand of the consumers. Hence, we do not model any uncertainty in appliance demand. Furthermore, the consideration of how to arrange the scheduling of different devices separately is out of the scope of this thesis. It is assumed that flexible appliances are available for shifting. As discussed earlier, the only DR option considered in this study is load shifting. Thus, we assume that shifting appliances does not change the total amount of electricity consumed.

- *Residential sector demand profiles.* To model residential demand, the measured household data of 63 households in the Netherlands are used (data courtesy of the Dutch Distribution System Operator (DSO) Alliander). The data is available for the period from June 1st, 2012 until May 31st, 2013. This period is therefore used as the modeled year. The breakdown of electricity use in appliance-type is based on a British study [173]. Residential electricity demand characteristics for the Netherlands [174] are comparable with residential electricity demand characteristics for Great Britain [175]. The influence on variables such as income, family composition and type of dwelling on the demand profiles of the residential consumers is studied for the Netherlands in [176]. However, this is not considered in this thesis as the demand profiles are aggregated by the aggregator, causing a reduction in the differences between the demand profiles. The total residential demand for the modeled year is 217 MWh, of which 142 MWh is non-flexible, 27 semi-flexible, and 48 flexible.

- *Service sector demand profiles.* Service sector demand is modeled based on Commercial Building Models of the United States Department of Energy [177]. More information on the service sector demand modeling is given in [178]. Separate demand profiles for different appliances in the service sector are available. Note that no semi-flexible appliances are defined in the service sector based on [34, 177]. The service sector demand profiles are scaled such that their total annual demand from appliances except for heat pumps equals that of the residential demand modeled, 217 MWh/year, of which 180 MWh/year is non-flexible and 37 MWh/year is flexible. The annual demand for residential and service sectors (except for heat pumps) is taken as equal to avoid any influence of the difference in the annual demand on the results.

- *Heat pump demand profiles.* Electrification of heat is taken into account for both residential and service sector consumers. Heat pumps are regarded as flexible appliances. Residential heat pump demand profiles are based on historic heating demand data of the same 63 households as used for modeling other residential appliances (data courtesy of the Dutch DSO Alliander). Service sector heat pump demand profiles are based on the same Commercial Building Models [177] as used for modeling other service sector appliances. Heat pump demand profiles are calculated from historic space heating data as described in [179]. Heat pump penetration is assumed to be 50% in both residential and service sectors. This assumption leads to different annual electricity demands by heat pumps in residential consumers (79 MWh/year) and service sector consumers (18 MWh/year). Figure 4.4 demonstrates the annual and daily demand profiles in the residential and service sector, including heat pumps, in terms of percentage of total demand.

4

- *Shifting time of the appliances.* Based on the review of literature [34], the maximum shifting time for the flexible appliances is assumed to be two hours (eight PTUs) in the MPC model for flexible appliances.

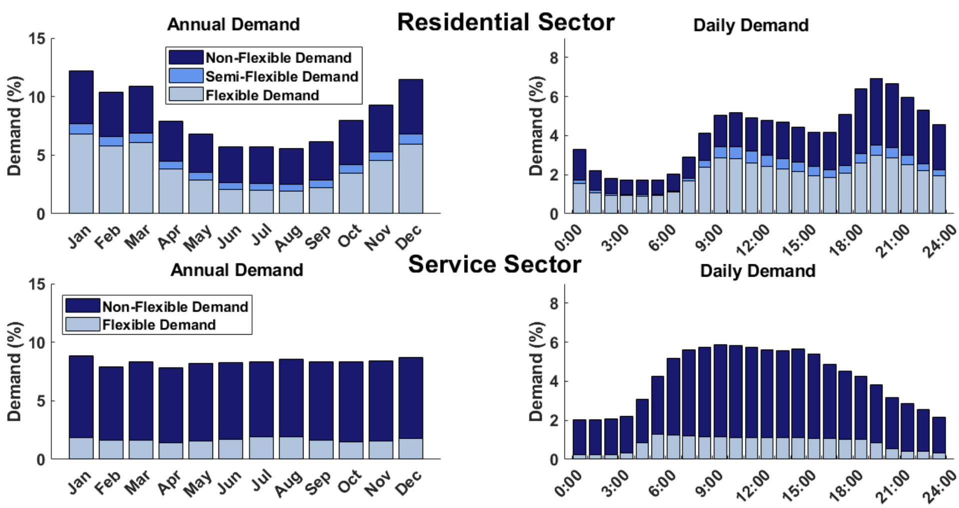

Figure 4.4: Annual and daily demand profiles of the residential and service sectors. Left graphs illustrate the annual demand expressed as a percentage of total annual demand. Right graphs show average daily demand, with hourly demand given as a percentage of the total daily demand. Heat pumps are included in flexible appliances.

4.4.2. Solar electricity generation profiles

Solar power generation is modeled based on solar insolation data from the Royal Netherlands Meteorological Institute (KNMI) [180]. These insolation data are converted to solar PV output using the algorithm developed by Walker [181] and technical specifications from Solarex MSX-60 PV panels [182]. It is assumed that 50% of the residential sector consumers own solar PV panels, and that the service sector produces an equal amount of solar power per year. Uncertainty in solar power generation is considered by modeling solar generation forecasts based on historic data by Gaussian noise (i.e., error) addition to the measured historical data. The magnitude of the error increases with increasing forecast horizon. The method is described in [183].

Two forecast scenarios are modeled: high and low forecast error. In the high forecast error scenario, the total capacity of the modeled solar panels for each consumer type is 0.1 MW. Given the small size of the joint solar PV panel area, the relative root mean squared error is taken to range from 25% of the measured value for the next hour, to 40% of the measured value for 24 hours ahead of time. These values are based on a literature review of real solar forecasting models [184] and are thus representative of the real situation. In the low forecast error scenario, the errors are assumed to be five times lower, ranging from 5% for the next hour to 8% for 24 hours ahead of time.

4.4.3. Prices

In this chapter, the aggregator is assumed to be a price-taker with respect to the DAM and imbalance prices. The model takes historic prices into account from the same period (June 1st, 2012 until May 31st, 2013) as the appliance data. Both the DAM and imbalance prices are taken into account. For the DAM prices, historical EPEX wholesale electricity prices are used (data courtesy of the Dutch DSO Alliander). Dutch imbalance price data are obtained from TenneT [185]. The imbalance prices from two consecutive days in June 2012 are depicted in Figure 4.5. Note that the average imbalance prices are not given to be able to show their volatility within a single day, as well as between two days. In most of the PTUs, positive and negative imbalance prices are equal to each other.

4.4.4. Data granularity

The time resolution in the MPC model is 15 minutes. This data granularity is required to realistically model the Dutch balancing market. However, most data, with the exception of residential demand data, are only available with hourly granularity. Therefore, other appliances, solar generation forecasts and actual solar generation data are interpolated as follows. For appliances: for each quarter hour, corresponding hourly appliance data are divided by four. For solar generation forecasts: these are made with hourly granularity. Quarter hourly forecasts are obtained from hourly forecasts by dividing the forecast for each hour by four.

4.5. Case study 1: Results

This section presents results of the case study using the MPC model described in Section 4.3.

4.5.1. Aggregator's imbalances

Figure 4.6 shows the reduction in the total amount of imbalances (Δ_{total}) for the months March, June, September and December with and without DR for internal

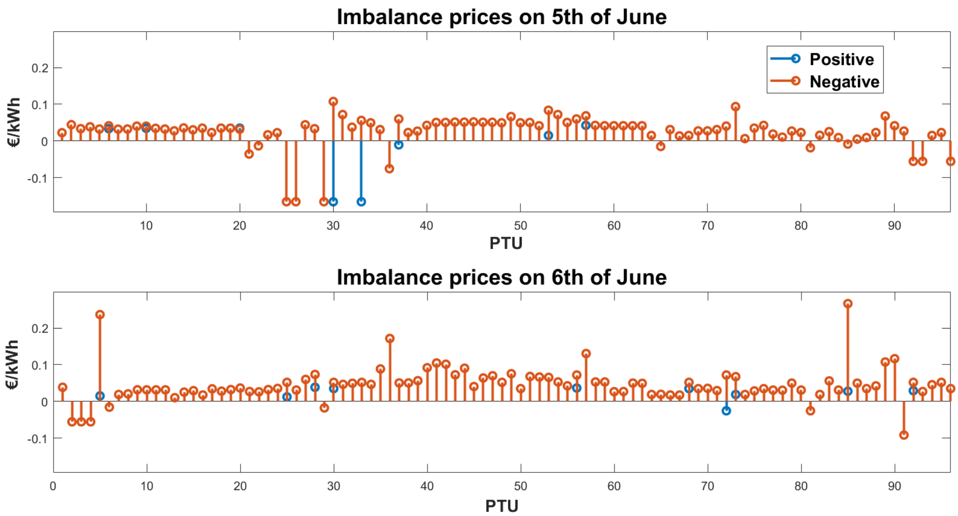

Figure 4.5: Positive and negative imbalance prices on two consecutive days in June 2012 (5$^{\text{th}}$ and 6$^{\text{th}}$ of June) in the Netherlands.

balancing. This figure shows considerable seasonal differences. In December, the total amount of imbalances is the lowest. This can be explained by the fact that absolute solar generation forecast errors are smaller in this month due to lower solar generation. The total amount of imbalances is highest in June. In March and September, the total imbalances are comparable. Moreover, comparing the residential sector with the service sector, no considerable distinction between these sectors in terms of the total amount of imbalance reduction is observed.

Table 4.2 presents the maximum and the average reduction in the total amount of imbalances, as a percentage of the imbalances without internal balancing. According to this table, for the residential sector in June, the aggregator's total amount of imbalances can be reduced between 0% and 30%, with an average reduction of 8.7%. The minimum reduction in imbalances (0%) occurs when the imbalances cannot be reduced by internal balancing. In December, the highest relative reduction in imbalances is achieved for both the maximum and the average values, in spite of the low total imbalances in December. This is caused by the small absolute forecast errors, combined with highest flexible appliance demand because of high heat pump usage in December, as illustrated in Figure 4.4. Similar to Figure 4.6, the results from the residential and service sector do not differ notably from each other.

4.5.2. The impact of types of forecast errors

Table 4.2 shows that there is a large variation between the maximum and the average values each month. This is caused by the uneven reduction of imbalances over different days: imbalances can be decreased using the MPC model by a considerable amount on certain days, whereas on other days, the imbalance reduction is limited.

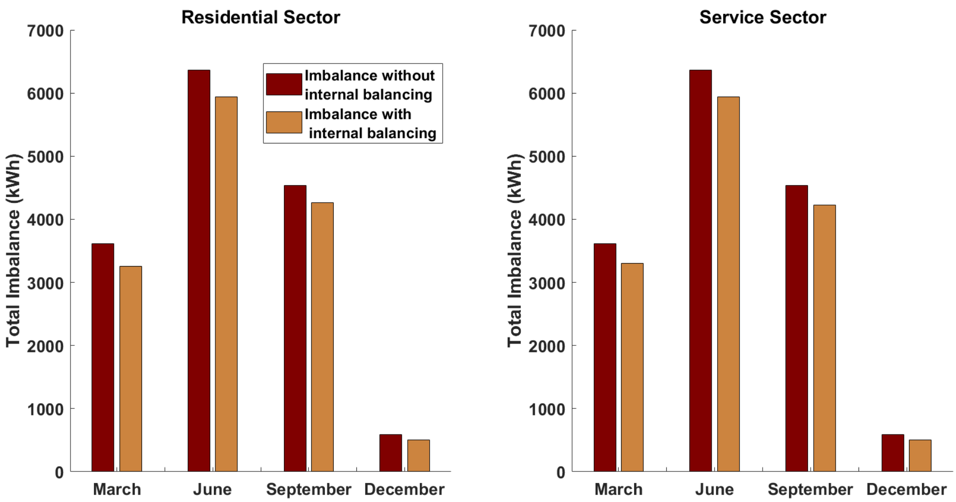

Figure 4.6: Total amount of imbalances for March, June, September and December with and without internal balancing.

Table 4.2: Maximum (Max) and average (Avg) reduction of imbalances in different seasons and different consumer types, given as percentage of imbalances without DR for internal balancing.

	June		September		December		March	
	Max	Avg	Max	Avg	Max	Avg	Max	Avg
Residential	30%	8.7%	52%	9.1%	74%	15%	44%	12.1%
Service	39%	9%	48%	10.1%	74%	16.3%	45%	11.6%

The cause of this variation can be attributed to the *types of forecast error*. This is illustrated for three days in June. June 8th, 11th, and 25th are selected for this purpose, due to their different forecast characteristics. The results associated with these days are shown in Figures 4.7, 4.8 and 4.9.

Figure 4.7 shows (1) the day-ahead solar generation forecast the aggregator received just before the DAM closure, and (2) the updated last available solar generation forecasts received on the day of delivery. The difference between these two is called *forecast errors*. On June 11th, the day-ahead solar generation forecast overestimated solar generation for the entire day. In other words, the day-ahead forecast is greater or equal to the updated forecast for every PTU. Therefore, the forecast errors on this day are continually negative. This day is an example of a *single-direction forecast error day*. On the other hand, on June 8th, the forecast error switches its sign; it is positive at some PTUs and negative at others. June 8th and 25th show characteristics of a *switching forecast error day*.

Figure 4.8 presents the results for the scheduled flexible appliances at the end

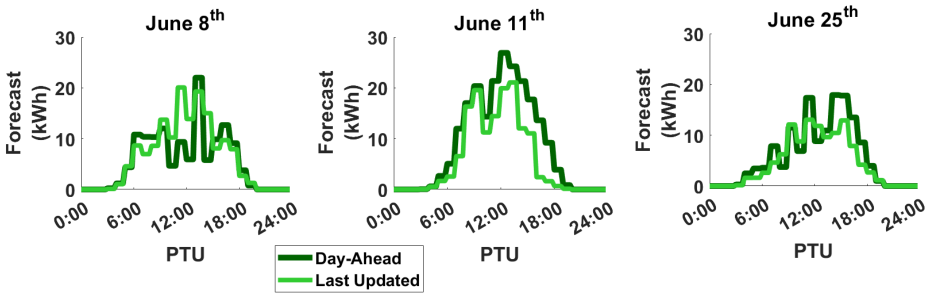

Figure 4.7: Day-ahead solar generation forecast, updated solar generation forecast for selected days in June.

of the model ($P_{t'}^{final,f}$), using the MPC model on the selected four days in June. The dark red lines in the upper four charts represent the original flexible appliance demand in the residential sector. The light red lines in the upper four charts are the scheduled flexible appliance demand in the residential sector. Likewise, the dark blue lines in the lower four graphs indicate the original flexible appliance demand in the service sector. The light blue lines in the lower four charts represent the scheduled flexible appliance demand in the service sector. The flexible appliances are only shifted from approximately 5:00 to 21:00 since there is no solar generation outside these hours, and thus no imbalances. On June 11th, the scheduled flexible appliance demand remains the same as the original flexible appliance demand in both the residential and service sector despite the large imbalances on this day. On the other days, the flexible appliances are shifted to other PTUs to minimize the total imbalances.

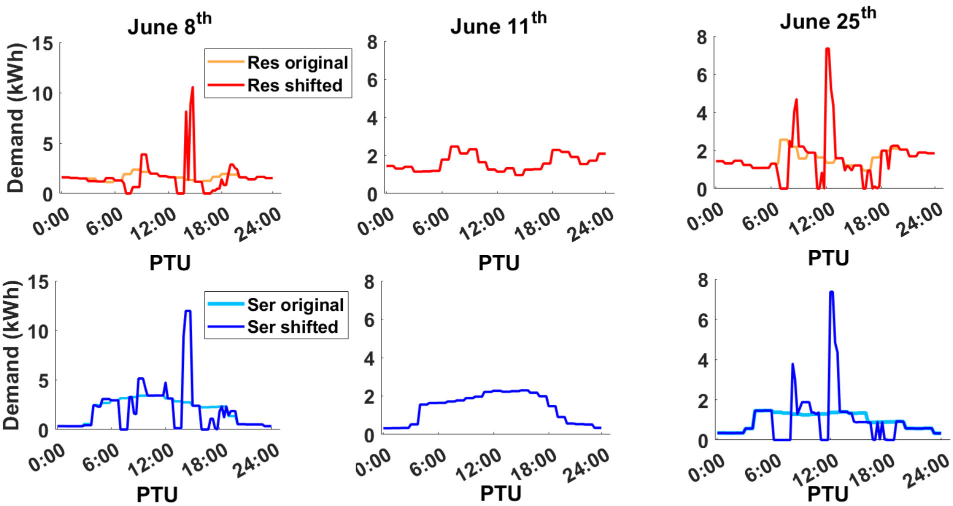

Figure 4.8: The scheduled flexible appliance demand for selected days in June.

Figure 4.9 shows how the imbalances are reduced in residential and service sectors on the selected four days in June. The black dashed line shows the imbalances without DR. The red and blue lines represent the imbalances with DR for internal balancing in the residential sector and the service sector, respectively. It is important to point out that the imbalance without DR is identical in both sectors as they are assumed to have the same area for solar panels and that the imbalances result solely from the solar generation forecast errors.

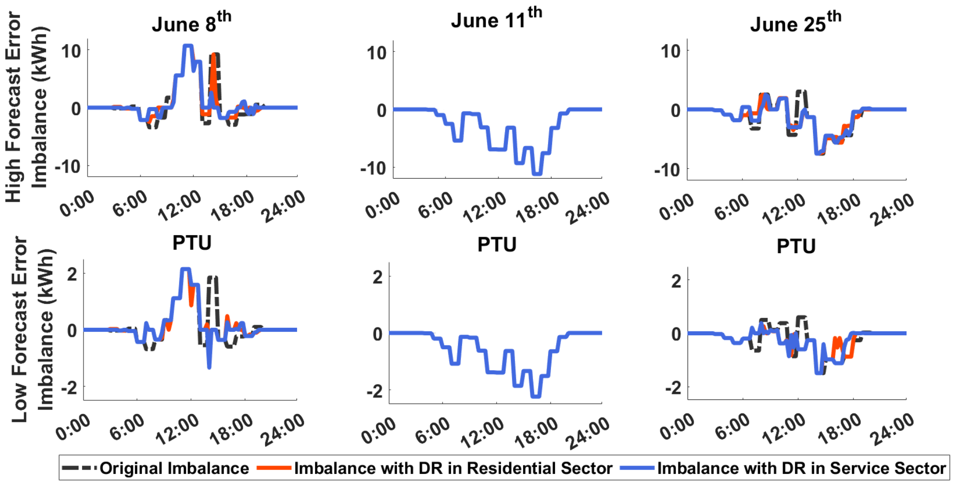

Figure 4.9: The total amount of imbalances in the residential and service sector for selected days in June. (Note the difference in scale on the y-axis.)

As shown in Figure 4.9, the imbalances only occur from approximately 5:00 to 21:00 since there is no solar generation outside these hours. On June 11th, the imbalances remain the same for both residential and service sectors; the reduction in the total amount of imbalances on this day is equal to 0%. However, the imbalances are reduced on the other days. This means that the imbalances can only be decreased using DR for internal balancing if there are so-called switching forecast errors within the same day, as might be expected. On these switching error days, the flexible appliances can be shifted from the PTUs with underestimation of solar generation to the PTUs with overestimation of solar generation. In contrast, on single-direction error days, DR for internal balancing cannot resolve the imbalances since solar generation is overestimated or underestimated for the entire day. However, it cannot be known to the aggregator in advance whether the day will be a switching error or a single error day.

4.5.3. The impact of magnitude of forecast errors

To gain understanding of the impact of the magnitude of forecast errors on the imbalance reduction, the same analysis is carried out for the same selected days in June, but with a smaller magnitude of forecast errors: low forecast error scenario. The results from this analysis are depicted in the lower graphs of Figure 4.9. In comparison to the high forecast error scenario, the absolute amount of imbalances is lower for each day in the low forecast error scenario, due to the smaller magnitude of forecast errors. In addition, a higher percentage of imbalance reduction is achieved in low forecast error scenario since the total amount of flexible appliances remains the same and the absolute amount of imbalances is reduced. However, despite the lower absolute amount of imbalances, not all the imbalances can be resolved even in the low forecast error scenario. One reason for this is the time limitation on load shifting: the flexible appliances can only be shifted 8 PTUs before or after the original timing of consumption. Another reason is the type of forecast error. For example, on June 11th, the reduction in the total amount of imbalances is still equal to 0% as it is a single-direction error day.

4.5.4. The impact of types of consumers

The difference between the residential and service sector is noticeable in Figure 4.9. Especially on June 8th, the reduction in the service sector is greater than the residential sector. This can be explained by the differences in the demand profiles of the residential and the service sectors. Residential consumption peaks in the early morning and evening hours, while service sector consumption primarily occurs during the daytime hours, coinciding with the highest absolute imbalances. In addition, although the imbalance reductions are approximately the same for the residential and service sector as given in Figure 4.6, the service sector has relatively fewer flexible appliances. Thus, the utilization of the flexible appliances for internal balancing is higher in the service sector compared to the residential sector, also as a result of the demand profiles in the service sector.

4.5.5. Aggregator's imbalance costs

Based on the schedule for the flexible appliances, the imbalance cost for the aggregator for each day in June is computed and depicted for the residential sector in Figure 4.10 when internal balancing is implemented, and when it is not implemented. Negative cost values signify a profit to the aggregator. This figure shows that the cost values do not decrease when internal balancing is implemented. The same also applies for the service sector. For this reason, even though the total amount of imbalances is reduced by implementing internal balancing, the imbalance costs for the aggregator remain nearly identical. This can be explained with two reasons:

- The objective of the MPC model is not to minimize the aggregator's imbalance costs, but to minimize the individual imbalances of the aggregator. As both the positive and negative imbalances are to be minimized, the revenue that might come from the positive imbalances and the cost that might be generated by the negative imbalances are not optimized, and cancel each other out. This is a significant barrier for not achieving any decrease in the imbalance cost.

- The average imbalance price in June (considering both positive and negative) is equal to 0.0479 €/kWh. Also, the average amount of imbalance reduction in a day (positive and negative) is approximately equal to 14 kWh. As a result, changes in the individual imbalances do not lead to substantial changes in the imbalance cost. How this gets affected by the number of consumers and imbalance prices are addressed in the discussion section.

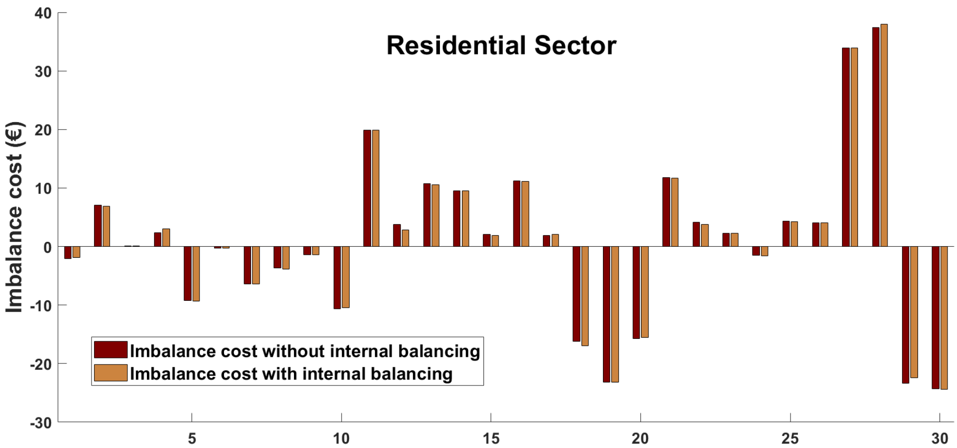

Figure 4.10: Imbalance costs for the aggregator with and without internal balancing, for every day in June in the residential sector. Negative cost values signify a profit.

Having almost the same imbalance cost shows that implementing internal balancing with consumers' appliances does not provide financial incentives to the aggregator, and hence is not economically feasible as a business model for the aggregator. The consequences of not having financial incentives are addressed in the discussion section.

4.6. Discussions

An MPC model is formulated to reduce the aggregator's individual imbalances and applied to a case study in the Netherlands. The results show that DR for internal balancing using the MPC model is successful in reducing the aggregator's individual imbalances. Yet, it is not an economically feasible business model for the aggregator. In this section, we discuss these results, and study the impact of different factors on the results, to make our conclusion about economic feasibility of internal balancing more robust.

Type and magnitude of forecast errors. The reduction in the total amount of imbalances can be attained only on the switching error days. In line with this, on single-direction error days, the imbalances cannot be decreased. Hence, the ability of internal balancing to reduce the total amount of imbalances is limited by solar generation forecasts. In addition, the results from the low forecast error scenario indicate that as the magnitude of solar generation forecast errors decreases, internal balancing is able to reduce higher percentage of imbalances.

Last updated forecasts. In this chapter, the last updated forecast, which is received by the aggregator shortly before the beginning of every hour, is assumed to correspond to actual solar generation. The total amount of imbalances and the imbalance costs are calculated using the last updated solar generation forecasts. However, in real-life, the last updated forecast might differ from the actual solar generation. In this case, the aggregator has to deal with different imbalance and imbalance costs. Even though the accuracy of 1-hour ahead solar generation forecasts is considered high [186], it is worthwhile to study internal balancing with forecasts very close the real time.

Number of consumers. If the number of consumers in the aggregator's portfolio increases, the available number of flexible appliances becomes higher. That causes the average amount of imbalance reduction of imbalances without DR to increase. Yet, the imbalances and imbalance costs without DR also increase as the number of flexible appliances increases. Hence, this does not impact the imbalance cost.

Higher imbalance prices. Higher imbalance prices might result in a higher decrease in imbalance costs. However, this requires a significant increase in the imbalance prices, which is not very likely to occur. Even then, the positive and negative imbalance costs still cancel each other out. Hence, we do not anticipate this can change the results in a considerable way.

Different consumers' assets. This analysis is carried out with consumers' flexible appliances. Other consumers' assets, such as BESSs and EVs, have larger power capacity and less limitation on shifting time. As a result, higher amount of imbalance reduction can be reached. We anticipate the reduction in the imbalance cost to be also higher than with appliances, yet not significantly to make it economically feasible, since positive and negative imbalance costs still cancel each other out.

Other renewable generation. This chapter takes solely solar power generation into consideration. This means that other renewable generation, like wind, might influence the economic feasibility of internal balancing. One of the major differences between solar and wind generation is that solar power generation becomes zero during nighttime. Due to this difference, the MPC model presented in this chapter runs per day, and does not include intertemporal constraints that connect the model between two consecutive days. Hence, it is not possible to use this model for wind power generation.

Due to this contrast between wind and solar, wind power generation is expected to be higher than solar power generation during the nighttime, and thus to result in higher individual imbalances. The question remains on to what extent these imbalances during nighttime can be reduced by flexible appliances. Although this requires a more detailed analysis to make a conclusion, Figure 4.4 indicates the demand from flexible appliances are lower at nighttime, compared to the daytime hours. This may suggest that the reduction in the imbalances does not change significantly with wind power generation.

Incentives. The results also indicate that even though DR for internal balancing succeeds in reducing the aggregator's individual imbalances, the aggregator's imbalance costs do not decline and stay nearly the same. This is in line with the findings from [166] that studies CHPs to minimize imbalances. From the TSO's perspective, DR for internal balancing is considered useful for the power system in terms of reducing the aggregator's individual imbalances. However, from the aggregator's perspective, DR for internal balancing is not profitable. As a result, the aggregator is not incentivized to use DR for internal balancing.

The results and the MPC model reported in this chapter can be valuable for both aggregators and TSOs. It can also be concluded from the results that TSOs should provide external incentives and subsidies, in order to motivate aggregators to implement internal balancing with DR. TSOs can use these results to apply relevant incentive mechanisms to financially motivate aggregators to use DR for internal balancing. With the appropriate incentives, aggregators might become financially interested in implementing internal balancing, and thus to reduce their individual imbalances.

Minimizing imbalance costs. It is shown that internal balancing with consumers' appliances is not profitable for the aggregator. This may be solved by minimizing the aggregator's imbalance costs. However, it is not possible to employ the MPC model in this chapter to minimize the imbalance cost. Even though the MPC model can be modified to implement passive balancing by adding imbalance prices in the objective function, the model requires imbalance price data for the entire horizon, i.e., the entire day. However, it is rather difficult to predict the imbalance prices accurately in advance (even one day ahead) since they are very volatile (see Figure 4.5). In real-life, TenneT publishes real-time on system imbalance and an imbalance price, very close to the real-time [187]. Based on that information, decisions about the generation or demand can be made solely for the next PTU.

To resolve this, the historical imbalance prices can be used. Yet, this is not realistic since these prices contain significant amount of uncertainty in real-life. In some other papers, a certain ratio between imbalance prices and DAM prices is assumed [106, 188]. Thus, DAM prices are multiplied by this ratio to obtain imbalance prices. However, this is not sufficiently detailed and does not predict imbalance prices with high accuracy. Moreover, in [166], imbalance prices are modeled based on DAM prices and reserve prices, with an approximation using autoregressive models. Although the general pattern of data seems to be correct, the model fails to predict the peaks in particular.

Passive balancing. Passive balancing differs from internal balancing. With internal balancing, the aggregator minimizes their imbalance cost by remaining close to their e-program. On the other hand, with passive balancing, the aggregator minimizes their imbalance cost by intentionally deviating from their e-program, i.e., by creating intentional individual imbalance (positive or negative) opposite direction of the system imbalance.

It should be emphasized that passive balancing can only be implemented under three conditions: (1) publication of the real-time information, (2) legally being able to create intentional imbalances and (3) application of single pricing as imbalance pricing mechanism [54, 57, 64]. Even though the Dutch imbalance pricing mechanism is a combination of both single and dual pricing, single pricing is used for most of the time. Moreover, the Dutch TSO, TenneT, publishes information on system imbalance and an imbalance price, very close to the real-time [187]. Thus, regulations in the Netherlands make passive balancing possible. However, this is not true for every country due to the aforementioned conditions, such as Germany and France [54].

Passive balancing can be explained with the following example:

- When the system imbalance is negative, the TSO activates upward reserve. An aggregator (or also only BRP) with positive imbalance gets paid positive imbalance price, which is based on upward reserve price with single pricing (See Table 4.1). Upward reserve prices are generally higher than the DAM prices. That means that the aggregator earns more money than they would have if they had sold the same amount of electricity in the DAM. This incentivizes the aggregator to have a positive imbalance, opposite to the system imbalance.

- When the system imbalance is positive, the TSO activates downward reserve. An aggregator (or also only BRP) with negative imbalance pays negative imbalance price, which is based on downward reserve price with single pricing (See Table 4.1). Downward reserve prices are typically lower than the DAM prices. That means that the aggregator pays less money than they would have if they had purchased the same amount of electricity in the DAM. This incentivizes the aggregator to have a negative imbalance, opposite to the system imbalance.

Hence, with passive balancing, the opportunity costs between the imbalance prices and DAM prices encourages aggregators to deviate from their e-programs intentionally, to the opposite direction of system imbalance.

The downside of passive balancing is that it gives the aggregator less incentive to remain close to their e-program. This makes e-programs less reliable, and jeopardizes the effective and accurate planning of the system balance. Also, since intentional deviations based on passive balancing are not communicated with the TSO in advance, they may make congestion management more difficult. In addition, passive balancing might be risky as the system imbalance can change its direction quickly (within seconds). In that case, the aggregator's individual imbalance becomes as the same direction as the system imbalance, which harms the system balance. Also, in that case, both upward and downward reserves might get activated in the same PTU, which causes dual pricing to be applied, and this is not profitable for the aggregator [61].

4.7. Conclusions

The aim of this chapter is to evaluate the impact of internal balancing to reduce the individual imbalances of an aggregator, and to assess whether this is an economically feasible business model for the aggregator. For internal balancing, DR from flexible appliances in both residential and service sectors are considered. A comprehensive Model Predictive Control model is presented to reduce the aggregator's individual imbalances. This model is applied to a case study in the Netherlands.

The results show that internal balancing with consumers' appliances using Model Predictive Control model is successful in reducing the aggregator's individual imbalances up to 30% in June. However, the aggregator's imbalance costs remain almost equal with and without internal balancing. In a broader perspective, a reduction of the aggregator's individual imbalances is beneficial for the power system. Notwithstanding, from the aggregator's point of view, it does not provide any financial benefits for aggregator to reduce their individual imbalances.

The results presented in this chapter may provide a base to explore external incentives and subsidies by policymakers and TSOs to stimulate an active role of aggregators to implement internal balancing. Moreover, future work can incorporate the difference between the last updated solar generation forecast and actual solar generation. After exploring internal balancing with consumers' appliances, we study the potential of consumers' appliances in the business model *trading flexibility in the DAM* in the next chapter.

5

Finding optimal flat-rate retail price

Bir yer var, biliyorum;
Her şeyi söylemek mümkün;
Epeyce yaklaşmışım, duyuyorum;
Anlatamıyorum.

Orhan Veli Kanık

5.1. Introduction

After analyzing the economic feasibility of *internal balancing* with consumers' appliances, we focus on the business model *trading flexibility in the DAM* with consumers' appliances in this chapter. This business model has been studied extensively in the literature [74, 81, 82]. Yet, as described in Chapter 3, these studies mostly neglect to involve economic relation between the aggregator and the consumers. While assessing the economic feasibility of the aggregator's business models, it is important to also take into account the consumers' perspective. Consumers should also economically benefit from the business models to give permission to the aggregator to use their assets. This means that the aggregator needs to offer a *financial reward* to the consumers to get them interested. Therefore, an assessment of economic feasibility without the economic relation between the aggregator and their consumers is incomplete and gives misleading results.

The aim of this chapter is to provide insights on which financial reward mechanism the aggregator should offer to the consumers that make *trading flexibility* *in the DAM* with appliances economically feasible for both the aggregator and the consumers. Flat-rate retail prices are chosen as financial reward mechanisms owing to their simplicity [97]. To achieve this, an optimization model is presented in this chapter which minimizes the consumers' costs through shifting appliances. It is applied to a case study from the Netherlands. Based on the optimization results, the optimal range of flat-rate retail prices is found.

An overview of the system, as well as the assumptions used are described in Section 5.2. In Section 5.3, the optimization model equations are formulated. The input data are outlined in Section 5.4. In Section 5.5 and 5.6, the results are described and discussed. Finally, the conclusions are drawn in Section 5.7.

5.2. System description

The system considered in this chapter, as well as the assumptions made in the system are described in this section.

5

5.2.1. System overview

In this chapter, the aggregator participates in the DAM on behalf of their consumers in the residential and service sectors. Part of these consumers own their own PVs. The aggregator purchases and sells electricity in the DAM with an hourly DAM price ($\lambda^{da}_{d,t}$) [121, 167]. On the other hand, the aggregator sells electricity to consumers with a flat-rate (fixed) retail price (λ^{ret}) and buys excess solar generation from the consumers for a also flat-rate feed-in tariff (λ^{feedin}) (See Figure 5.1).

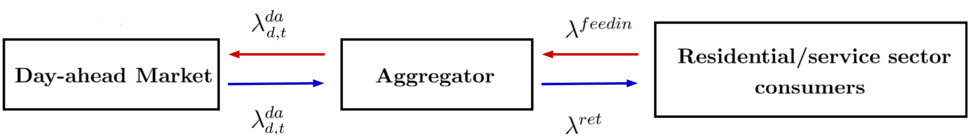

Figure 5.1: Relations between actors in the system

Feed-in tariff (FiT) is a payment for electricity that is sold to the electricity grid [189]. It is a common support policy which is employed to promote RES, along with net metering. Although there are some other support policies to stimulate the deployment of RES [190], FiT and net-metering are the most common ones used in many European countries [191]. Net-metering works by utilizing a meter that is able to record electricity exchange with the grid. At the end of a given month, the consumer needs to pay the net electricity used at the retail price [189].

Since 2004, the Netherlands has this net metering policy [192], for residential and service sector consumers with a small capacity connection (less than 3*80 A) to the grid. Together with the decrease in the costs of PV systems, net metering policy is considered to have been an important factor in the capacity growth of PV systems over the past years in the Netherlands, where the capacity grew by 91% between the years 2011 and 2015 [193].

However, net metering policy has been under discussion nowadays, mainly due to the fact that it does not incentive consumers to increase their level of self-consumption. In other words, consumers are not motivated to reduce the electricity bought from or sold to the grid since the prices for buying and selling electricity are equal to each other, i.e., retail price. For this reason, it has been decided to gradually phase out net-metering policy starting from 2023 [194]. On the other hand, with FiT, the price to sell electricity is lower than retail price, which encourages the consumers to increase their self-consumption. Thus, we consider FiT for the consumers with PV systems in this chapter.

The aggregator is given the permission to operate the consumers' appliances within pre-specified limits with DR. The only DR option considered in this study is shifting, which refers to shifting of electricity demand to another time period. The appliances that can be used for shifting are semi-flexible and flexible appliances. It should be underlined that semi-flexible appliances are also taken into account for DAM trading in this chapter, contrary to Chapter 4 where we focus on internal balancing. The reason for this is the difference in the time horizon between these two business models; internal balancing takes place very close to the real-time, whereas DAM trading is scheduled one-day ahead. Longer time-horizon with DAM trading enables the consumers to be notified in advance for using semi-flexible appliances. This is explained in more detail in 2.1.1.

In this chapter, for the aggregator to operate the consumers' semi-flexible and flexible appliances, strategies 1A and 1C (See Section 3.3.1) are considered within *trading flexibility in the DAM*. The aggregator operates consumers' appliances:

- to minimize the aggregator's DAM cost in Strategy 1A.
- to minimize consumers' electricity cost in Strategy 1C.

Strategies 1A and 1C are formulated into an optimization model with two approaches: aggregator optimized, and consumer optimized, respectively, which are elaborated in the next section. Note that Strategy 1B is not included since it entails consumers' operation on their own with time-varying tariffs, which are not considered in this chapter.

5.2.2. Assumptions

The following assumptions are made in this chapter:

- It is assumed that the aggregator has perfect information on the electricity demand of consumers' appliances, as well as on the solar generation. For this reason, the individual imbalances of the aggregator that might be caused by the forecast errors are not accounted for in this chapter, unlike Chapter 4.
- The aggregator is a price-taker with respect to the market prices, but a price-maker with respect to the retail price they charge their consumers.
- The consideration of how to allocate the schedule within the appliances in different buildings in the residential and service sectors is not studied in this chapter. It is assumed that semi-flexible and flexible appliances are available for shifting, and the focus is on the economic feasibility of the business model.

5.3. Optimization model

The optimization model in this chapter consists of three main steps: reference case calculations, optimization with two approaches (aggregator optimized, and consumer optimized), and profitability conditions. These steps are illustrated in Figure 5.2, and explained in this section.

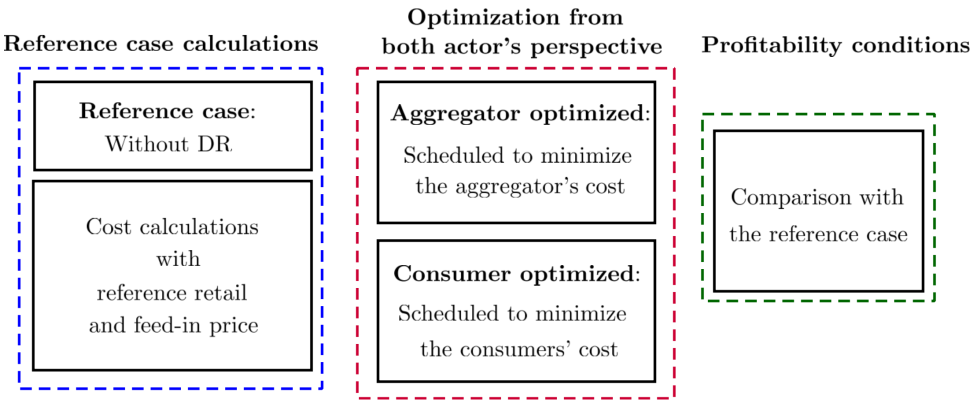

Figure 5.2: Steps in the model

5.3.1. Reference case calculations

The reference case is defined as the situation without DR. In addition, the reference case entails reference flat-rate retail price ($\lambda^{ret,ref}$) and reference flat-rate feed-in tariff ($\lambda^{feedin,ref}$), which are the prices consumers receive without DR. In this step, the cost of the aggregator and consumers for the reference case ($C_{agg}^{dac,ref}$ and $C_{cons}^{el,ref}$, respectively) are calculated.

The cost of the aggregator in the DAM, the total cost of the aggregator, and the cost of the consumers are calculated with the following equations:

Aggregator's costs:

$$C_{agg}^{da} = \sum_{d=1}^{D} \sum_{t=1}^{T} \lambda_{d,t}^{da} P_{d,t}^{buy} - \lambda_{d,t}^{da} P_{d,t}^{sell} \tag{5.1}$$

$$C_{agg}^{dac} = \sum_{d=1}^{D} \sum_{t=1}^{T} \lambda_{d,t}^{da} P_{d,t}^{buy} - \lambda_{d,t}^{da} P_{d,t}^{sell} - \lambda^{ret} P_{d,t}^{buy} + \lambda^{feedin} P_{d,t}^{sell} \tag{5.2}$$

Consumers' electricity cost:

$$C_{cons}^{el} = \sum_{d=1}^{D} \sum_{t=1}^{T} \lambda^{ret} P_{d,t}^{buy} - \lambda^{feedin} P_{d,t}^{sell} \tag{5.3}$$

Equation (5.1) gives the cost of the aggregator from the DAM for a month. The first term in this equation is the cost of the aggregator buying electricity from the

DAM, whereas the second term is the revenue from selling surplus solar generation to the DAM. Equation (5.2) presents the sum of the cost of the aggregator from the DAM and from the consumers for a month, which includes the cost/revenue coming from the consumers in addition to the cost/revenue from the DAM. The cost of the consumers for a month is stated in Equation (5.3). To compute the cost of the aggregator and the consumers for the reference ($C_{agg}^{dac,ref}$ and $C_{cons}^{el,ref}$, respectively), the values for the reference case are inserted in these equations.

5.3.2. Optimization with two approaches

Optimization with aggregator optimized and consumer optimized approaches are mathematically formulated in this section. In the aggregator optimized approach, the objective is to determine the shifting of the semi-flexible and flexible appliances, in order to minimize the aggregator's cost. On the other hand, in the consumer optimized approach, the objective is to minimize the consumers' cost. These can be formulated as a Mixed Integer Linear Programming problem. They are implemented in GAMS and solved using solver CPLEX. The nomenclature for this chapter is given in Appendix C.

The model is run separately for every day $d \in \{1, 2, \ldots, D\}$ in a given month. We put together the results from each month, to obtain the annual results. The model is built with time resolution t per hour.

5

Aggregator optimized approach:

$$\text{Minimize} \quad \sum_{d=1}^{D}\sum_{t=1}^{T} \lambda_{d,t}^{da} P_{d,t}^{buy} - \lambda_{d,t}^{da} P_{d,t}^{sell} \tag{5.4}$$

subject to

$$P_{d,t}^{buy} - P_{d,t}^{sell} + P_{d,t}^{PV} = P_{d,t}^{nf} + P_{d,t}^{scheduled} \qquad \forall t, d \tag{5.5}$$

$$P_{d,t}^{f} + P_{d,t}^{sf} = \sum_{t'=max(t-t_{shift},1)}^{min(t+t_{shift},T)} P_{d,t,t'}^{shifted} \qquad \forall t, d \tag{5.6}$$

$$P_{d,t}^{scheduled} = \sum_{t'=max(t-t_{shift},1)}^{min(t+t_{shift},T)} P_{d,t',t}^{shifted} \qquad \forall t, d \tag{5.7}$$

$$0 \leq P_{d,t,t'}^{shifted} \qquad \forall t, d \tag{5.8}$$

$$0 \leq P_{d,t}^{buy} \leq P_{\max}^{buy}\, y_{d,t} \qquad \forall t, d \tag{5.9}$$

$$0 \leq P_{d,t}^{sell} \leq P_{\max}^{sell}\, (1 - y_{d,t}) \qquad \forall t, d \tag{5.10}$$

$$y_{d,t} \in \{0, 1\} \qquad \forall t, d \tag{5.11}$$

The objective function in Equation (5.4) aims to minimize the cost of the aggregator for the participation in the DAM, which is the sum of the cost of the aggregator buying electricity and the revenue obtained from selling surplus solar generation in the DAM. The power balance constraint in Equation (5.5) ensures that the demand from the consumers is satisfied by the supply at all times. Equation (5.6) describes that the flexible and semi-flexible appliances can be shifted forward and backward up to maximum shifting time (t_{shift}) in order to limit discomfort for the consumers. Equation (5.7) calculates the total scheduled load at each hour shifted from other hours. Note that the summations in Equations (5.6) and (5.7) have limits to ensure that the appliances can be shifted only within the same day, not within different days.

The amount of power that can be purchased or sold in the DAM is limited within the grid requirements in Equation (5.9) and (5.10). It should be noted y_t in Equation (5.11) is a binary variable which is equal to 1 if electricity is purchased and 0 if electricity is sold.

Consumer optimized approach:

$$\text{Minimize} \quad \sum_{d=1}^{D}\sum_{t=1}^{T} \lambda^{ret} P_{d,t}^{buy} - \lambda^{feedin} P_{d,t}^{sell} \tag{5.12}$$

In the consumer optimized approach, the objective function in Equation (5.4) is replaced by Equation (5.12) so as to minimize the cost of consumers. This equation consists of electricity bought from the aggregator at the retail price and electricity sold to the aggregator at FiT. The other constraints remain the same.

5.3.3. Profitability conditions

After the optimization results with both approaches are found, the cost of the aggregator and the consumers are compared with the reference case, $C_{agg}^{dac,ref}$ and $C_{cons}^{el,ref}$. For the business model to be profitable for both the aggregator and the consumers, (1) the aggregator's cost for a month needs to be lower than the reference case cost for the same month, and (2) the consumers' cost needs to be lower than the reference case cost for the same month. These are called *profitability conditions*, and are given as follows:

$$C_{agg}^{dac} < C_{agg}^{dac,ref} \tag{5.13}$$

$$C_{cons}^{el} < C_{cons}^{el,ref} \tag{5.14}$$

Based on these profitability conditions, we aim to find at which flat-rate retail prices both actors could make profit. The profitable flat-rate retail prices are derived from the profitability conditions and are given in Equation (5.15). According to these equations, the profitable retail price ($\lambda^{ret,prof}$) should satisfy:

$$\lambda^{ret,prof} < \frac{\sum_{d=1}^{D}\sum_{t=1}^{T}\lambda_t^{feedin}P_{d,t}^{sell} + C_{cons}^{el,ref}}{\sum_{d=1}^{D}\sum_{t=1}^{T}P_{d,t}^{buy}}$$
$$\lambda^{ret,prof} > \frac{\sum_{d=1}^{D}\sum_{t=1}^{T}\lambda_{d,t}^{feedin}P_{d,t}^{sell} + C_{cons}^{el,ref} + C_{agg}^{da} - C_{agg}^{da,ref}}{\sum_{d=1}^{D}\sum_{t=1}^{T}P_{d,t}^{buy}} \quad (5.15)$$

After the profitable retail price is found, the aggregator's DAM cost, the aggregator's cost from the DAM and their consumers, and the consumers' cost are calculated according to the Equations 5.1-5.3. The economic feasibility is analyzed by comparing these costs with the costs in the reference case.

5.3.4. Analysis of different factors

In order to gain a better understanding of the economic feasibility of *trading flexibility in the DAM* with appliances, we vary various factors in the optimization models and analyze their impact on the economic feasibility. These are listed below:

5

- **Different day-ahead market prices:** The optimization model is run with the DAM prices from 2018, in order to assess the impact of different DAM prices on the economic feasibility.
- **Time of use tariff:** Financial reward mechanism is taken as TOU tariff, instead of flat-rate retail price.
- **Aggregator's objective function:** In the aggregator optimized approach, the objective function in Equation 5.4 is equal to Equation 5.1 which minimizes the aggregator's DAM cost. However, this can be taken equal to Equation 5.2 which minimizes the aggregator's cost from both the DAM and the consumers in their portfolio.
- **Peak-shaving:** The optimization model is run while aiming to reduce the peak of electricity demand of appliances. This is done by changing Equation 5.9 in the optimization model.

5.4. Case study 2: Data

The demand data used in this chapter for residential and service sectors, as well as heat pumps are taken from the case study described in Chapter 4.4, which is obtained from the Netherlands between 1st of June 2012 and 31st of May 2013. More detailed information on the datasets is given below:

• *Residential sector demand profiles.* Measured household demand profiles of 63 households in the Netherlands are used. The total residential demand for the modeled year is 217 MWh, of which 34% is semi-flexible and flexible appliances.

• *Service sector demand profiles.* Modeled service sector demand profiles are used, as described in [195]. Similar to Chapter 4, no semi-flexible appliances are defined in the service sector based on [34, 177]. The total service sector demand is 230 MWh annual, of which 17% comes from flexible appliances. Note that the annual electricity demand for the two consumer sectors differs.

- *Heat pump demand profiles.* Heat pumps are included in electricity demand by the flexible appliances. Heat pump penetration is assumed to be 50% in residential and service sectors and amounts for 79 MWh/year for residential consumers and for 18 MWh/year for service sector consumers.

- *DAM electricity prices.* EPEX DAM electricity prices between 1st of June 2012 and 31st of May 2013 are used. In addition to this, EPEX DAM electricity prices from 2018 are used to assess the impact of changes in electricity prices over years, which are obtained from [196].

- *Solar electricity generation profiles.* Three PV penetration scenarios are used for both consumer sector types: 25%, 50%, and 75% penetration, with respective annual generation of 53 MWh, 105 MWh and 158 MWh.

5

- *Retail price and feed-in tariff.* The reference flat-rate retail price is taken as the average retail price between the years 2012 and 2017 in the Netherlands, which is equal to 0.1822 €/kWh [197]. In contrast to retail prices, a historical FiT cannot be taken from the Netherlands since it is not implemented. Hence, the retail price and FiT from Germany are compared with the Dutch retail price. Since the ratio between the German retail price and the German FiT is 3.5, the reference FiT is taken as 0.05 €/kWh [198, 199].

To analyze the impact of financial reward mechanisms, TOU tariff is used which divides the day into two periods: higher electricity price period, and lower electricity price period. Yet, the average daily price in these two periods is equal to the reference flat-rate retail price. This reward mechanism is displayed in Figure 5.3.

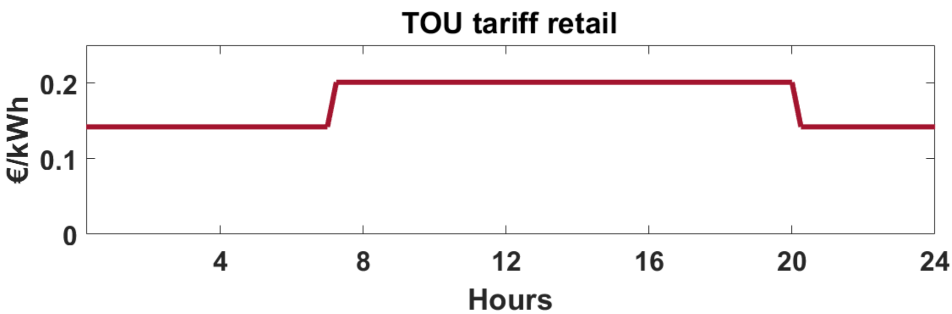

Figure 5.3: Time of use tariff.

- *Shifting time.* The maximum shifting time for the flexible appliances is assumed to be two hours based on [34, 200]. This means that the semi-flexible and flexible appliances can be shifted maximum two hours forward or backward than the time they were planned to be used, assuming no uncertainty in their data.

5.5. Case study 2: Results

This section presents the results of the case study using the optimization models described in Section 5.3.

5.5.1. Shifting of appliances

Top three graphs in Figure 5.4 show the average profile of original flexible appliances in the residential sector in June, together with how these semi-flexible and flexible appliances are scheduled in the aggregator and consumer optimized approaches. Bottom three graphs in this figure display the average DAM electricity prices in June, together with the average solar generation in June given 25%, 50%, and 75% PV penetration. These graphs demonstrate that the average DAM prices are more likely to become higher during the peak hours: early morning hours and early evening hours. This pattern can be explained by Dutch working habits and industrial production. Particularly, the electricity demand in the morning hours rises as people wake up and start their work, and in the early evening hours when people return home from work.

In the aggregator optimized approach, semi-flexible and flexible appliances are shifted to the hours with lower DAM electricity prices in order to decrease the aggregator's cost. Consequently, higher electricity demand of appliances can be seen at 15:00-16:00 in the afternoon and at 21:00-22:00 in the evening. By this way, the aggregator can help reduce the electricity demand during the peak hours. Moreover, by having less electricity demand around noon, the aggregator can sell higher solar generation in the DAM. Note that how appliances are shifted does not differ with PV penetrations in the aggregator optimized approach due to the fact that this shifting only depends on the DAM prices.

On the other hand, in the consumer optimized approach, semi-flexible and flexible appliances are shifted to the hours when there is abundant solar generation (mainly around noon) since, in this way, consumers reduce the electricity bought from the aggregator. However, in 75% PV penetration scenario, the appliances are not shifted to the noon hours, but mostly around 10:00 and around 15:00. In this scenario, since the solar generation around noon is very high enough, it becomes more profitable for the consumers to sell this generation to the aggregator. Similarly, solar generation around 10:00 and 15:00 is high enough that the appliances are shifted to these hours. How much electricity is purchased and sold by the consumers is depicted in Figure 5.5. In this figure, positive values imply that electricity is purchased from the aggregator, whereas negative values imply that the electricity is sold to the aggregator. Electricity sold increases as PV penetration becomes higher.

Figures 5.6 and 5.7 show the same graphs for the consumers in the service sector. Similar to the residential sector, in the aggregator optimized approach, semi-flexible and flexible appliances are shifted to the hours with lower DAM electricity price values, while in the consumer optimized approach, semi-flexible and flexible appliances are shifted to the hours when there is abundant solar generation. Electricity sold to the aggregator is lower in the service sector, in comparison with the residential sector. This can be explained by the differences in the electricity demand of semi-flexible and flexible appliances in the residential and the service

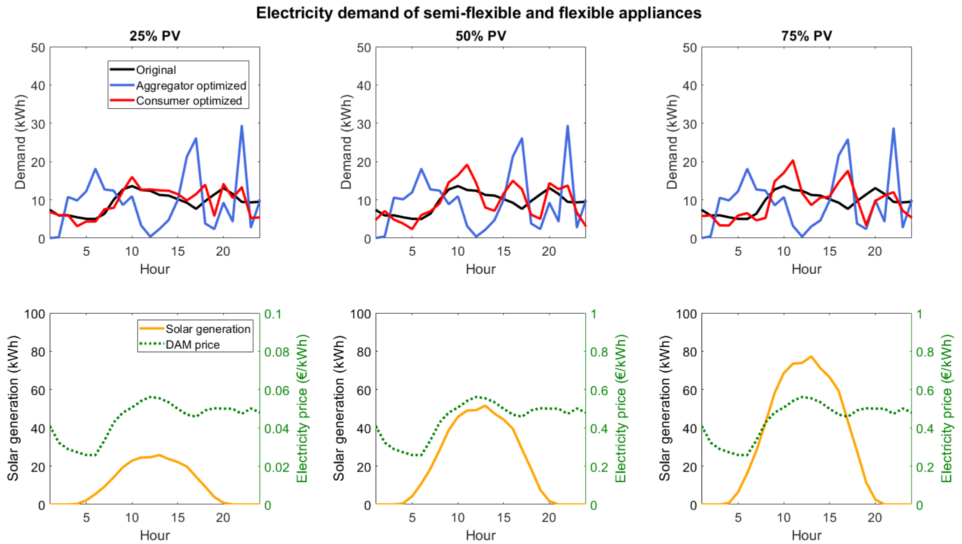

Figure 5.4: Scheduling of semi-flexible and flexible appliances with aggregator and consumer optimized approaches, DAM price, and solar generation (25%, 50%, 75% PV penetration) in residential sector in June 2012. Average values in June are given.

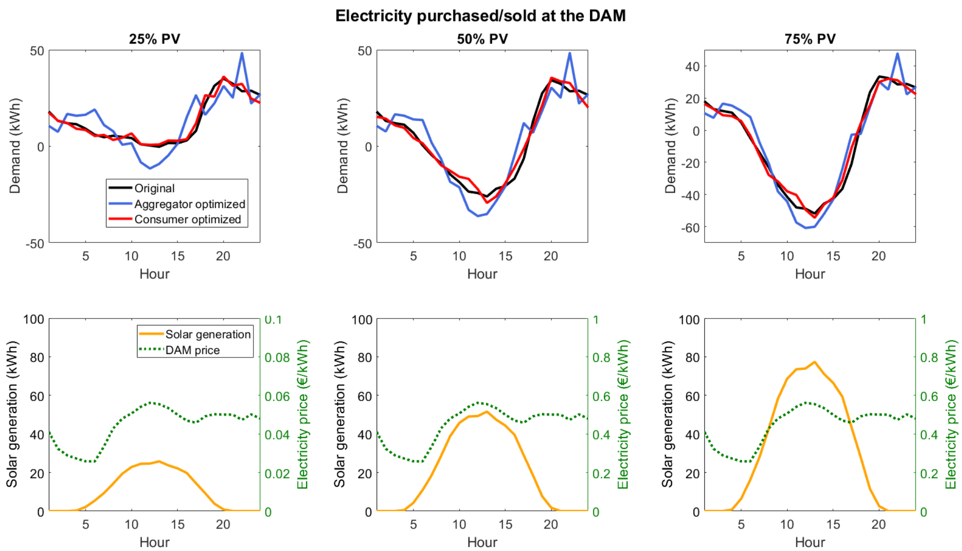

Figure 5.5: Electricity purchased/sold with aggregator and consumer optimized approaches, DAM price, and solar generation (25%, 50%, 75% PV penetration) in residential sector in June 2012. Average values in June are given. Note the axis difference in top right graph.

sectors. In the residential sector, total annual demand of semi-flexible and flexible appliances accounts for nearly 73 MWh, giving a non-flexible demand of 144 MWh.

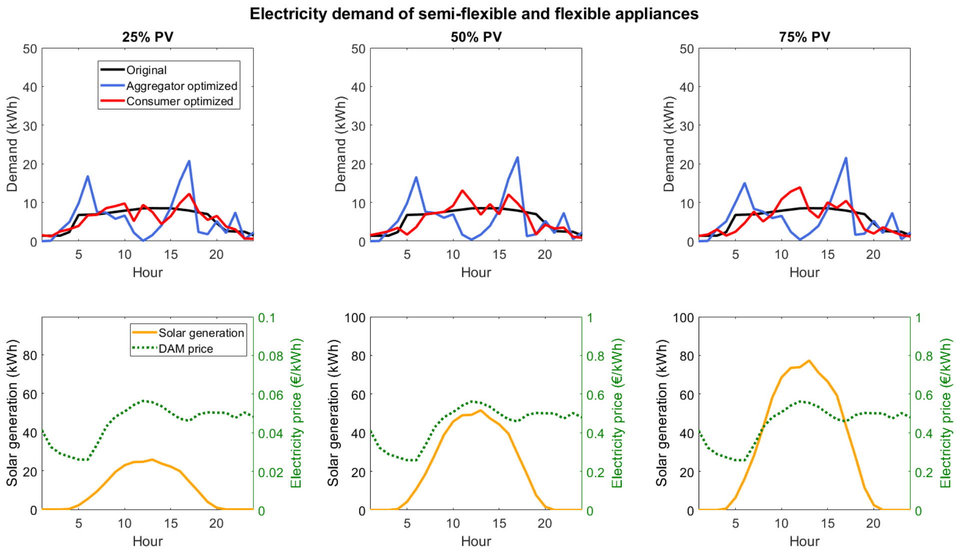

Figure 5.6: Scheduling of semi-flexible and flexible appliances with aggregator and consumer optimized approaches, DAM price, and solar generation (25%, 50%, 75% PV penetration) in service sector in June 2012. Average values in June are given.

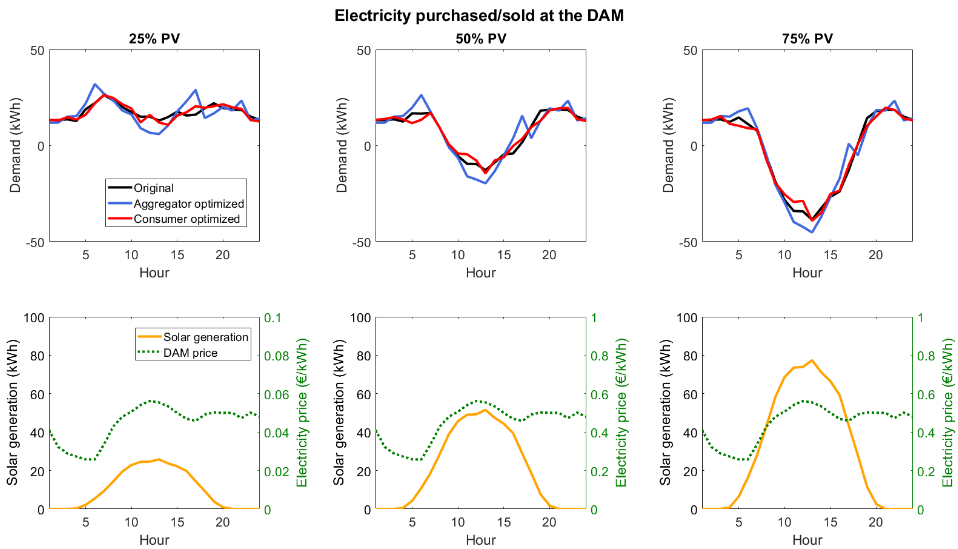

Figure 5.7: Electricity purchased/sold with aggregator and consumer optimized approaches, DAM price, and solar generation (25%, 50%, 75% PV penetration) in service sector in June 2012. Average values in June are given. Note the axis difference in top right graph.

Contrarily, in the service sector, semi-flexible appliances are not available, and total annual demand of flexible appliances is equal to 40 MWh, giving a higher non-flexible demand: 190 MWh. Higher electricity demand from non-flexible appliances causes the service sector to sell lower amount of electricity to the aggregator.

5.5.2. Profitable flat-rate retail prices

Based on the optimization results, profitable flat-rate retail prices are calculated using the profitability conditions in Section 5.3.3. With the consumer optimized approach, there is no retail price that is profitable for the aggregator. With this approach, even though the cost of consumers drops, the aggregator gains less than in the reference case for all scenarios analyzed, which makes this business model not economically feasible for the aggregator. Thus, the results from the consumer optimized approach are not further addressed.

Figure 5.8 demonstrates the profitable retail prices for the aggregator optimized approach for June. In other words, this figure displays the retail price values that are profitable for both the aggregator and consumers for different FiTs in June. The shaded areas on the lines show the profitable retail price range and the darker lines show the midpoint of the range. The part above the line gives retail prices profitable only for the aggregator, while the part below the line is profitable only for the consumers. The results indicate that for each FiT, there is only a small range of flat-rate retail prices that are profitable for both aggregator and consumers.

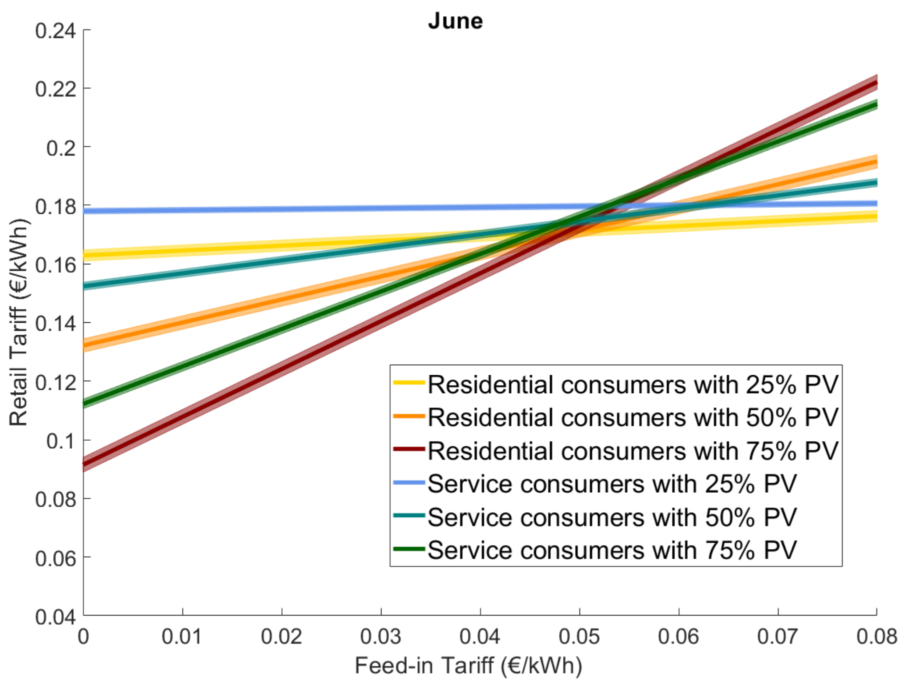

Figure 5.8: Profitable retail prices for different feed-in tariffs for June 2012.

The general trend is that, as the FiT increases, higher retail prices need to be offered as well for the business model to be profitable for both actors. Additionally, as PV penetration increases, the slope of the lines become steeper. This could be explained by higher revenue the consumers earn with higher PV penetrations. Due this higher revenue, to make it economically feasible for both actors, the aggregator needs to offer higher retail prices for FiTs larger than the reference FiT, while the aggregator needs to offer lower retail prices for FiTs smaller than the reference FiT. On the other hand, as PV penetration decreases, the profitable retail prices vary to a smaller degree for different FiTs, e.g., the residential sector consumers with 25% PV penetration.

Comparing residential and service sectors, the slope of the service sector lines is flatter than of the residential lines. This can be explained by the differences in the electricity demand profiles of the residential and the service sectors. Residential demand peaks in the evening hours, while service sector demand primarily lies in the daytime hours. As shown in Figure 5.4, aggregator-optimized approach shifts electricity demand to the cheaper evening hours. As the service sector has low demand during these hours, and the maximum shifting time is only two hours, the service sector can provide less flexibility. This lower flexibility leads to relatively smaller interdependency between retail price and FiT for the service sector, than for the residential sector.

A similar analysis is done for other months as well. For instance, in December, the profitable retail prices do not differ significantly with different FiT and different PV penetrations, since solar generation is smaller in December in comparison with June. Also in the other months, there is only a small range of flat-rate retail prices that are profitable for both aggregator and consumers.

5.5.3. Aggregator's and consumers' costs

After the midpoint of profitable retail price range is found for each month, the yearly cost of the aggregator and consumers are calculated. Tables 5.1 and 5.2 present the aggregator's DAM cost (from Equation 5.1) and the aggregator's cost from the DAM and consumers (from Equation 5.2), and the residential and sector consumers' cost (from Equation 5.3) for one year with 50% PV penetration. In these tables, the first column represents the reference case, i.e., reference retail price without DR. The second and third columns give the costs for the reference retail price with DR, and for the profitable retail price with DR, respectively. Note that the reference FiT is taken in the calculations, to be able to compare them. How much the cost values changed compared to the reference case is also given in percentages in the parenthesis. Negative cost values imply profit. Also, negative percentages imply a decrease in the cost. Note that the aggregator's DAM cost does not change with reference and profitable retail since it does not include any retail price or FiT.

If the reference retail price is offered to the consumers when DR is performed, there is a substantial rise in the consumers' cost compared to the reference case. Accordingly, the consumers are not incentivized to cooperate with the aggregator, and are not interested in the business model. Unlike the consumers, the aggregator financially benefits from this case.

When the profitable retail price is offered, the consumers' cost declines compared

Table 5.1: Cost of the aggregator and residential sector consumers for one year with 50% PV penetration in k€. Negative cost implies profit.

	Reference retail without DR	Reference retail with DR	Profitable retail with DR
Consumers' cost	39.2	40.6 (3.7%)	38.6 (-1.5%)
Aggregator's DAM cost	10.6	9.4 (-11.3%)	9.4 (-11.3%)
Aggregator's cost	-28.5	-31.2 (-9.3%)	-29.1 (-2.1%)

Table 5.2: Cost of the aggregator and service sector consumers for one year with 50% PV penetration in k€. Negative cost implies profit.

	Reference retail without DR	Reference retail with DR	Profitable retail with DR
Consumers' cost	27.6	28.4 (2.7%)	27.5 (-0.6%)
Aggregator's DAM cost	6.8	6.5 (-4.7%)	6.5 (-4.7%)
Aggregator's cost	-20.8	-21.8 (-5.12%)	-20.9 (-0.8%)

5

to the reference case and the aggregator makes profit at the same time as well. Therefore, it is shown that if the aggregator offers profitable retail price instead of the reference retail price, both of the actors receive profit, and thus might be interested in the business model. Nonetheless, the consumers' cost decreases only slightly, 1.5% and 0.6% in residential and service sectors, respectively. Similarly, the aggregator's cost drops by 2.1% and 0.8% in residential and service sectors, respectively. These results show that the economic feasibility of the business model *trading flexibility in the DAM* with appliances is very limited. The limited economic feasibility can be explained by the revenue from the DAM. The revenue the aggregator makes from the DAM is not sufficiently high to make *trading flexibility in the DAM* with appliances economically feasible for both the aggregator and the consumers.

Comparing residential and service sectors in Tables 5.1 and 5.2, the aggregator's and consumer's costs are lower in the service sector due to lower annual electricity demand in the service sector. Furthermore, the decrease in the aggregator's and consumers' cost in the service sector is also lower than the residential sector owing to less flexibility the service sector provides. Thus, it appears to be a less profitable option in comparison to the residential sector.

5.5.4. Impact of different factors

In this section, we discuss various factors that might influence the economic feasibility of *trading flexibility in the DAM* with appliances. Table 5.3 presents the aggregator's cost from the DAM, the aggregator's cost from the DAM and consumers, and the residential sector consumers' cost in June. We use this case for comparison purposes in order to assess the impact of different factors.

Table 5.3: Cost of the aggregator and residential sector consumers in June with 50% PV penetration in €. Negative cost implies profit.

	Reference retail without DR	Reference retail with DR	Profitable retail with DR
Consumers' cost	1248	1327 (6.3%)	1227 (-1.7%)
Aggregator's DAM cost	55	13 (-76%)	13 (-76%)
Aggregator's cost	-1192	-1314 (-10.2%)	-1213 (-1.8%)

Different day-ahead market prices:

The optimization models are also run with the DAM prices from 2018, in order to assess the impact of different DAM prices on the economic feasibility. We acknowledge that this is not compatible with the rest of the data. Despite that, it is sufficient for the purpose of assessing the impact of different DAM prices. Figure 5.9 illustrates scheduling of semi-flexible and flexible appliances for the aggregator optimized approach with 50% PV penetration and with the DAM prices in June 2012 and 2018 in residential sector. The DAM prices increased between 2012 and 2018. Yet, the general pattern remains the same. Shifting of the semi-flexible and flexible appliances also follows a similar pattern in June 2012 and June 2018, with slight differences.

The cost of the aggregator and the residential sector consumers with the DAM prices from 2018 in June is given in Table 5.4. The aggregator's DAM cost is higher because the prices from 2018 are on average higher than the prices from 2012. However, the decrease in the aggregator's cost remains to be small. Also, the decrease in the consumers' cost is small. Thus, the economic feasibility is again found to be limited with the DAM prices from 2018.

Table 5.4: Cost of the aggregator and residential sector consumers with DAM prices from 2018 in June with 50% PV penetration in €. Negative cost implies profit.

	Reference retail without DR	Reference retail with DR	Profitable retail with DR
Consumers' cost	1248	1332 (-1.6%)	1228 (6.7%)
Aggregator's DAM cost	94	53 (-43%)	53 (-43%)
Aggregator's cost	-1153	-1279 (-10.8%)	-1173 (-1.7%)

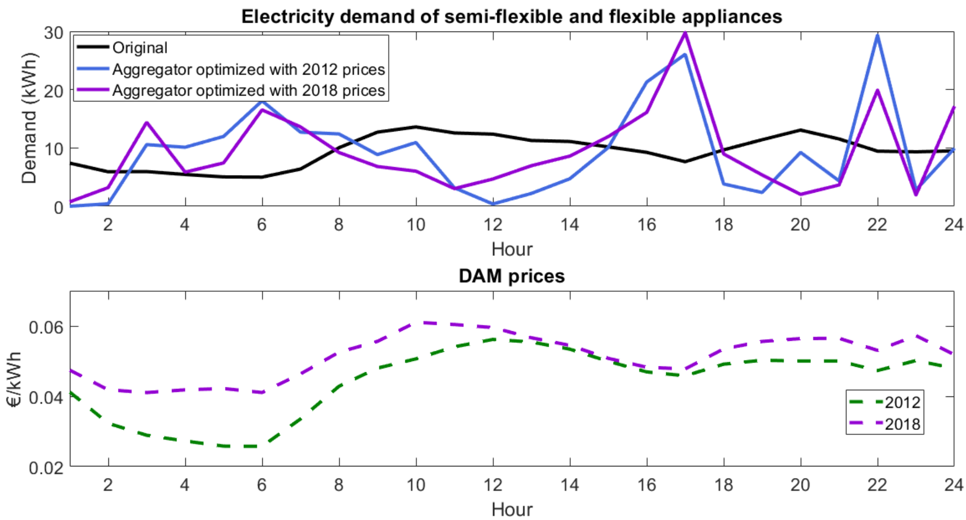

Figure 5.9: Scheduling of semi-flexible and flexible appliances with aggregator optimized approach with 50% PV penetration, and with the DAM prices in June 2012 and 2018 in residential sector. Average values in June are given.

Time of use tariff:

In order to consider other financial reward mechanisms between the aggregator and the consumers, the profitable flat-rate retail price is replaced by TOU tariff. The cost of the aggregator and the residential sector consumers with TOU tariff in June is shown in Table 5.5. Compared to the flat-rate tariff, the consumers' cost decreases slightly due to TOU tariff. Note that the aggregator's DAM cost does not change with TOU tariff since it does not include any retail price or FiT. Moreover, the aggregator's cost declines solely by 0.3% with TOU tariff because of the higher retail prices during the day. This decrease is less than the decrease with profitable flat-rate retail price in Table 5.3. Hence, TOU tariff does not improve the economic feasibility.

Table 5.5: Cost of the aggregator and residential sector consumers with TOU tariff in June with 50% PV penetration in €. Negative cost implies profit.

	Reference retail without DR	Reference retail with DR	TOU retail with DR
Consumers' cost	1248	1327 (6.3%)	1209 (-3.12%)
Aggregator's DAM cost	55	13 (-76%)	13 (-76%)
Aggregator's cost	-1192	-1314 (-10.2%)	-1196 (-0.3%)

Aggregator's objective function:

In the aggregator optimized approach, the objective function minimizes the aggregator's DAM cost. This can be changed to minimize the aggregator's cost from both the DAM and the consumers in their portfolio. Figure 5.10 illustrates scheduling of semi-flexible and flexible appliances with 50% PV penetration in residential sector and with these two different objectives. The main distinction between these two occurs around noon hours. When only the DAM cost is minimized, semi-flexible and flexible appliances are shifted to the hours with lower DAM electricity prices in order to decrease the aggregator's DAM cost. Also, by having less electricity demand around noon hours, the aggregator can sell higher solar generation in the DAM. Nevertheless, when the aggregator's cost from both the DAM and the consumers is minimized, the aggregator sells less electricity in the DAM as this also means the aggregator needs to pay FiT to the consumers to purchase the solar generation from them.

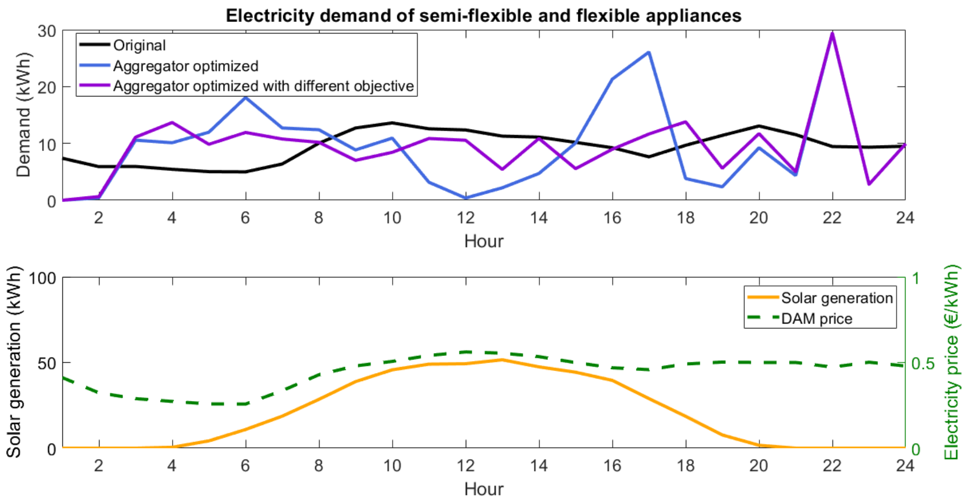

Figure 5.10: Scheduling of semi-flexible and flexible appliances with aggregator optimized approach with 50% PV penetration, and with different objective function in residential sector. Average values in June are given.

The cost of the aggregator and the residential sector consumers in June while minimizing the aggregator's cost from both the DAM and the consumers is shown in Table 5.6. Since the objective function is not to minimize the aggregator's DAM cost, the aggregator's DAM cost with DR is 27 €, higher than in Table 5.3. Yet, because of the same reason, the aggregator's cost with reference retail and DR decreases significantly, by 20%. Since the aggregator makes this money from the consumers, the consumers' cost increases significantly, by 17%. However, when the profitable flat-rate retail price is offered, the decrease in the aggregator's and the consumers' cost becomes small as well and comparable to the values in Table 5.3. This shows that changing the aggregator's objective does not alter the limited economic feasibility.

Table 5.6: Cost of the aggregator and residential sector consumers with different objective function in June with 50% PV penetration in €. Negative cost implies profit.

	Reference retail without DR	Reference retail with DR	Profitable retail with DR
Consumers' cost	1248	1463 (17.2%)	1234 (-1.1%)
Aggregator's DAM cost	55	27 (-50%)	27 (-50%)
Aggregator's cost	-1192	-1436 (-20.4%)	-1207 (-1.2%)

Peak-shaving

Figure 5.11 displays scheduling of semi-flexible and flexible appliances with 50% PV penetration in residential sector, without and with peak-shaving. As it might be anticipated, the main difference between these two are the peak values of the electricity demand of appliances. With peak-shaving results, the electricity demand of appliances are shifted, yet the peak electricity demand remains slightly lower than the without shifting. This indicates that the aggregator is able to reduce the electricity demand during the peak hours. In addition, they can also help with congestion by peak-shaving, as mentioned in Strategy 5A in Section 3.3.5.

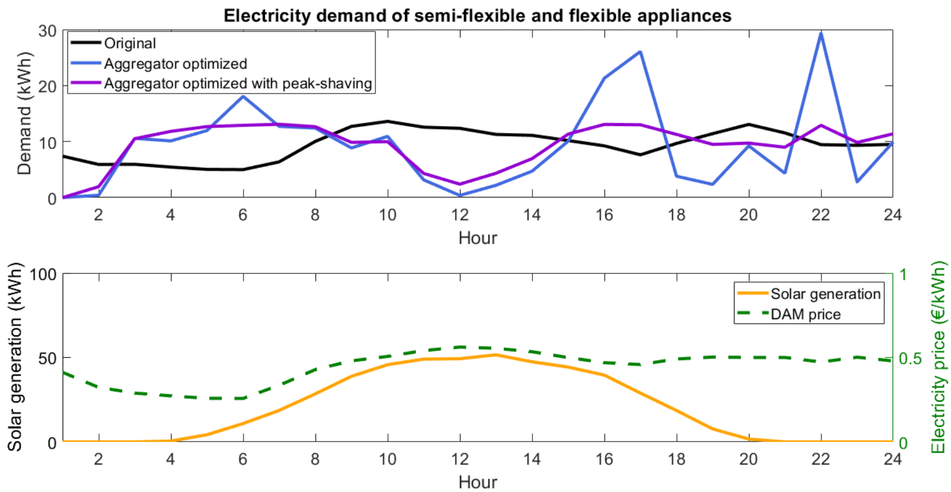

Figure 5.11: Scheduling of semi-flexible and flexible appliances with aggregator optimized approach with 50% PV penetration, and with peak-shaving in residential sector. Average values in June are given.

The cost of the aggregator and the residential sector consumers with peak-shaving in June is shown in Table 5.7. Compared without peak-shaving, there is a smaller decrease in aggregator's DAM cost since the aggregator is able to shift smaller amount of appliances, not to create peaks. For this reason, the decrease in the aggregator's cost is also found to be smaller (1.3%) than without peak-shaving.

Table 5.7: Cost of the aggregator and residential sector consumers with peak-shaving in June with 50% PV penetration in €. Negative cost implies profit.

	Reference retail without DR	Reference retail with DR	Profitable retail with DR
Consumers' cost	1248	1317 (5.5%)	1232 (-1.2%)
Aggregator's DAM cost	55	23 (-58%)	23 (-58%)
Aggregator's cost	-1192	-1290 (-8.2%)	-1208 (-1.3%)

5.6. Discussions

In this chapter, profitable flat-rate retail prices are found that make the business model *trading flexibility in the DAM* with appliances economically feasible for both the aggregator and the consumers. With these profitable prices, the annual cost of the aggregator and the consumers are calculated and compared to the reference case. The results show that the profitable retail prices yield profits for both the aggregator and the consumers. Nevertheless, the profits are not substantial. Thus, the economic feasibility of the business model *trading flexibility in the DAM* with appliances and flat-rate retail prices is very limited. We also vary different factors in the optimization models to gain a better understanding of their impacts on the economic feasibility. This analysis shows that different DAM prices, financial reward mechanisms and aggregator's objective do not improve the economic feasibility.

The limited economic feasibility is caused by insufficient revenue gained from the DAM. This revenue is affected by the shifting time of appliances, as well as the current DAM prices, which are described below:

Shifting time. The maximum shifting time in this chapter is restricted to two hours to decrease the consumers' discomfort [34, 200]. This assumption limits how far the semi-flexible and flexible appliances can be shifted, and thus the potential of DR with these appliances and the economic feasibility of this business model. Increasing the shifting time gives more flexibility to the aggregator and can increase the aggregator's revenue from the DAM. However, this creates more inconvenience to the consumers. Improved insulation of flexible appliances, such as heat pumps and air-conditioners and buildings can increase their thermal inertia, and thus also increase the maximum shifting time without reduction in consumers' comfort.

Future DAM prices. DAM prices may change in the future, particularly due to increasing share of RES in the power system, which might influence the economic feasibility of *trading flexibility in the DAM*. In order to evaluate this influence, the DAM prices from June 2012 and 2018 are compared in this chapter. Going from 2012 to 2018, the DAM prices have become higher, yet their general patterns have remained the same. This can be explained by the findings from [201]. The authors in [201] do not find a significant influence of RES on the DAM prices in the Netherlands between the years 2006 and 2011. Despite that, they suggest that this may change as the share of RES continues to grow. As the DAM prices get affected more significantly by the renewable generation, the variability of RES can be also reflected more significantly in these prices.

The impacts of increasing share of RES on DAM prices are studied in the literature [201, 202]. For instance, as the share of RES increases, negative prices in the DAM are observed more often [203]. This is caused by high renewable generation during low electricity demand periods. Note that there are no negative electricity prices in the Dutch DAM price data between 1st of June 2012 and 31st of May 2013, and in June 2018. Furthermore, growing RES penetration is also expected to affect the price volatility in the DAM [202, 204]. Therefore, how the increasing share of RES impacts the DAM prices, and also the economic feasibility of *trading flexibility in the DAM* requires further analysis.

In addition, the optimization models in this chapter are built with the following assumptions:

Distribution of shifting between consumers. The optimization model in this chapter works with the aggregated electricity demand of consumers in the residential and service sectors. Hence, the model does not take into account how the shifting is allocated between individual consumers. For this reason, it is not possible to show the cost of individual consumers. Additionally, the allocation between different consumers might not be fair; certain consumers' appliances might be employed more frequently, than the others. This may create discontent for the consumers, and they may get demotivated to engage in the business model. Therefore, algorithms for fair distribution of shifting between individual consumers can be studied.

Individual imbalances of the aggregator. The aggregator's individual imbalances in the balancing market are not taken into consideration. Nevertheless, considering the limited economic feasibility of the business model, it is not recommended to incorporate the individual imbalances as a future research.

Different consumers' assets. This analysis is carried out with consumers' semi-flexible and flexible appliances. Other types of assets are not incorporated. Characteristics of different assets, such as BESSs, might influence the economic feasibility of trading flexibility in the DAM. This is considered in the next chapter.

5.7. Conclusions

The aim of this chapter is to provide insights on which flat-rate retail prices the aggregator can offer to the consumers that make *trading flexibility in the DAM* with appliances economically feasible for both the aggregator and the consumers. Optimization models are formulated with two approaches: aggregator optimized, and consumer optimized. With the consumer optimized approach, there is no profitable flat-rate retail price for the aggregator. On the other hand, with the aggregator optimized approach, there is only a small range of flat-rate retail prices where the business model becomes profitable for both actors simultaneously. However, even in that range, the decrease in the cost values is rather small.

Therefore, the results show that the economic feasibility of the business model *trading flexibility in the DAM* with appliances and flat-rate retail prices is very limited. We also vary different factors in the optimization models to gain a better understanding of their impacts on the economic feasibility. This analysis shows that different DAM prices, financial reward mechanisms and aggregator's objective do not improve the economic feasibility.

The analysis of economic feasibility in this chapter might change with future DAM prices, caused by increasing share of RES. Thus, it is recommended to study the impact of increasing share of RES on the DAM prices, as well as on the economic feasibility of trading flexibility in the DAM. The next chapter studies *trading flexibility in the DAM* with BESSs, and analyzes its economic feasibility.

6

Economic analysis of aggregator's business models with batteries

I am between two cities,
one knows nothing of me,
the other knows me no longer.

Jean-Paul Sartre

6.1. Introduction

After we show in the previous chapter that the economic feasibility of *trading flexibility in the DAM* with appliances is limited, this chapter focuses on the economic feasibility of the business model with battery energy storage systems (BESSs). BESSs have received a high degree of attention in recent years [16, 205] since it is essential to obtain flexibility, and thus to facilitate the integration of RES.

BESSs can be operated by the aggregator to minimize the consumers' cost by charging and discharging at the right moments considering electricity prices and RES generation. For this purpose, an individual BESS or a shared BESS can be used. An individual BESS is located within a house, whereas a shared BESS[1] is shared between a group of consumers who are typically located in close proximity of this shared BESS [206]. Different projects involving a shared BESS from Germany and Australia are described in [207]. In addition to using the individual and shared

[1]This is also called community BESS.

BESSs for a single purpose, it is also possible to combine multiple business models of the aggregator, introduced as benefit stacking in Section 3.4.7.

In the Netherlands, due to the net-metering where the FiT is equal to the retail price, there is currently no incentive for consumers to deploy BESSs. However, with the phasing-out of net-metering, deploying BESSs might become more economically feasible for consumers, despite the investment cost. Economic feasibility of individual BESSs is analyzed in [208, 209], and compared with a shared BESS in [210]. However, only consumers' costs are studied in these papers, without looking from the aggregator's point of view. Moreover, the economic feasibility of benefit stacking for both the consumers and the aggregator is also understudied.

The aim of this chapter is to analyze the economic feasibility of *trading flexibility in the DAM* for both the aggregator and the consumers, and with different scenarios: no BESSs, individual BESSs, a shared BESS, and individual BESSs with benefit-stacking. For benefit stacking, a combination of two business models is chosen. In these scenarios, the aggregator's and the consumers' cost are assessed while also taking into account investment cost of the BESSs. Besides, various financial reward mechanisms that the aggregator offers to the consumers are studied.

In this chapter, the scenarios are formulated in optimization models with real electricity demand and solar generation data from an urban area in the Netherlands. By this way, we address the research sub-questions: "What are the financial reward mechanisms between the aggregator and the consumers that make business models economically feasible for both?" and "What is the impact of combining business models on operational and economic feasibility?".

Combination of business models is discussed in Section 6.2. An overview of the financial reward mechanisms and the scenarios are described in Sections 6.3 and 6.4. In Section 6.5, the optimization model equations are formulated. Cost calculations for the consumers and the aggregator are given in Section 6.6. The input data are outlined in Section 6.7. In Section 6.8 and 6.9, the results are described and discussed. Finally, the conclusions are drawn in Section 6.10.

6.2. Combining business models

In this section, we discuss which business models are chosen to be combined. When multiple business models are combined, the operation of business models might conflict with each other. For instance, the operation of one business model might require charging, while the other might require discharging. This is elaborated in Section 6.4.3. For this reason, we limit the number of business models to be combined to two.

Which two business models can be combined is presented in Table 6.1. Since the business model *trading flexibility in the intra-day market* is not studied in this thesis, this is also not combined with other business models. Similarly, managing congestion is also mainly not considered in this thesis. We select the business model *trading flexibility in the DAM* as the first business model. In this chapter, this business model is combined with *providing power reserves*. Among power reserves, Frequency Containment Reserve (FCR) is selected for two reasons: (1) there is a lack of studies on FCR, as mentioned in Section 3.4.3, (2) the prices of automatic Frequency

Table 6.1: Combination of business models for this thesis. ∼ signifies not considered in this thesis, ✓signifies considered in this thesis, • signifies possible to consider in this thesis.

	Trading flexibility in the DAM	Trading flexibility in the IDM	Providing power reserves	Internal balancing	Managing congestion
Trading flexibility in the DAM		∼	✓	•	∼
Trading flexibility in the IDM	∼		∼	∼	∼
Providing power reserves	✓	∼		•	∼
Internal balancing	•	∼	•		∼
Managing congestion	∼	∼	∼	∼	

Restoration Reserve (aFRR) and manual Frequency Restoration Reserve (mFRR) have decreased in 2019 [211]. Note that there are other possible business model combinations shown in Table 6.1. These are discussed in the discussions.

6.3. System description

In this chapter, the residential consumers who own PVs, can purchase electricity from the aggregator at retail price, and can sell electricity to the aggregator at the FiT, similar to Chapter 5. However, different from Chapter 5, the aggregator offers various financial reward mechanisms to the consumers, which are described in this section. Furthermore, this section also explains different BESS scenarios.

6.3.1. Financial reward mechanisms

For the retail price, flat-rate and time of use (TOU) tariff, retail prices are considered. The TOU tariff, which involves different electricity prices for different periods of a single day, is intended to encourage consumers to shift their electricity demand from periods with higher prices to periods with lower prices. Note that other time-varying retail prices, such as retail time pricing (RTP), are not studied in this chapter since TOU is commonly used with BESSs [212–214].

For FiT, flat-rate and time-varying FiT are considered. Time-varying FiT is discussed in [215, 216], and defined as time of export (TOE) tariff in [215]. In TOE tariff, the export of electricity is discouraged with lower prices during certain periods of a day, mostly during the hours with higher solar generation, in order to reduce the electricity sent to the grid, and not to cause congestion. With flat-rate FiT, higher electricity sent to the grid can lead to congestions [217]. To prevent congestions with greater penetration of RES, the level of renewable energy curtailment has increased in recent years [218]. TOE tariff combined with BESSs can be useful in reducing congestions in the grid, as well as the amount of curtailment.

Based on this information, three financial reward mechanisms are considered in this chapter: (1) flat-rate retail and flat-rate FiT, (2) TOU tariff retail and flat-rate FiT, and (3) TOU tariff retail and TOE tariff FiT.

6.3.2. Scenarios considered

With these financial reward mechanisms, the following scenarios are considered in this chapter:

Scenario 1: No BESS. In Scenario 1, the consumers have their PVs. Yet, it is assumed that the consumers do not own a BESS, and flat-rate retail price and FiT are taken into account. This scenario is used as a reference case, and illustrated in Figure 6.1(a).

Scenario 2: Individual BESSs. In this scenario, every consumer owns their individual BESSs, together with PVs. The individual BESSs can be used to store surplus of solar generation. Alternatively, the BESSs is also permitted to store electricity purchased from the grid. The individual BESSs is located within a house and operated by the aggregator to minimize the consumers' electricity costs (Strategy 1C in Section 3.3). All financial reward mechanisms are considered in this scenario. This scenario is illustrated in Figure 6.1(b).

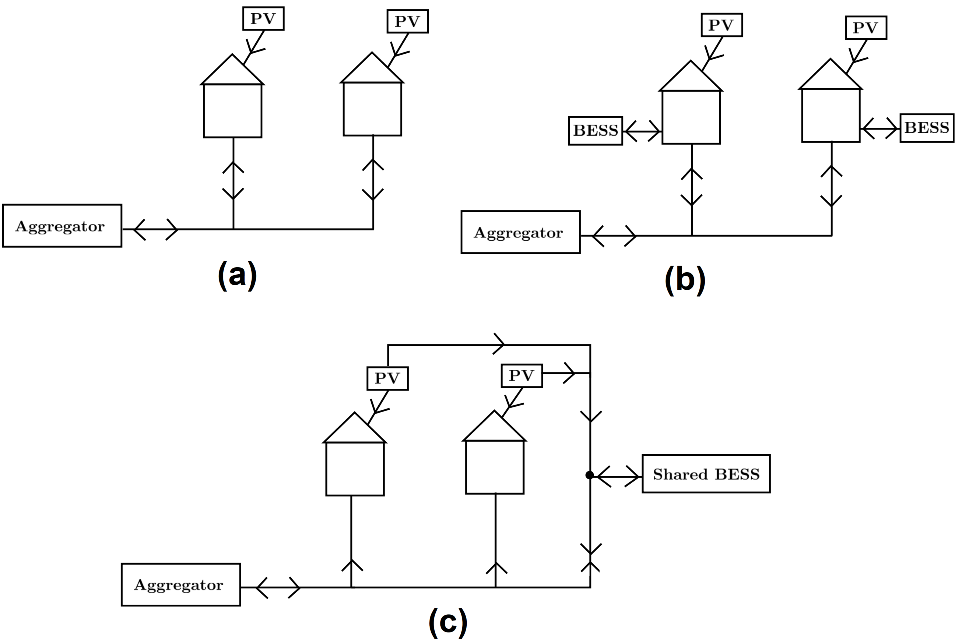

Figure 6.1: Illustration of scenarios considered. (a) depicts Scenario 1, (b) Scenarios 2, 4 and 5, and (c) Scenario 3. Arrows represent electricity flows.

Scenario 3: Shared BESS. In this scenario, N consumers are connected to a shared BESS. The consumers can store their surplus electricity from the PV system. Alternatively, the shared BESS can also be charged from the grid. Similar to Scenario 2, the shared BESS is operated by the aggregator to minimize the consumers' electricity costs (Strategy 1C in Section 3.3). Note that this scenario allows the consumers to use electricity from solar generation of other consumers as well. All financial reward mechanisms are considered in this scenario. This scenario is illustrated in Figure 6.1(c).

It is assumed that the shared BESS is invested in and owned by the consumers. Each consumer can be allocated to a certain share of the shared BESS, either equally or depending on the amount of electricity taken from the grid, or sent to the grid [210]. Additionally, the investment from each consumer in the shared BESS can be calculated based on this share. How the shared BESS needs to be divided between consumers, and the corresponding investment costs are not accounted for in this chapter.

Table 6.2: Different scenarios considered.

	BESS	**Financial reward**	**Investor**	**FCR**
Scenario 1	Without	Flat-rate retail & FiT	N/A	N/A
Scenario 2	Individual	All	Consumer	No
Scenario 3	Shared	All	Consumer	No
Scenario 4	Individual	All	Consumer	Yes
Scenario 5	Individual	All	Aggregator	Yes

Scenario 4: Individual BESSs with benefit stacking, consumers invested. In this scenario, the aggregator can use a certain share of the consumers' individual BESSs for participation in FCR, which is also called FCR share. This means that certain share of BESS capacity is reserved to be operated by the aggregator solely for FCR purposes. The optimal FCR share to minimize the consumer's cost is found in this scenario. On the other hand, the rest of the capacity is operated to minimize the consumers' costs from buying and selling electricity, similar to Scenario 2. For this reason, this scenario involves benefit stacking, i.e., combines *trading flexibility in the DAM* and *providing power reserves*. More information regarding the aggregator's FCR participation is outlined in the next section.

Scenario 5: Individual BESSs with benefit stacking, aggregator invested. This scenario is similar to Scenario 4, apart from the investor. The aggregator invests in the individual BESSs.

6.4. Aggregator's FCR participation by pooling

6.4.1. FCR power capacity

In Scenario 4, the aggregator participates in weekly FCR auctions, by pooling consumers' individual BESSs. Power capacity from each individual BESS sums up to the aggregator's total weekly FCR power capacity (P_w^{FCR}), as shown in Equation (6.1). The aggregator bids this amount in the FCR auctions.

$$P_w^{FCR} = \sum_{n=1}^{N} P_{w,n}^{FCR} \tag{6.1}$$

When the aggregator's bid is accepted in FCR auctions, the aggregator needs to be able to deliver the FCR power ($P^{FCR,delivered}$) in both upward and downward directions for the entire period (one week), according to the Equations (6.2)-(6.4). These equations are also illustrated in a plot in Figure D.1 in Appendix D.1. According to these equations, the FCR power is not supposed to be delivered within the frequency deviation ($|\Delta f|$) less than 10 mHz. For deviations between 10 mHz and 200 mHz, the FCR power delivered should proportionally follow the frequency deviation, and deliver the full FCR bid for deviations higher than 200 mHz. Non-delivery of the FCR power leads to financial penalties from the TSO. It is assumed in this chapter that the aggregator's bids are accepted every week, which might not be the case. Unfortunately, TenneT does not disclose which bidders are contracted for FCR. Consequently, the acceptance rate is not known.

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$$P^{FCR,delivered} = 0 \qquad |\Delta f| < 10\text{mHz} \tag{6.2}$$

$$P^{FCR,delivered} = \frac{P_w^{FCR}\Delta f}{200mHz} \qquad 10\text{mHz} \leq |\Delta f| \leq 200\text{mHz} \tag{6.3}$$

$$P^{FCR,delivered} = P_w^{FCR} \qquad |\Delta f| > 200\text{mHz} \tag{6.4}$$

As discussed in Section 3.1.1, only power capacity is procured in FCR auctions, meaning that the aggregator gets paid only for the power capacity, but not for the energy capacity. The TSO buys the power capacity for FCR from the aggregator, who receives a financial compensation (λ_w^{FCR}) per MW for a specific week for the power capacity they are able to provide.

6.4.2. FCR energy capacity

Even though the aggregator does not receive any remuneration for the energy capacity, according to FCR regulations by TenneT [62], FCR power capacity is required to be delivered for at least 15 minutes in both directions in an alert state[2]. This implies that a certain energy capacity of BESS needs to be reserved to be used in alert states. Consequently, the following equation needs to be satisfied for the energy capacity of an individual BESS ($E_{w,n}^{FCR}$):

$$E_{w,n}^{FCR} = P_{w,n}^{FCR}/4 + P_{w,n}^{FCR}/4 \tag{6.5}$$

The first term in Equation (6.5) calculates the energy capacity for upward FCR delivered for 15 minutes, i.e., this energy capacity is kept charged. The second term

[2] Alert state is defined as frequency deviation: $|\Delta f| \geq 50$ mHz for 15 minutes, $|\Delta f| \geq 100$ mHz for 5 minutes or $|\Delta f| \geq 200$ mHz instantaneously. The alert states do not occur very frequently, particularly $|\Delta f| \geq 200$ mHz. Nevertheless, they occur several times a year. In case of non-delivery of FCR, the aggregator faces financial penalties.

in Equation (6.5) calculates the energy capacity for downward FCR delivered for 15 minutes, i.e., this energy capacity is kept empty. The energy capacity of BESS reserved for FCR is fixed for one week, and cannot be changed. In order to be able to use the consumers' individual BESSs for FCR, the aggregator pays a fee to the consumers, per kWh per week, defined as capacity fee (λ^{cap}) in this chapter.

Energy capacity from each individual BESS sums up to the total weekly FCR energy capacity (E_w^{FCR}), as shown in Equation (6.6).

$$E_w^{FCR} = \sum_{n=1}^{N} E_{w,n}^{FCR} \tag{6.6}$$

6.4.3. Benefit stacking with pooling

Note that when combining multiple business models with the BESSs, these business models might conflict with each other. For instance, trading flexibility in the DAM might require electricity to be discharged from a certain BESS at a specific moment, while electricity might need to be charged to the BESS to provide FCR at the same moment. Since the BESS cannot be charged and discharged at the same time, it is not possible to combine these business models using a single BESS. However, as the aggregator is able to pool a large number of individual BESSs, this gives them flexibility for benefit stacking. For example, when the electricity needs to be charged to the BESSs to provide FCR, although a certain BESS might be charged, since the aggregator pools a large number of individual BESS, there is likely to be individual BESSs that are discharging at the moment. By this way, the aggregator can use already charging BESSs to provide FCR.

In addition, there might be idle BESSs available, i.e., not being charged or discharged. These can be used by the aggregator to provide FCR as well. Yet, this changes the energy stored in the BESS, which might affect the other business model at a later point. Therefore, benefit stacking with BESSs requires advanced control algorithms to ensure both business models can be operated with minimum conflicts with each other. In this chapter, we assume that the aggregator can pool a large number of individual BESSs and have algorithms to allow benefit stacking. Our focus is to determine the economic feasibility of different BESS scenarios, including the scenario with benefit stacking.

Note that it is also possible to provide FCR with a single large BESS, like the shared BESS. However, it becomes difficult to use the shared BESS for benefit stacking because the business models may conflict with each other. Related to this, the possibility of combining FCR with another business model using a large BESS is found to be limited in [219]. Also, appliances, in particular semi-flexible appliances, are also not considered since their characteristics make them less suitable to provide power reserves, as explained in Section 3.4.5. For this reason, only individual BESSs are considered for benefit stacking.

6.5. Optimization model

To address the scenarios considered in this chapter, two different optimization models are formulated. Since Scenario 1 does not include BESSs, the aggregator's and the consumers' costs are calculated without an optimization model. Mathematical formulation of optimization models for Scenarios 2, 3, 4 and 5 are explained in this section. Depending on the financial reward mechanism, the retail price and FiT in these models can be flat-rate or time-varying. The nomenclature for this chapter is presented in Appendix D.2.

6.5.1. Scenarios 2, 4 & 5

The following model is run separately for every consumer $n \in \{1, 2, \ldots, N\}$, and for every week $w \in \{1, 2, \ldots, 52\}$ in the reference year. We put together the results from each consumer and week, to obtain them for the entire year. The model is built with time resolution t per PTU. Due to weekly runs, the total number of PTUs, T is equal to 672.

$$\text{Minimize} \sum_{t=1}^{T} \lambda_t^{ret} P_{t,n}^{buy} - \lambda_t^{feedin} P_{t,n}^{sell} - \lambda_w^{cap} E_{w,n}^{FCR} \tag{6.7}$$

subject to

$$P_{t,n}^{buy} - P_{t,n}^{sell} + P_{t,n}^{PV} = P_{t,n}^{demand} + P_{t,n}^{char,ind} - P_{t,n}^{dis,ind} \quad \forall t \tag{6.8}$$

$$E_{t,n}^{bat,ind} = E_{t-1,n}^{bat,ind} + \eta P_{t,n}^{char,ind} \delta - (1/\eta) P_{t,n}^{dis,ind} \delta \quad \forall t \tag{6.9}$$

$$0 \leq s_{w,n}^{FCR} \leq 1 \tag{6.10}$$

$$P_{w,n}^{FCR} = P_{\max}^{bat,ind} s_{w,n}^{FCR} \tag{6.11}$$

$$E_{w,n}^{FCR} = P_{w,n}^{FCR}/2 \tag{6.12}$$

$$0 \leq E_{t,n}^{bat,ind} \leq E_{max}^{bat,ind} - E_{w,n}^{FCR} \quad \forall t \tag{6.13}$$

$$E_{1,n}^{bat,ind} = (E_{\max}^{bat,ind} - E_{w,n}^{FCR})/2 \tag{6.14}$$

$$E_{1,n}^{bat,ind} = E_{T,n}^{bat,ind} \tag{6.15}$$

$$P_{t,n}^{char,ind} \leq P_{\max}^{bat,ind} \, y_{t,n} \quad \forall t \tag{6.16}$$

$$P_{t,n}^{dis,ind} \leq P_{\max}^{bat,ind} \, (1 - y_{t,n}) \quad \forall t \tag{6.17}$$

$$y_{t,n} \in \{0, 1\} \quad \forall t \tag{6.18}$$

$$0 \leq P_{t,n}^{buy} \leq P_{\max}^{ind} \, u_{t,n} \quad \forall t \tag{6.19}$$

$$0 \leq P_{t,n}^{sell} \leq P_{\max}^{ind} \, (1 - u_{t,n}) \quad \forall t \tag{6.20}$$

$$u_{t,n} \in \{0, 1\} \quad \forall t \tag{6.21}$$

The objective function in Equation (6.7) aims to minimize the total cost of all the consumers, which consists of electricity bought from the aggregator at the retail price and electricity sold to the aggregator at the FiT, and the revenue gained from offering FCR capacity to the aggregator at the capacity fee. This model is run separately for every consumer n since it concerns individual BESSs. Note that this model can be used for Scenarios 2, 4 and 5. Hence, in Scenario 2 where FCR is not offered, all variables related to FCR are equal to zero. Furthermore, variables and parameters related to FCR possess index w due to the weekly FCR auctions, instead of an index t which indicates PTU. This implies that these do not vary between PTUs, but between weeks.

The power balance constraint in Equation (6.8) ensures that the electricity demand from the consumers is satisfied by the electricity supply at all times. The electricity demand can be met by solar power generation, electricity bought from the aggregator, or electricity discharged from BESS. Equation (6.9) describes the charging/ discharging process of the BESS. According to this equation, energy stored in BESS depends on how much energy in the BESS was available in the previous time step, and whether the BESS is charged or discharged in the current time step. Moreover, charging and discharging efficiency of BESS are also taken into account.

Equation (6.10) makes sure that share of the BESS reserved for FCR ($s^{FCR}_{w,n}$) is positive and less than 1. Equation (6.11) calculates the power capacity reserved for FCR by multiplying the share of the BESS reserved for FCR with its maximum power capacity. Equation (6.12) finds the energy capacity reserved for FCR, as described in (6.5). Based on that, Equation (6.13) makes sure that the energy stored in the BESS for consumers' usage remains less than FCR capacity subtracted from the maximum energy capacity of the BESS. Equation (6.14) states the initial energy stored in the BESS. In Equation (6.15), the energy stored in the BESS in the final time step is constrained to be equal to that of initial time step.

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Equations (6.16) and (6.17) make sure that the charging and discharging of the BESS occur within the power limits of the battery. A binary variable y_t, which is introduced in Equation (6.18), guarantees that the BESS cannot be charged and discharged simultaneously. This binary variable y_t being 1 indicates the BESS can only be charged, whereas being 0 indicates the BESS can only be discharged.

The amount of electricity that can be purchased or sold by a single household to the grid is limited by the grid capacity requirements in Equations (6.19) and (6.20). It should be noted that the binary variable u_t is equal to 1 if electricity is purchased and 0 if electricity is sold.

6.5.2. Scenario 3

The following model is also run separately for every week $w \in \{1, 2, \ldots, 52\}$ in the reference year. The model is also built with time resolution t per PTU. Unlike the previous model, this model is not run separately for every consumer n, but N consumers are summed due to the shared BESS.

$$\text{Minimize} \quad \sum_{n=1}^{N} \sum_{t=1}^{T} \lambda_t^{ret} P_{t,n}^{buy} - \lambda_t^{feedin} P_{t,n}^{sell} \tag{6.22}$$

subject to

$$\sum_{n=1}^{N} P_{t,n}^{buy} - \sum_{n=1}^{N} P_{t,n}^{sell} + \sum_{n=1}^{N} P_{t,n}^{PV} = \sum_{n=1}^{N} P_{t,n}^{demand} + P_{t}^{char,shar} - P_{t}^{dis,shar} \quad \forall t \quad (6.23)$$

$$E_t^{bat,shar} = E_{t-1}^{bat,shar} + \eta P_t^{char,shar}\delta - (1/\eta) P_t^{dis,shar}\delta \quad \forall t \quad (6.24)$$

$$0 \leq E_t^{bat,shar} \leq E_{max}^{bat,shar} \quad \forall t \quad (6.25)$$

$$E_1^{bat,shar} = E_{max}^{bat,shar}/2 \quad (6.26)$$

$$E_1^{bat,shar} = E_T^{bat,shar} \quad (6.27)$$

$$P_t^{char,shar} \leq P_{max}^{bat,shar}\, y_t \quad \forall t \quad (6.28)$$

$$P_t^{dis,shar} \leq P_{max}^{bat,shar}\,(1-y_t) \quad \forall t \quad (6.29)$$

$$y_t \in \{0,1\} \quad \forall t \quad (6.30)$$

$$0 \leq \sum_{n=1}^{N} P_{t,n}^{buy} \leq P_{\max}^{shar}\, u_t \quad \forall t \quad (6.31)$$

$$0 \leq \sum_{n=1}^{N} P_{t,n}^{sell} \leq P_{\max}^{shar}\,(1-u_t) \quad \forall t \quad (6.32)$$

$$u_t \in \{0,1\} \quad \forall t \quad (6.33)$$

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The objective function in Equation (6.22) minimizes the total cost of all the consumers that own the shared BESS. The power balance constraint in Equation (6.23) ensures that the electricity demand from the consumers is satisfied by the electricity supply at all times. Equations (6.31)-(6.33) restrict the amount of electricity that can be purchased or sold by all the households to the grid within the grid requirements. The explanations for Equations (6.24)-(6.30) are the same as in the previous model. Yet, the shared BESS is given in these equations for this scenario, instead of the individual BESS.

The optimization problems are implemented in GAMS using MILP and solved using solver CPLEX.

6.6. Cost calculations

All scenarios are evaluated and compared with respect to the costs given in this section: consumers' operational and total cost, and aggregator's total cost.

6.6.1. Consumers' operational and total cost

Consumers' annual operational cost is provided in Equation (6.34), which is also given in the objective function in Equation (6.7). Note that this is the cost for N number of consumers involved.

$$C_{cons}^{oper} = \sum_{n=1}^{N}\sum_{t=1}^{T}[\lambda_t^{ret} P_{t,n}^{buy} - \lambda_t^{feedin} P_{t,n}^{sell}] - \sum_{n=1}^{N}\sum_{w=1}^{W}[\lambda_w^{cap} E_{w,n}^{fcr}] \quad (6.34)$$

Consumers' annual total cost is given in Equation (6.35). For Scenarios 2 and 4, this is composed of the investment cost of an individual BESS for N number of consumers divided by the lifetime expectancy of the BESS, added to the annual operational cost from Equation (6.34). For Scenario 3, the investment cost of the shared BESS is taken.

$$\begin{aligned} C^{tot}_{cons} &= C^{oper}_{cons} + N \cdot (C^{inv,ind}/lf) \text{ for Scenarios 2 \& 4} \\ C^{tot}_{cons} &= C^{oper}_{cons} + (C^{inv,shar}/lf) \text{ for Scenario 3} \end{aligned} \tag{6.35}$$

6.6.2. Aggregator's total cost

Aggregator's total annual cost is calculated in Equation (6.36). It is equal to aggregator's revenue from FCR participation and the cost from paying consumers the capacity fee, in addition to C^{tot}_{agg} in Equation (5.2).

$$C^{tot}_{agg} = \sum_{n=1}^{N} \sum_{w=1}^{W} [\lambda^{FCR}_{w} E^{FCR}_{w,n} - \lambda^{cap} E^{FCR}_{w,n}] + C^{dac}_{agg} \tag{6.36}$$

6.7. Case study 3: Data & assumptions

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The optimization models are evaluated for a case study with residential consumers in the Netherlands. The reference year is taken as 2018, since measured residential electricity demand and solar power generation data are available for that period. The numeric results are based on the following datasets:

- *Consumers' electricity demand.* Residential consumers' electricity demand data are measured in 20 anonymous households in Amsterdam, as a part of City-Zen project [220]. The data measure how much electricity taken from the grid in time resolution of PTUs. Yet, it does not provide the total electricity demand of these households.

- *Solar power generation.* Solar power generation data are also obtained from City-Zen project [220]. It is important to note that solar power generation data do not involve the total solar power generation, but only the solar power generation sent to the grid. Despite this, the data can still be used in the optimization models since solar generation used by the appliances cannot be sent to the grid or to the BESSs. The average electricity taken from the grid, and solar generation sent to the grid of 20 households in July, September, December, and March in 2018 are demonstrated in Figure 6.2.

- *BESS characteristics.* Both individual and shared BESS are assumed to be lithium-ion batteries with charging/discharging efficiency of 95%, resulting in a round trip efficiency of nearly 90% [221]. Additionally, maximum energy capacity and power capacity of individual and shared BESS are given in Table 6.3. The investment cost for the individual BESS is assumed to be 4.5 k€ based on [222, 223], while for the shared BESS 597 € per kWh [224]. The lifetime expectancy of both

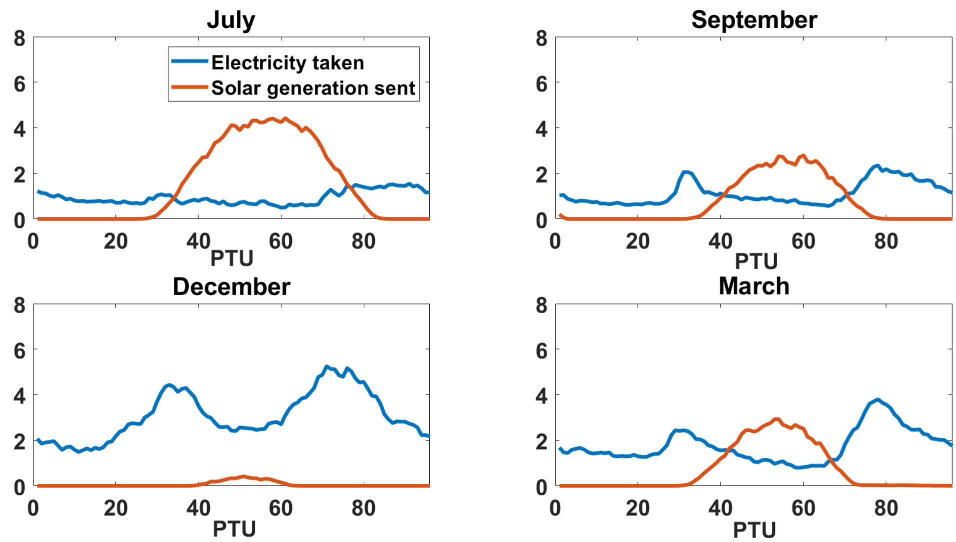

Figure 6.2: Average electricity taken from the grid and solar generation sent to the grid in July, September, March, and December in 2018.

individual and shared BESS is taken as 20 years, according to [225, 226]. Moreover, self-discharge of BESS is neglected, due to low self-discharge characteristics of lithium-ion batteries [227].

Table 6.3: BESS characteristics

Input	Value	Unit
Individual BESS maximum energy capacity ($E_{max}^{bat,ind}$)	6.6	kWh
Individual BESS initial energy stored	3.3	kWh
Shared BESS maximum energy capacity ($E_{max}^{bat,shar}$)	132	kWh
Shared BESS initial energy stored	66	kWh
Charging/discharging efficiency	95	%

- *Grid.* Maximum allowed power to be taken and sent to the grid ($P_{max}^{buy,ind}$ and $P_{max}^{sell,ind}$, respectively) is 8 kW per household [224, 228]. In shared BESS scenarios, maximum power to be taken and sent to the grid corresponds to $N \cdot 8\,\text{kW}$ ($P_{max}^{buy,shar}$ and $P_{max}^{sell,shar}$), in which N is equal to 20.

- *DAM electricity prices.* EPEX DAM electricity prices from 2018 are used, which are obtained from [196].

- *FCR prices from TSO.* Weekly prices from FCR auctions for FCR compensation (λ^{FCR}) are obtained from TenneT for the year 2018 [229].

- *Financial reward mechanisms.* Three financial reward mechanisms are considered. Financial reward mechanism 1 (FR1): Flat-rate retail and flat-rate FiT. Similar to previous chapters, flat-rate retail price is taken as 0.1822 €/kWh which is the average retail price between the years 2012 and 2017 in the Netherlands [197]. Flat-rate FiT is taken as 0.05 €/kWh [198, 199].

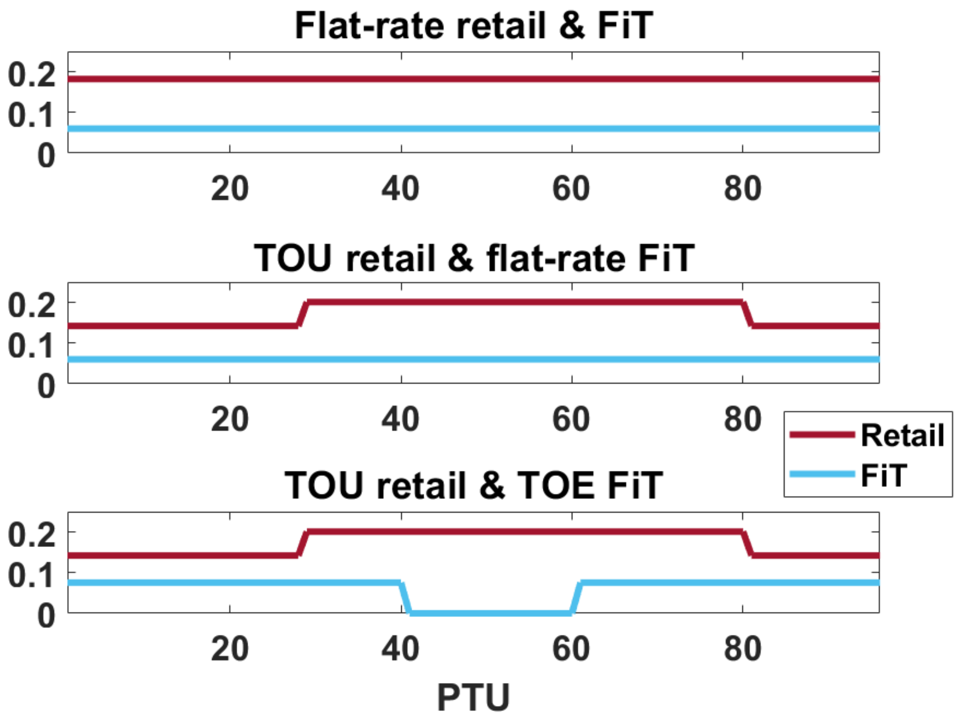

Figure 6.3: Financial reward mechanisms. Top graph shows financial reward mechanism 1 (flat-rate retail and FiT), middle graph shows financial reward mechanism 2 (TOU tariff retail and flat-rate FiT), and bottom graph shows financial reward mechanism 3 (TOU tariff retail and TOE tariff FiT).

Financial reward mechanism 2 (FR2): TOU tariff retail and flat-rate FiT. Flat-rate FiT is the same as the previous mechanism. TOU tariff divides the day into two periods: higher electricity price period, and lower electricity price period [230]. Yet, the average daily price in these two periods is equal to flat-rate retail price. This reward mechanism is displayed in Figure 6.3.

Financial reward mechanism 3 (FR3): TOU tariff retail and TOE tariff FiT. TOU tariff is identical to the previous case. TOE tariff divides the day into two periods: zero electricity price period (around noon), and non-zero electricity price period (the rest of the day). TOE tariff in [215] involves a negative electricity price, instead of zero. However, since it is not very realistic that consumers would agree to pay to sell electricity, TOE tariff is adapted as zero in this thesis. In non-zero period, the FiT is taken as 0.065 €/kWh, to make the average daily price equal to flat-rate FiT, as shown in Figure 6.3.

- *Capacity fee for FCR.* Capacity fee is taken as 0.1 €/kWh, 0.3 €/kWh, and 0.5 €/kWh per week. These are based on the remuneration fees in the CrowdNett project by Eneco, where BESSs are used for providing FCR [231].

6.8. Case study 3: Results

After describing the optimization models and the data from the case study, this section first explains how the BESSs are charged and discharged in the scenarios considered. After that, the results of the cost calculations given in Section 6.6 are presented to evaluate and compare these scenarios.

Scenario 2

Figure 6.4 shows average daily values of solar generation, electricity bought from the aggregator, sold to the aggregator, charged to the BESSs, discharged from the BESSs for total 20 consumers for three financial reward mechanisms in July, March and December 2018 for Scenario 2. The left column in this figure displays the results for FR1, the middle column for FR2, and the right column for FR3. These months are selected owing to their different solar generation profiles, as depicted in Figure 6.2.

In FR1, the amount of electricity bought and sold decreases compared to Scenario 1, where there is no BESS, as shown in Figure 6.2. This can be explained by charging the solar generation to the individual BESSs. By this way, the solar generation is utilized to a greater extent for the electricity demand of the consumers.

Comparing FR1 and FR2, a higher amount of electricity is bought in FR2 during the periods with lower retail price, and charged to the BESSs to be used when the retail price is higher. This leads to a higher peak in the electricity bought in FR2 in these periods, e.g., around PTU 80, although it is still within the capacity of the electricity cables. This peak occurs because peak-shaving constraint is not incorporated in the optimization model. Nonetheless, note that these periods are off-peak periods, meaning that the electricity demand in the power system is lower. Moreover, in FR3, the electricity sold to the grid becomes lower, compared to the other two financial reward mechanisms, due to zero period in TOE tariff. During this period, most of the electricity is charged to the BESSs, instead of being sold.

Seasonal distinctions are also observed in Figure 6.4. Higher solar generation in July enables a higher amount of electricity to be sold to the aggregator and charged to the BESSs, in comparison to the other two months. In line with that, in December, there is almost no electricity sold to the aggregator due to low solar generation. Moreover, TOE tariff in FR3 in December barely makes any difference compared to FR2. This can also be attributed to low solar generation in December.

Scenario 3

Figure 6.5 shows the same values for Scenario 3. The shared BESS in this scenario allows the consumers to utilize its energy capacity more effectively compared to individual BESS, due to differences in electricity demands of different consumers. For instance, a certain consumer is able to use the electricity stored earlier in the shared BESS by other consumers. This is not possible with the

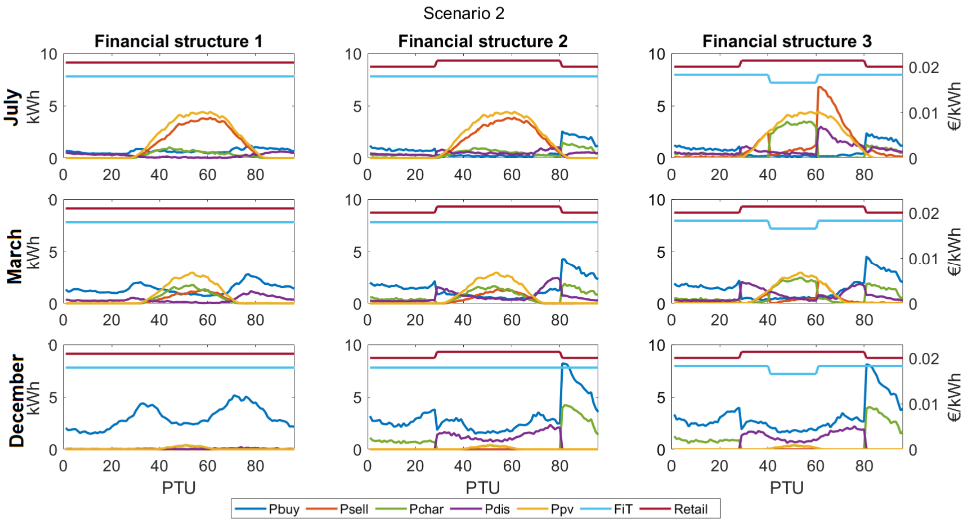

Figure 6.4: Scenario 2: Average daily values of solar generation, electricity bought from the aggregator, sold to the aggregator, charged to the BESS, discharged from the BESS for 20 consumers for three financial reward mechanisms in July, March and December 2018.

individual BESS. Moreover, the energy capacity of an individual BESS is not used in the absence of its owners. On the other hand, with the shared BESS, their solar generation can still be sent to the BESS and be used by the other consumers. Therefore, a shared BESS can be used more effectively with a capacity that is equal to the sum of individual BESSs.

In this scenario, the amount of electricity charged to the shared BESS is higher, compared to Scenario 2, due to the fact that every consumer can send their excess solar generation to the shared BESS. In fact, because of this reason, in FR3 in July no electricity is sold during the zero period in TOE tariff, which is financially advantageous for the consumers. Because of charging a higher amount of electricity to the shared BESS, electricity that needs to be bought decreases in July when no electricity is bought at all. Moreover, charging higher electricity to the shared BESS implies that the electricity sold is also reduced. Yet, this is still financially advantageous for the consumers as buying electricity is more costly than not selling electricity.

In March and December, the electricity bought is lower when the retail price is higher in FR2 and FR3 to minimize the cost. For the same reason, a higher amount of electricity is bought and charged to the shared BESS when the retail price is lower in FR2 and FR3. Note that there are also some spikes in electricity bought and charged in March and December during the periods with lower retail prices. Since the retail prices and FiT are fixed during these periods, the optimization model does not distinguish any difference in the cost values. Hence, it does not matter for the optimization model to have a spike at a certain moment, and a lower value later. Additionally, in December in FR1, the shared BESS made no difference compared to

Scenario 2, owing to nearly zero solar generation and flat-rate retail price and FiT. Nevertheless, in FR2 and FR3, the amount of electricity charged increases during low retail price periods, to be used when the retail price is higher.

This scenario also allows the consumers to use electricity from solar generation of other consumers. As a result, in certain moments, electricity charged to the shared BESS is lower than solar generation, e.g., in March around PTU 50.

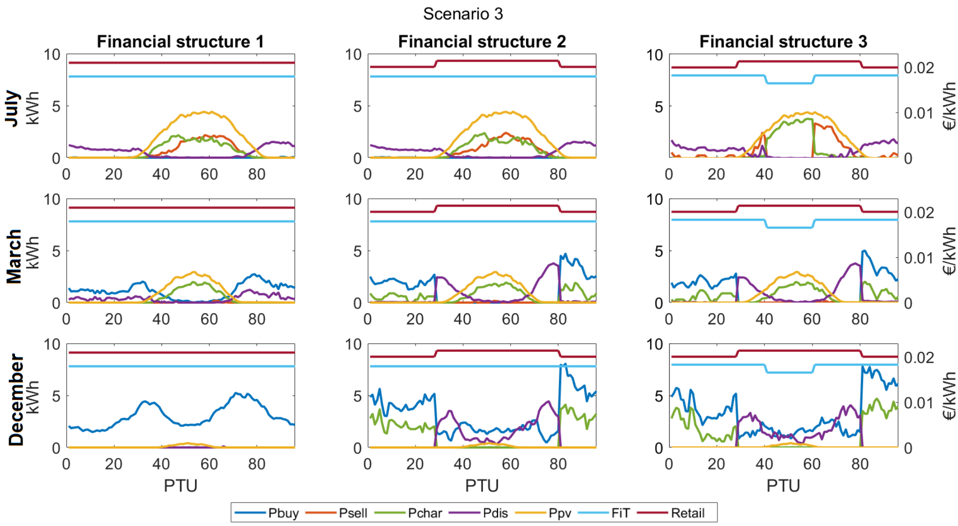

Figure 6.5: Scenario 3: Average daily values of solar generation, electricity bought from the aggregator, sold to the aggregator, charged to the BESS, discharged from the BESS for 20 consumers for three financial reward mechanisms in July, March and December 2018.

Scenario 4

The average FCR shares of 20 consumers' BESSs with different capacity fees and three financial reward mechanisms in July, March, and December are presented in Table 6.4. The FCR shares in FR1 are higher than in FR2 and FR3, due to flat-rate retail and FiT. For instance, since the prices are fixed throughout the day, a great amount of electricity is sold to the aggregator in July. The BESSs are charged and discharged for only a small amount in July, as depicted in the top left graph in Figure 6.4. Since the BESSs are not used used greatly, a high share can be reserved for FCR to achieve a lower cost.

The FCR shares in FR1 in March are the lower than in June and December since the consumers use their BESSs to a larger extent in FR1 in March; they charge and discharge their BESSs more frequently, as displayed in Figure 6.4. Similarly, the FCR shares in December are highest in December as the BESSs are nearly never used as illustrated in the bottom left graph in Figure 6.4. As a result, there is a bigger capacity that can be reserved for FCR. Furthermore, as a general trend, as the capacity fee goes up, the FCR share also increases in all months, because of higher revenue obtained from the FCR share.

Table 6.4: Average FCR shares of 20 consumers' BESSs for different capacity fees and three financial reward mechanisms in July, March, December.

	FR1			**FR2**			**FR3**		
Capacity fee	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
July	0.76	1.00	1.00	0.72	0.86	1.00	0.26	0.63	0.90
March	0.54	0.96	1.00	0.52	0.76	1.00	0.39	0.73	0.95
December	1.00	1.00	1.00	0.52	1.00	1.00	0.49	1.00	1.00

The FCR shares in FR2 are slightly lower than those of FR1, owing to TOU tariff. TOU tariff causes the BESSs to be used more substantially, in order to minimize the consumers' electricity cost. As a result, the FCR shares drop. The most remarkable drop between FR1 and FR2 occurs in December for capacity fee 0.1 €/kWh, since the BESSs are almost never used in FR1 in December, as given in the bottom left graph in Figure 6.4. The FCR shares in FR3 are lower than in the other two financial reward mechanisms. This can also be explained by more frequent charging and discharging of the BESSs. The zero period in TOE tariff results in higher electricity charged to the BESSs since there is no revenue gained from selling electricity to the aggregator in this period. Hence, higher share of the BESSs is required to be used to minimize the consumers' electricity cost.

Figure 6.6 depicts average daily values of solar generation, electricity bought from the aggregator, sold to the aggregator, charged to the BESS, discharged from the BESS for total 20 consumers for three financial reward mechanisms in July, March and December 2018 for Scenario 4 with capacity fee 0.3 €/kWh. It can be observed that the amount of electricity charged to and discharged from the BESSs declines compared to the Scenario 2, in particular in FR3. This can be explained by the FCR share which is reserved to be used for FCR purposes. Apart from that, the general pattern of the results appear to be similar to Scenario 2.

6.8.1. Aggregator's total cost and consumers' operational cost

Figure 6.7 displays the aggregator's annual cost and consumers' annual operational costs with four scenarios and for three financial mechanisms. The consumers' annual operational cost decreases in all scenarios, compared to Scenario 1 where there is no BESS. The biggest decline happens in Scenario 3 because of the shared BESS. Comparing Scenarios 2 and 4, the consumers' annual operational cost is lower in Scenario 4, due to benefit stacking with providing FCR. Moreover, the aggregator's annual cost increases (profit decreases) in Scenarios 2 and 3, compared to Scenario 1, while it lessens significantly in Scenario 4, due to the revenue from FCR participation. These indicate that combining business models helps to decrease both the consumers' and the aggregator's cost. Note that the consumers' and the aggregator's annual operational cost does not change from since these two scenarios only differ with respect to invesment cost.

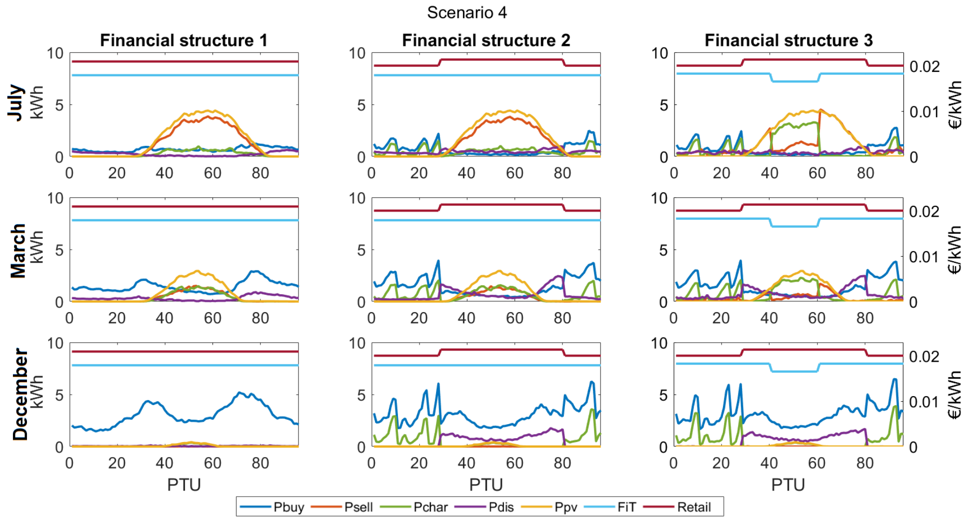

Figure 6.6: Scenario 4: Average daily values of solar generation, electricity bought from the aggregator, sold to the aggregator, charged to the BESS, discharged from the BESS for 20 consumers for three financial reward mechanisms in July, March and December 2018.

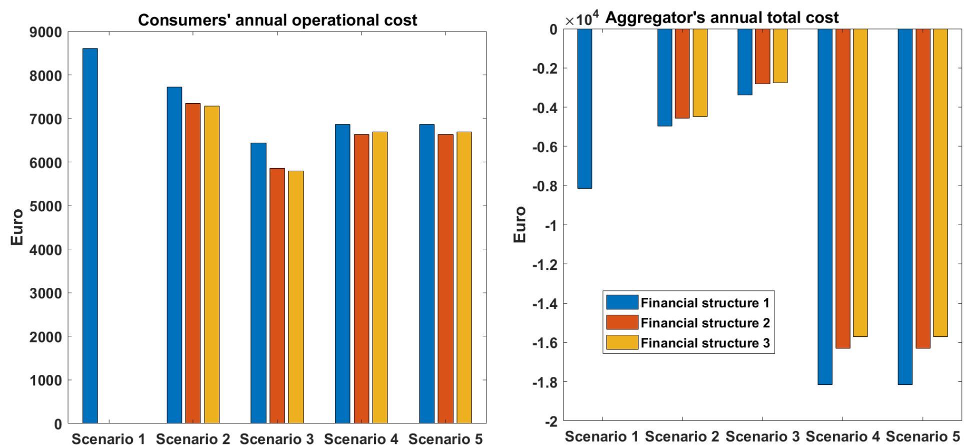

Figure 6.7: Consumers' annual operational cost and aggregator's annual total cost with five scenarios and for three financial mechanisms. Negative cost values mean profit.

In Scenarios 2 and 3, the lowest consumers' operational cost is attained with FR3. This points out that TOE tariff gives more financially appealing results for the consumers than flat-rate FiT, despite zero period in TOE tariff, because of the higher price than the flat-rate FiT during the rest of the day. On the contrary, in Scenario 4, FR2 results in a lower operational cost, than FR3. In FR3, lower FCR shares are found, as explained previously and shown in Table 6.4. Consequently, the revenue gained from offering FCR capacity to the aggregator decreases. In addition to this, due to FCR share, smaller energy capacity of the BESSs is available for charging and discharging, causing the consumers to sell higher amount electricity to the aggregator during zero period in TOE tariff, which is not financially advantageous for the consumers.

From the consumers' perspective, it is more beneficial that the aggregator offers FR3 in Scenarios 2 and 3. On the other hand, it is more beneficial that the aggregator offers FR2 in Scenario 4, which also creates profit for the aggregator. Therefore, without taking into account the investment cost of BESSs, Scenario 4 with FR2 appears to provide economically feasible results for both the aggregator and the consumers. The investment costs are added in the next section.

6.8.2. Consumers' total cost

The investment cost of the BESSs is added to find the consumers' annual total cost, shown in Figure 6.8. The consumers' annual cost increases in Scenarios 2,3 and 4 with the addition of the investment cost, compared to Scenario 1, which indicates that the consumers need to pay a considerable higher cost in every scenario when they invest in the BESSs. This is not economically feasible for the consumers, and thus they are not interested in investing in the BESSs.

On the other hand, in Scenario 5, where the aggregator invests in the BESSs, the consumers' cost becomes lower than all the other scenarios, including Scenario 1, which means that this scenario is economically feasible for the consumers. However, this comes at the expense of the aggregator's profit since it is lower than Scenario 4.

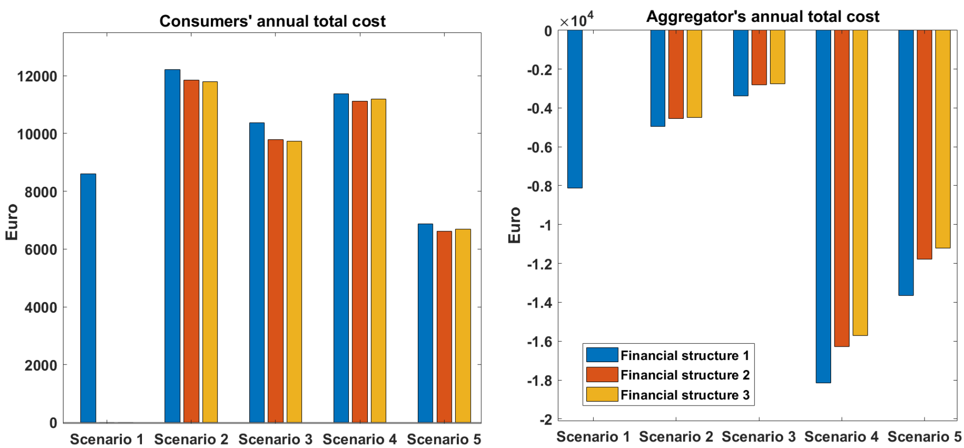

Figure 6.8: Consumers' annual total cost and aggregator's annual total cost with five scenarios and for three financial mechanisms. Negative cost values mean profit.

6.9. Discussions

The following paragraphs first discuss further insights from the results, followed by the limitations in this chapter.

Economic feasibility. The results of the case study show that business models with the BESSs are not economically feasible for the consumers due to their investment cost. The individual BESSs, the shared BESS, as well as benefit stacking with the individual BESSs (*trading flexibility in the DAM* and *providing FCR*) are considered. In all the scenarios, investing in the BESSs remains to be an infeasible option for the consumers, even though the consumers' total cost decreases with the shared BESS in Scenario 3, and benefit stacking in Scenario 4. By contrast, in Scenario 5 where the aggregator invests in the BESSs, consumers' total cost is lower than Scenario 1 (without BESS), i.e., economically feasible. However, this comes at the expense of the aggregator's profit since the aggregator's profit declines due to the investment cost of BESSs. Note that the aggregator still makes a relatively high profit, but it is lower than Scenario 4. Although this is the only scenario where the economic feasibility is achieved for both the aggregator and the consumers, investing in the BESSs may not be preferable for the aggregator. To solve this, the following can be considered:

- The investment cost of the BESSs can be divided between the aggregator and the consumers in such a way that it is still economically feasible for both actors. How this division needs to be carried out is recommended as a future study. Similarly, the BESSs can be purchased by the aggregator, and can be leased to the consumers. The amount of money for lease should be determined to make it economically feasible for both actors.
- Providing FCR helps the TSO with the system balance. As the conventional power plants are closed down, the aggregator's FCR participation plays a more crucial role for the system balance. The TSO can provide subsidies aimed at encouraging BESS adoption.
- Technological advancements in the BESSs are expected to result in a drop in their investment cost [232], which can make BESSs financially attractive for the consumers in the coming years. In line with this, International Renewable Energy Agency reports a cost reduction of 65% for lithium-ion BESSs from 2010 to 2017 [233]. This can make the BESSs financially attractive for the consumers to invest in the coming years, without needing the aggregator's investment.

Forecasts. Results given in this chapter are based on perfect information in electricity demand of the consumers and solar generation. Thus, the aggregator's imbalances and imbalance costs are not considered. They can be incorporated into this chapter as a next step.

Daily FCR auctions. The optimization models in this chapter are built based on weekly FCR auctions. For this reason, the optimization models are run for a week, and $E^{FCR}_{w,n}$ is reserved for a week. However, FCR capacity is auctioned daily instead of weekly since July 2019. As discussed in 3.4.3, auctions with shorter time horizon enables the aggregator to forecast electricity demand and RES generation more accurately, and also to make use of BESS capacity more effectively. For instance, with weekly auctions, the BESSs might be underutilized for FCR because of daily differences in solar generation and electricity demand over a week. Nonetheless, according to [211], the daily auctions have resulted in more volatile FCR prices, which makes price deviations higher from one day to another. Therefore, it is useful to analyze the influence of daily auctions on the economic feasibility of providing FCR.

FCR bids' acceptance. In this chapter, we assume that FCR bids placed in the auctions get accepted every week, which might not be the case. Thus, the aggregator's revenue from FCR and consumers' revenue from capacity fee will be lower than what is found here. Unfortunately, TenneT does not disclose which bidders are contracted for FCR. Consequently, the acceptance rate is not known. Yet, in case of non-acceptance, (1) the BESSs can still be used for Scenario 2, and thus are not entirely idle, and (2) thanks to the daily auctions, the BESSs remain unused for FCR for a shorter period of time.

FCR with pooling the individual BESSs. In this chapter, the aggregator pools individual BESSs, and uses a certain share of these BESSs to provide FCR. The minimum capacity to be allowed to participate in FCR auctions is 1 MW. The number of consumers considered in this chapter is not sufficient to reach 1 MW. Hence, the aggregator needs to pool larger number of consumers to attain the minimum capacity.

Also, pooling a large number of individual BESSs gives the aggregator the flexibility to utilize charging, discharging or idle BESSs to provide FCR. In this chapter, we assume the aggregator has advanced control algorithms to ensure that both business models can be operated with minimum conflicts with each other. However, very little attention has been given in the literature to how to control individual BESSs when they are pooled by an aggregator. Thus, this requires more elaborate studying.

Moreover, in this chapter we reserve the energy capacity of the BESSs for an alert state where at least 15 minutes of full FCR power capacity needs to be delivered. Otherwise, financial penalties need to be paid. This is a very risk-averse approach since alert states occur several times a year, not very frequently. Therefore, it can be interesting to study whether the aggregator is still able to deliver FCR power in alert states by pooling the individual BESSs, but without reserving the energy capacity. Besides, it is also interesting to see how this impacts the aggregator's profit.

FCR with the shared BESS. It is also possible to provide FCR with a single large BESS, like the shared BESS. However, the possibility of combining FCR with another business model with a large BESS is found to be limited in [219]. A further analysis on this can be performed to analyze the other power reserves, i.e., aFRR and mFRR, with the shared BESS, instead of FCR. Since the regulations of aFRR and mFRR enable participation closer to the real-time, as explained in Section 3.1.1, the aggregator can estimate whether there is a conflict between business models more accurately.

It is also possible to invest in a single large BESS and use that solely for FCR purposes. Nevertheless, since this does involve the aggregator gathering the consumers' assets, this is not addressed in this thesis.

Combining other business models. In this chapter, the business model *trading flexibility in the DAM* is combined with *providing power reserves*. In Table 6.1, there are other possible combinations considering the business models covered in this thesis:

- Combining *trading flexibility in the DAM* and *internal balancing*: We study internal balancing in Chapter 4 and conclude that it is not economically feasible. Hence, it is anticipated that combining these two business models does not significantly improve their economic feasibility.

- Combining *providing power reserves* and *internal balancing*. It is found in this chapter that *providing power reserves* is able to generate a substantial decrease in the cost of the consumers and the aggregator. Therefore, it is expected that *internal balancing* can benefit from combining with *providing power reserves*. This can be studied as future research.

BESS characteristics. Degradation of the BESSs is not explicitly modeled in this chapter. Yet, it is assumed that the BESSs have a lifetime expectancy of 20 years [225, 226]. Moreover, degradation of the BESSs might be expected to increase due to higher usage of the BESSs with benefit stacking. Yet, it is found in [234] that degradation of batteries in EVs due to combined operation of charging for driving the EVs and providing power reserves is not very different, compared to operation of charging for driving the EVs. We assume that the same holds for the BESSs.

6

Also, maintenance cost of the BESSs is not incorporated in the cost calculations. This is generally taken as 1.5% of the investment cost per year [235], which is a small amount. Hence, it does not impact the costs in a substantial way.

Electricity bought and sold at other periods. We show in this chapter that in FR2 the electricity bought becomes lower during periods with high retail price. This is beneficial to limit the electricity bought during the peak periods. However, the electricity bought becomes higher during periods with low retail price. Similarly, in FR3 electricity sold becomes lower during periods low FiT, while it becomes higher during periods with high FiT. This leads to peaks in these periods and might also create new congestions if several aggregators follow these financial reward mechanisms. This can be overcome by incorporating peak-shaving constraints in the optimization models as future work.

6.10. Conclusions

The aim of this chapter is to assess the economic feasibility of *trading flexibility in the DAM* with BESSs for both the aggregator and the consumers. For this purpose, several BESS scenarios are considered: (1) individual BESSs, (2) shared BESS, and (3) individual BESSs with benefit-stacking, where the business model *trading flexibility in the DAM* is combined with *providing power reserves*. In these scenarios, various financial reward mechanisms that the aggregator offers to the consumers are studied: flat-rate retail and FiT, TOU tariff retail and flat-rate FiT, and TOU tariff retail and TOE tariff FiT. Optimization models are formulated for these scenarios, and applied to a case study in the Netherlands. Both the aggregator's and the consumers' cost are analyzed, while also taking into account the investment cost of the BESSs.

The results of the case study show that business models with the BESSs are not economically feasible for the consumers due to their investment cost. In all the scenarios, investing in BESSs remains to be an infeasible option for the consumers, even though the consumers' total cost decreases with the shared BESS, and benefit stacking. In terms of aggregators' total cost, Scenario 4 is the only scenario where the aggregator makes profit, and thus is economically feasible for the aggregator. Nevertheless, this is still problematic for the aggregator since the consumers are not interested in investing in the BESSs.

Based on the analysis of the results in this chapter, combining business models *trading flexibility in the DAM* and *providing FCR* using the individual BESSs, which are invested by the aggregator is a feasible scenario in a multi-actor context: (1) economic feasibility: it is economically feasible for both the aggregator and the consumers, (2) operational feasibility: it helps with the system balance. However, by investing in the consumers' BESS, the aggregator's profit declines, even though it is still higher than in the scenario with no BESS. This may not be favorable by the aggregator. To overcome this, the investment cost of the BESSs can be divided between the aggregator and the consumers in such a way that it is still economically feasible for both of them. Future work can study how the investment cost of the individual BESSs should be divided between the consumers and the aggregator.

7

Conclusions

A society's competitive advantage will come not from how well its schools teach the multiplication and periodic tables, but from how well they stimulate imagination and creativity.

Albert Einstein

This final chapter concludes the work described in this thesis by summarizing its main results and insights, providing answers to the main research question and the sub-questions, and by summarizing its main contributions. The chapter ends with recommendations for future research, and with suggestions for aggregators.

7.1. Conclusions and answers to research questions

This thesis has the objective to analyze the operational and economic feasibility of possible aggregators' business models, to utilize flexibility from residential and service sector consumers to facilitate integration of RES in the power system. In line with that, the main research question addressed in this thesis is:

What is the operational and economic feasibility of aggregator's business models in residential and service sectors in a multi-actor context?

The main research question is decomposed into a set of sub-questions. The following paragraphs summarize the main findings in these sub-questions.

Sub-question 1: What are the different strategies to implement the aggregator's business models with respect to economic and operational aspects?

Sub-question 1 is posed with the objective of giving an overview of the possible business models and the extent to which they differ in terms of operational and economical aspects, before analyzing their operational and economic feasibility in depth. This sub-question is answered in Chapter 3, by conducting a literature review and by applying a framework to analyze the selected papers in a structured way. This framework involves the following aspects:

- *Operational aspects*: which consumers' assets are operated, who operates them, for what purpose, and how they are operated.
- *Economic aspects*: how the aggregator makes profit and how consumers' cost is reduced.

Five business models are considered: trading flexibility in the day-ahead market (DAM), trading flexibility in the intra-day market, providing power reserves by pooling, balancing portfolio internally (also known as internal balancing), and managing congestion. Based on the literature review and analysis using the framework, different operational and economic strategies are determined that the aggregator can use to implement these business models.

Several knowledge gaps are identified with respect to these strategies: (1) Business models involving intra-day market, internal balancing, and Frequency Containment Reserve (FCR) are understudied. (2) Economic relations between the aggregator and the electricity markets, and between the aggregator and the consumers need to be incorporated simultaneously while assessing the economic feasibility of the business models. In line with that, there is a small literature on the financial rewards aggregators offer to their consumers. (3) Business models involving BESSs should be combined.

Nevertheless, business models concerning the intra-day market are not studied in this thesis, owing to their limited liquidity in the Netherlands. The remaining knowledge gaps are addressed in the next sub-questions. To do that, we use different case studies with Dutch residential and service sector consumers who are able to produce their own solar generation.

Sub-question 2: What is the operational and economic feasibility of internal balancing with consumers' appliances?

We analyze the operational and economic feasibility of this business model for the aggregator. A comprehensive MPC model is presented in Chapter 4, which determines how the appliances need to be operated to reduce the aggregator's individual imbalances, caused by uncertainties in solar generation. This model is applied to a case study using data from Dutch residential and service sectors.

The results from this chapter show that internal balancing with consumers' appliances using the MPC model is successful in reducing the aggregator's individual imbalances up to 30%. However, the aggregator's imbalance costs remain almost equal with and without internal balancing. From the power system's perspective, internal balancing by aggregators can be beneficial to maintain the system balance. However, from the aggregator's perspective, it does not provide any financial benefits for the aggregator to implement it. We also discuss which factors can impact the results, to make the results more robust. Based on the insights we gain from the case study, we conclude that internal balancing is not an economically feasible business model. Therefore, if policymakers or TSOs wish to stimulate an active role of aggregators in implementing internal balancing, it is required to introduce external incentives and subsidies.

Sub-question 3: What are the financial reward mechanisms between the aggregator and the consumers that make business models economically feasible for both?

While assessing the economic feasibility of the business models, it is also important to consider the consumers' perspective. This sub-question focuses on the financial rewards between the aggregator and the consumers, while the aggregator implements business model *trading flexibility in the DAM*. This business model has been studied extensively in the literature. Yet, most of these studies neglect to involve financial rewards between the aggregator and the consumers, while assessing its economic feasibility. This sub-question aims to determine the financial reward mechanisms that the aggregator needs to offer to the consumers to be allowed to use their assets for the business model. This is studied for two cases: using consumers' appliances, and using consumers' BESSs, addressed in Chapters 5 and 6, respectively.

The aim in Chapter 5 is to determine which flat-rate retail prices the aggregator can offer to the consumers to make *trading flexibility in the DAM* with appliances economically feasible for both the aggregator and the consumers. To achieve this, an optimization model is presented which minimizes the consumers' costs by shifting the electricity demand of the appliances within two-hour time intervals. The model is applied to a case study from the Netherlands. The results show that there is only a small range of retail prices where the business model becomes profitable for both actors simultaneously. Besides that, the decrease in the cost is even then rather low. Therefore, we conclude that the economic feasibility of the business model *trading flexibility in the DAM* with appliances and flat-rate retail prices is very limited. We analyze the influence of different factors on the economic feasibility. The insights from this analysis indicate that limited economic feasibility is caused by insufficient revenue gained from the DAM, which is restricted by the shifting time of appliances, as well as the current DAM prices.

Because of this limited feasibility with appliances, Chapter 6 analyzes the economic feasibility of *trading flexibility in the DAM* with battery energy storage systems (BESSs), comparing the following scenarios: with no BESS (S1), with individual BESSs (S2), and with a shared BESS (S3). For these three scenarios, various financial reward mechanisms are studied: (1) FR1: flat-rate retail and flat-rate feedin tariff (FiT), (2) FR2: time of use retail and flat-rate FiT, and (3) FR3: time of use retail and time of export FiT. Optimization models are presented to determine how to charge and discharge the BESS in order to minimize the consumers' costs in the BESS scenarios. Based on the optimization results, the aggregator's cost, the consumers' operational cost, and the consumers' total cost including the investment cost for the BESSs, are calculated.

In both individual BESSs and the shared BESS scenarios, the lowest consumers' operational cost is attained with FR3: time of use retail and time of export (TOE) feed-in tariffs. This points out that TOE gives more financially appealing results for the consumers than flat-rate FiT, despite zero period in TOE tariff, because of the higher price than the flat-rate FiT during the rest of the day. When comparing the individual BESSs and shared BESS scenarios, the consumers' operational cost is lower with the shared BESS, since a shared battery can be used more effectively. Nonetheless, when the investment costs are included, the consumers' total costs in both scenarios and in three financial reward mechanisms, become higher than in the scenario without BESS. This indicates that the business model *trading flexibility in the DAM* with BESS is not economically feasible for the consumers, and that they are currently not interested in investing in the individual or shared BESS. To overcome infeasibility, we can combine multiple business models, which is studied in the next sub-question.

Sub-question 4: What is the impact of combining business models on operational and economic feasibility?

This sub-question aims to evaluate the impact of combining business models on economic feasibility for both the aggregator and the consumers, which is addressed in Chapter 6. It is rather complicated to operate the consumers' assets with multiple business models since their operation might conflict with each other. Consequently, we only consider combining two business models at once. As explained in Section 6.2, the business models *trading flexibility in the DAM* and *providing power reserves* are combined given their regulations and the business models considered in this thesis.

We consider two additional scenarios with individual BESSs where *trading flexibility in the DAM* is combined with *providing power reserves*, more specifically providing FCR. The only distinction between these two additional scenarios is who invests in the individual BESSs: the consumers, or the aggregator. Note that only individual BESSs are used for this purpose since the operation of shared BESS for two business models might conflict with each other. Yet, this can be resolved with individual BESSs by pooling them. Also, appliances are also not considered since their certain characteristics make them less suitable to provide power reserves. An optimization model is formulated to find the optimal share of the individual BESSs reserved for FCR purposes, in addition to how to charge and discharge the BESS, in order to minimize the consumers' costs.

The results from this chapter show that combining these two business models leads to a bigger decrease in the consumers' operational costs, compared with the scenario with only *trading flexibility in the DAM*. Moreover, the aggregator is able to make a significant profit, which is gained mostly by providing FCR. However, the consumers' total cost is still not sufficiently low to make investing in the BESS financially attractive.

In the other scenario, the aggregator invests in the individual BESSs. This is a feasible scenario in a multi-actor context: (1) economic feasibility: it is economically feasible for both the aggregator and the consumers, (2) operational feasibility: it helps with the system balance. However, by investing in the consumers' BESS, the aggregator's profit declines, even though it is still higher than in the scenario with no BESS. This may not be preferable by the aggregator. To solve this, the following can be considered:

- The investment cost of the BESSs can be divided between the aggregator and the consumers in such a way that it is still economically feasible for both actors. Likewise, the BESSs can be purchased by the aggregator, and can be leased to the consumers. The amount of money for lease should be determined to make it economically feasible for both actors.
- Providing FCR helps the TSO with the system balance. As the conventional power plants are closed down, the aggregator's FCR participation plays a more crucial role for the system balance. The TSO can provide subsidies aimed at encouraging BESS adoption.
- Technological advancements in the BESSs are expected to result in a drop in their investment cost, which can make the BESSs financially attractive for the consumers to invest in the coming years, without needing the aggregator's investment.

7.2. Research contributions

The contributions of this thesis are as follows:

- *Aggregator's business models in multi-actor context.* This thesis provides a multi-actor approach to analyze the operational and economic feasibility of different aggregator's business models. It studies the business models from (1) aggregator's, (2) consumers', and (3) power system's perspectives, to understand whether it is possible to implement them.
- *Flexibility research.* By studying the aggregator's business models, this thesis contributes to facilitating flexibility in residential and service sectors, in order to support the energy transition. In this regard, it provides insights to the aggregators and policymakers on how to utilize flexibility through these business models.
- *Consumers' position.* This thesis also strengthens residential and service sector consumers' position in the power system through aggregator's business models, by helping the consumers take part in flexibility activities and by providing market access to them.
- *Optimization models.* Several optimization models related to aggregator's business models are formulated in this thesis. These models are applied with data from case studies in the Netherlands to analyze the operational and economic feasibility of the business models. These models can also be employed by aggregators using different data, to decide how to operate consumers' assets for different business models, as well as to assess their

economic feasibility. In addition, the models in Chapters 5 and 6 can be used to determine the financial rewards between the aggregator and the consumers.

7.3. Reflections

Analysis approach

The optimization models that are formulated in Chapters 5 and 6 assume that the aggregator has perfect knowledge of their consumers' solar generation and electricity demand, the electricity market prices. In reality, the aggregator uses forecasts of these, and the forecasts are very likely to differ from the actual values. Hence, these problems require decision making under uncertainty. Moreover, since the differences between the forecasts and actual values are not included, aggregator's individual imbalances, and imbalance costs caused by these differences are also not considered.

In this thesis, it is assumed that the aggregator possesses the supplier's role, which means that a supplier becomes an aggregator. However, as explained in Section 2.3, it is also possible that BRPs and independent actors become an aggregator. Challenges faced by aggregators with different roles while implementing their business models are described in Section 2.4. It is essential to consider these challenges while evaluating the business models for aggregators with a BRP's role or for independent aggregators. For instance, for aggregators with supplier's role requires only contracts with consumers, whereas an independent aggregator requires contracts with supplier, and BRPs. Hence, studying aggregators with other roles than suppliers, entails other economic relations that we do not consider in this thesis.

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This thesis assumes the aggregator to be price taker in the DAM. This implies that the aggregator is considered unable to significantly affect the DAM market prices. In other words, the market prices remain the same independently of the aggregator's strategy. Yet, as the number of consumers the aggregator has in their portfolio increases, it becomes more realistic that the aggregator also affects the electricity prices.

Research scope

In this thesis, the electricity market regulations from the Netherlands are considered which are described in Section 3.1.1. Therefore, the geographical scope of this thesis is mainly limited to the Netherlands. In Central Western European (CWE) countries, like the Netherlands, Germany, Belgium, France and Austria, these regulations vary to a small extent, even though some differences still exist [54]. Hence, the results can also be relevant for the other CWE countries.

The aggregator's business models in this thesis are restricted to trading on the short-term electricity markets. Long-term electricity markets, such as bilateral contracts, are not taken into account since these contracts are generally private, and there is no good overview of them. Moreover, within the short-term electricity markets, aggregator's business model related to the intra-day market is not studied in this thesis, owing to its current low liquidity in the Netherlands. Aggregator's business models in the industrial sector are also not taken into account in this thesis.

Electric Vehicles (EVs) are not considered in this thesis while analyzing aggregator's business models since these have a rather mature literature. The characteristics of EVs are more similar to BESSs with two distinctions. Firstly, EVs need to be charged for driving, and thus they have a certain electricity demand depending on the driving behavior of EV owners, such as their arrival, departure time, and number of distance traveled. Secondly, mobility characteristics of EVs allow them to be charged at different locations: private parking spaces like a garage or driveway, and public parking spaces, which can be located at both residential and service sectors. Therefore, the optimization models in this thesis need to be modified to be used for EVs.

7.4. Recommendations

7.4.1. Future research

Suggestions for future research are provided in this section. Some of these suggestions follow from the reflections in the previous section.

The results in this thesis show that the most promising solution to achieve economic feasibility in a multi-actor context is to combine two business models (*trading flexibility in the DAM* and *providing FCR*), while the aggregator invests in the individual BESSs. However, despite being profitable, the aggregator may not prefer to invest in the BESS. Thus, it is highly recommended to study how the investment cost of the BESSs should be divided between the aggregator and the consumers, while keeping it economically attractive for both actors. As an alternative, the aggregator can invest in the BESSs and lease them to the consumers, which also requires to study the lease in such a way that it is economically attractive for both. In addition, within *providing power reserves*, solely FCR is considered in this thesis. We expect the other power reserves also to generate high profits for aggregators, due to the high prices from the TSO, which can also be studied.

Being able to pool many BESSs is a significant economic advantage for an aggregator, especially when combining business models. Combining business models can be challenging since the operation of BESSs for different business models might conflict with each other. Thus, the aggregator needs to be able to use the pooled individual BESSs in such way that it avoids any conflicts. This necessitates advanced control algorithms to ensure that FCR can still be provided using pooled individual BESSs while the business models do not conflict with each other. Since our focus is not to develop control algorithms, we assume that the aggregator already has them. Nonetheless, this has been given little attention in the literature. Therefore, this is highly recommended to study as future work.

This work can also be extended by analyzing the impact of future electricity market prices, especially the DAM prices. Increasing share of RES in the power system is expected to influence the electricity market prices. Therefore, how the increasing share of RES impacts the DAM prices, and also the economic feasibility of business models like *trading flexibility in the DAM* requires further analysis.

Furthermore, the aggregator's business models are analyzed with respect to operational and economic aspects in this thesis. The social aspects of the business models, such as installing ICT infrastructures and consumers' privacy concerns due to having their data monitored, are not taken into consideration although these aspects are also critical while implementing business models. In line with this, in all the optimization models in this thesis, consumers are assumed to be only financially motivated. Even though the majority of the consumers consider cost to be significant according to a survey carried out in the Netherlands in [236], consumers' other motivations and concerns are also studied in the literature [70, 236]. Other possible motivations, such as being environmentally aware, and preferring comfort, having privacy concerns and acceptance issues, are not incorporated in this thesis. The work in this thesis can be extended by incorporating the social aspects (consumers' other preferences and motivations). It should be remarked that optimization models are not suitable to account for consumers' preferences and behaviors. Agent-based models can be used for this purpose, which is a modeling approach widely used for simulating social systems [237].

It is also possible for the aggregator to trade flexibility in the flexibility markets, primarily to help with congestion management. These markets are not considered in this thesis since currently they are mostly in the pilot phase. Detailed information regarding flexibility market pilots and their issues is given in [144]. As flexibility markets become more common, quantitative analysis on these markets can be interesting. Moreover, as discussed in Section 3.4, new market platforms like Energy Trading Platform Amsterdam might improve the liquidity of the intra-day market in the coming years. Depending on the developments, it might be useful to explore the opportunities in this market for the aggregator.

Another topic worth studying is the aggregator's business models in the industrial sector. Although the business models themselves do not alter in the industrial sector, how the aggregator implements these business models might change, as the characteristics of the assets in the industrial sector differ from the residential and service sectors. For example, assets in industrial sector, such as electric arc furnaces, cement milling and aluminum electrolysis, typically have large electricity demand, which may make them more suitable for *providing power reserves*, because of minimum bid size requirement. On the other hand, [238] states that industrial assets are more critical since interrupting them may result in a major loss in the production process of industrial products like steel, wood, paper. An analysis of aggregator's business models in the industrial sector, as well as a comparison with residential and service sectors is therefore recommended.

Also, this thesis studies a single aggregator and their interaction with the electricity markets and the consumers. As aggregators become more common in the power system, multiple aggregators might be available for consumers to choose. This might cause competition between these multiple aggregators. This competition may impact financial rewards aggregators offer to their consumers. Hence, the pricing taking into account competition between aggregators is worth studying.

7.4.2. Considerations for aggregators and policymakers

A business model of an aggregator needs to be operationally and economically feasible to be implemented. We conclude that it is challenging to achieve operational and economic feasibility of the aggregator's business models simultaneously for multiple actors. For instance, despite being able to decrease the system imbalance, internal balancing is found to be economically infeasible for the aggregator. It is therefore recommended to the TSO and policymakers to explore subsidy options as a financial means to get aggregators interested in implementing internal balancing.

Furthermore, we recommend aggregators not to consider business models involving consumers' appliances. The shifting time of these appliances is limited in order not to create discomfort to the consumers, which results in limited economic feasibility for both aggregators and their consumers. Furthermore, they are less suited to provide power reserves, which in particular holds for semi-flexible appliances, due to their characteristics, and the high dependence of their use on consumers' behavior.

Individual BESSs with multiple business models (*trading flexibility in the DAM* and *providing power reserves*) yields the most promising result to achieve operational and economic feasibility. The aggregator is capable of pooling a large number of BESSs to deliver FCR. Nevertheless, this requires the aggregator to invest in the consumers' BESS for the time being, even though giving a large amount of money may not be favored by aggregators. This can be resolved by splitting the investment cost with the consumers, or leasing the BESS to the consumers. Also, the investment cost for BESSs is expected to decline in the future, which can make BESSs more attractive for consumers to invest in.

We expect the other power reserves also to generate high profits for aggregators. Hence, overall it is recommended that aggregators focus on business models involving power reserves. However, aggregators' participation in power reserves also brings certain difficulties. For example, aggregators need to operate pooled BESSs to ensure that BESSs are available to deliver power reserves during the entire contract period. This becomes more troublesome when business models are combined. Also, the aggregator needs forecasts of the electricity demand of consumers and their renewable energy generation to decide about the power reserves capacity they should offer and the operation of the BESSs. Thus, aggregators require advanced algorithms to operate pooled BESSs, as well as advanced forecast models, in order not to fail to deliver power reserves. More focus on developing or acquiring such algorithms and models is recommended to aggregators.

Besides, TSOs can stimulate aggregators' participation in power reserves by changing regulations, such as shortening the time between the auction and activation of power reserves, increasing the auction frequency, and enabling asymmetric bids. Note that altering these regulations can also make appliances more suitable for *providing power reserves*. The downside of these changes is that TSOs may be less able to rely on power reserves to keep the system balance, and that they may put TSOs in a riskier position.

7.4.3. Final remarks

With the power system transitioning from fossil fuels to RES, this thesis provides a view of how aggregators' business models can facilitate flexibility from the demand-side. It shows that it is challenging to accomplish both operational and economic feasibility of these business models. The thesis also studies when and under which conditions they can be achieved. Aggregators are relatively new actors in the power system. Consequently, their business models, their contribution to the energy transition, and their interactions with other market actors, are very active fields of research. Although much work still needs to be done, this thesis has hopefully contributed to understanding how aggregators' business models can help integrating RES in the power system, and by that can support the energy transition.

A

Business model canvas framework

This appendix contains more details on the business model canvas framework described in Chapter 3. The framework consists of four areas of business, and nine blocks within areas: customer (customer segments, customer relationships, channels), offer (value proposition), infrastructure (key activities, key resources, key partners), and financial viability (cost structure, revenue stream). These blocks are described as follows:

- *Customer segments:* Different groups of people or organizations the company targets and creates value for.
- *Channels:* How the company reaches its customer segments.
- *Customer relationships:* How the company establishes relationships with its customer segments.
- *Value proposition:* The value the company creates for its customers through the services/products it offers.
- *Key activities:* Activities required for a business model.
- *Key resources:* Resources required for a business model.
- *Key partners:* Partnerships formed in a business model and their purposes.
- *Cost structure:* Costs incurred while implementing a business model.
- *Revenue streams:* Revenue generated while implementing a business model.

These blocks are displayed on the canvas framework in Figure A.1.

A

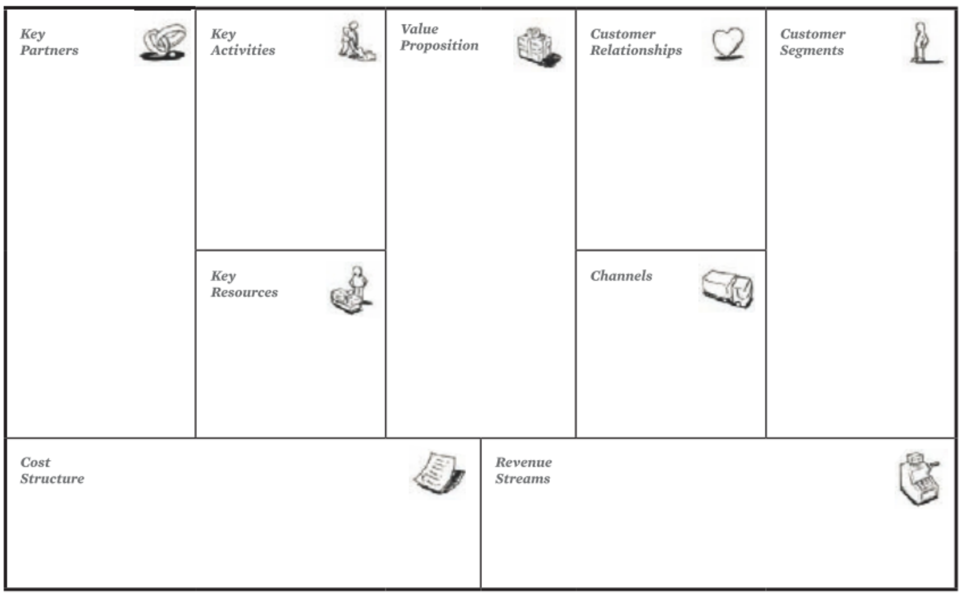

Figure A.1: Business model canvas framework by [66].

B

Chapter 4 appendix

B.1. Nomenclature

T Total number of Program Time Units (PTU)

t_{shift} Maximum shifting time [PTU]

$P^{nf}_{t'}$ Total electricity demand by non-flexible appliances for PTU t' where $t' \in \{1, 2, \ldots, T\}$ [kWh]

$P^{f}_{t,t'}$ Total electricity demand by flexible appliances at run t for PTU t' where $t, t' \in \{1, 2, \ldots, T\}$ [kWh]

$P^{sf}_{t'}$ Total electricity demand by semi-flexible appliances for PTU $t' \in \{1, 2, \ldots, T\}$ [kWh]

$P^{da}_{t'}$ Planned electricity exchange (purchasing/selling) with the power grid one day ahead, for PTU $t' \in \{1, 2, \ldots, T\}$ [kWh]

$P^{PVfor,da}_{t'}$ Day-ahead solar generation forecast for PTU $t' \in \{1, 2, \ldots, T\}$ [kWh]

$P^{PVfor,upd}_{t,t'}$ Updated solar generation forecast received at run t for PTU t' where $t, t' \in \{1, 2, \ldots, T\}$ [kWh]

$P^{final,f}_{t'}$ Scheduled electricity demand of flexible appliances for PTU t', at the end of the model where $t' \in \{1, 2, \ldots, T\}$ [kWh]

$P^{act}_{t,t'}$ Actual electricity exchange (purchasing/selling) with the power grid at run t for PTU t' where $t, t' \in \{1, 2, \ldots, T\}$ [kWh]

$P^{sch,f}_{t,t''}$ Scheduled electricity demand of flexible appliances at run t for PTU t'' where $t, t'' \in \{1, 2, \ldots, T\}$ [kWh]

$P^{shifted}_{t,t',t''}$ At run t, part of the original appliance from PTU t' shifted to PTU t'' where t, t' and $t'' \in \{1, 2, \ldots, T\}$ [kWh]

B

$\lambda^{+}_{t'}$ Positive imbalance price for PTU $t' \in \{1, 2, \ldots, T\}$ [€/kWh]

$\lambda^{-}_{t'}$ Negative imbalance price for PTU $t' \in \{1, 2, \ldots, T\}$ [€/kWh]

M A very large number

$y_{t'}$ Binary variable for PTU $t' \in \{1, 2, \ldots, T\}$

$\Delta^{+}_{t,t'}$ Positive imbalances at run t for PTU t' where $t, t' \in \{1, 2, \ldots, T\}$ [kWh]

$\Delta^{-}_{t,t'}$ Negative imbalances at run t for PTU t' where $t, t' \in \{1, 2, \ldots, T\}$ [kWh]

$\Delta_{t,t'}$ Imbalances at run t for PTU t' where $t, t' \in \{1, 2, \ldots, T\}$ [kWh]

Δ^{tot} Total amount of imbalances for a day [kWh]

C^{tot}_{imb} Total imbalance cost for a day [€]

B.2. Simplified example of MPC model

The use of Equations (4.5), (4.6), (4.7) from Chapter 4 is demonstrated with a simplified example in Figure B.1. In this example, we assume that there are only 4 PTUs, and t_{shift} is 1 PTU. Besides, in Figure B.1, we present only the run 1 of MPC model ($t = 1$).

Figure B.1(a) shows the original flexible appliance demand for the run 1 ($P^{f}_{\mathbf{1},t'}$). The blue lines in this figure represent the original flexible appliance demand. In Figure B.1(b), the positive and negative imbalances without DR are given. In the MPC model, the flexible appliances are shifted to minimize the sum of positive and negative imbalances according to the constraint in Equation (4.5) and the objective function in Equation (4.1). As a result of this MPC run, the scheduled demand of the flexible appliances ($P^{sch,f}_{1,t''}$) is computed based on Equation (4.6) and presented in Figure B.1(c). The red lines in this figure denote the flexible appliance which is shifted to another PTU. As a result of this MPC run, the positive and negative imbalances ($\Delta^{+}_{1,t'}$, $\Delta^{-}_{1,t'}$) are reduced and given in Figure B.1(e).

After the MPC run, the first PTU is implemented. However, before the next run, the updated flexible appliance demand for the run 2 ($P^{f}_{\mathbf{2},t'}$) is determined in accordance with Equation (4.7) and depicted in Figure B.1(d). The appliance, that is shifted from PTU $t' = 2$ to PTU $t' = 1$, is subtracted from the initial flexible appliance demand since the first PTU is already implemented. In a similar manner, the appliance, that is shifted from the PTU $t' = 1$ to PTU $t' = 2$ needs to remain for the second run as they are not served in the first PTU. Besides, for PTUs $t' = 3$ and $t' = 4$, the flexible appliance demand remain the same since these PTUs are not implemented.

Note that Equations (4.5), (4.6), (4.7) are formulated in such a way that once a flexible appliance, which is originally to be served at PTU t', is shifted from one PTU to another one, the same appliance cannot be shifted further than the $t' + t_{shift}$. Considering the same example as in Figure B.1, the parts of the appliance, which are shifted from the PTU $t' = 1$ to the PTU $t' = 2$ as a result of the first run, have to be served at the PTU $t' = 2$ in the second run. These parts cannot be shifted further than the PTU $t' = 2$. However, the flexible appliance which is initially to be served at the PTU $t' = 2$ can be shifted to the PTU $t' = 3$.

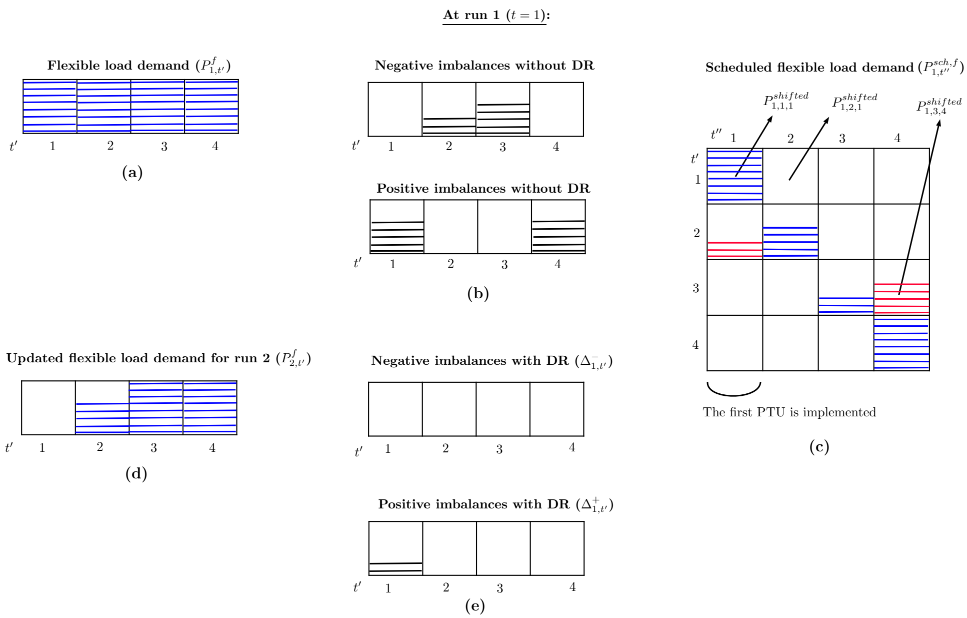

Figure B.1: The use of Equations (4.5), (4.6), (4.7) in a simplified example.

C

Chapter 5 nomenclature

$P_{d,t}^{nf}$ Total electricity demand by non-flexible appliances at day d and hour t [kWh]

$P_{d,t}^{sf}$ Total electricity demand by semi-flexible appliances at day d and hour t [kWh]

$P_{d,t}^{f}$ Total electricity demand by flexible appliances at day d and hour t [kWh]

$P_{d,t}^{PV}$ Solar generation at day d and hour t [kWh]

$P_{d,t}^{buy}$ Electricity purchased at the day-ahead market at day d and hour t [kWh]

$P_{d,t}^{sell}$ Electricity sold at the day-ahead market at day d and hour t [kWh]

$P_{d,t}^{scheduled}$ Scheduled electricity demand of flexible appliances at day d and hour t [kWh]

$P_{d,t',t}^{shifted}$ Appliances shifted at day d from time t' to t [kWh]

$P_{\max}^{buy}$ Maximum power that can be purchased from the grid [kW]

$P_{\max}^{sell}$ Maximum power that can be sold to the grid [kW]

T Total number of hours in a day

D Total number of days in a month

t_{shift} Maximum shifting time [h]

λ^{ret}	Retail electricity price for buying electricity [€/kWh]
λ^{feedin}	Feed-in electricity price for selling electricity [€/kWh]
$\lambda^{da}_{d,t}$	Day-ahead electricity price at day d and hour t [€/kWh]
C^{da}_{agg}	Aggregator's cost from the day-ahead market [€]
C^{dac}_{agg}	Aggregator's cost from the day-ahead market and from the consumers [€]
C^{el}_{cons}	Consumers' electricity cost [€]
$y_{d,t}$	Binary variable indicating whether electricity is purchased/sold at day d and hour t

D

Chapter 6 appendix

D.1. FCR power delivery

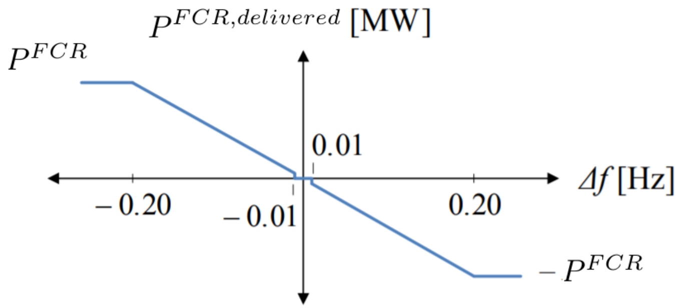

Figure D.1: FCR power delivery based on the frequency deviation, adapted from [239].

D.2. Nomenclature

T Total number of Program Time Units (PTUs)

N Total number of consumers

$P_{t,n}^{demand}$ Electricity demand of consumer n at PTU t [kW]

$P_{t,n}^{PV}$ Solar power generation of consumer n at PTU t [kW]

$P_{t,n}^{buy}$ Electricity purchased by consumer n at PTU t [kW]

$P_{t,n}^{sell}$ Electricity sold by consumer n at PTU t [kW]

$P_{t,n}^{char,ind}$ Electricity charged to the individual BESS by consumer n at PTU t [kW]

$P_{t,n}^{dis,ind}$ Electricity discharged from the individual BESS by consumer n at PTU t [kW]

$P_{t}^{char,shar}$ Electricity charged to the shared BESS at PTU t [kW]

$P_{t}^{dis,shar}$ Electricity discharged from the shared BESS at PTU t [kW]

$E_{t,n}^{bat,ind}$ Energy stored in the individual BESS by consumer n at PTU t [kWh]

$E_{t}^{bat,shar}$ Energy stored in the shared BESS at PTU t [kWh]

$P_{w,n}^{FCR}$ FCR power capacity from the BESS of consumer n at week w [kW]

$E_{w,n}^{FCR}$ FCR energy capacity from the BESS of consumer n at week w [kWh]

$s_{w,n}^{FCR}$ Share of BESS reserved for FCR from consumer n at week w

P_{w}^{FCR} Total FCR power capacity at week w [kW]

E_{w}^{FCR} Total FCR energy capacity at week w [kW]

$P_{\max}^{ind}$ Maximum electricity exchange with the grid [kW]

$P_{\max}^{shar}$ Maximum electricity exchange with the grid [kW]

$P_{\max}^{ind}$ Individual BESS charging/ discharging max power [kW]

$P_{\max}^{shar}$ Shared BESS charging/ discharging max power [kW]

$E_{\max}^{bat,ind}$ Individual BESS maximum energy capacity [kWh]

$E_{\max}^{bat,shar}$ Shared BESS maximum energy capacity [kWh]

η Efficiency of BESS charging/discharging

lf Lifetime expectancy of BESS [years]

Δf Frequency deviation from 50 Hz [Hz]

δ Time step duration

λ_{t}^{ret} Retail price consumer pays for buying electricity at PTU t [€/kWh]

λ_{t}^{feedin} Feed-in price consumer receives for selling electricity at PTU t [€/kWh]

λ_{w}^{cap} Capacity fee consumer receives for offering FCR capacity to the aggregator at week w [€/kWh]

λ_{w}^{FCR} FCR price the aggregator receives from the auctions at week w [€/kW]

P_{exc}^{tot}	Total electricity exchanged with the grid between PTUs 41 and 60 [kW]
C_{cons}^{oper}	Consumers' operational cost [€]
C_{cons}^{tot}	Consumers' total cost [€]
C_{agg}^{tot}	Aggregator's total cost [€]
$C^{inv,ind}$	Investment cost of the individual BESS [€]
$C^{inv,shar}$	Investment cost of the shared BESS [€]
$y_{t,n}$	Binary variable for charging/discharging, 1 for charging, otherwise 0, for consumer n at PTU t
$u_{t,n}$	Binary variable for selling/buying, 1 for buying, otherwise 0, for consumer n at PTU t
y_t	Binary variable for charging/discharging, 1 for charging, otherwise 0, at PTU t
u_t	Binary variable for selling/buying, 1 for buying, otherwise 0, at PTU t

E

Acronyms

$aFRR$	automatic Frequency Restoration Reserve
$BESS$	Battery energy storage system
BRP	Balance responsible party
BSP	Balance service provider
CHP	Combined heat and power
CPP	Critical peak pricing
CWE	Central Western European
DAM	Day-ahead market
DR	Demand response
DSM	Demand side management
DSO	Distribution system operator
EU	European Union
$EPEX$	European Power Exchange
ESS	Energy storage system
$ETPA$	Energy Trading Platform Amsterdam
EV	Electric vehicle

EWH	Electric water heater
FCR	Frequency Containment Reserve
FiT	Feed-in tariff
FR	Financial reward mechanism
$HEMS$	Home energy management system
ICT	Information and communication technologies
IDM	Intra-day market
$mFRR$	manual Frequency Restoration Reserve
MPC	Model predictive control
PTU	Program time unit
RES	Renewable energy sources
RTP	Real time pricing
TCL	Thermostatically controlled load
TOE	Time of export
TOU	Time of use
TSO	Transmission system operator

F

Definitions

This appendix aims to clarify certain concepts discussed throughout the thesis.

- **Consumers:** occupants/electricity users in residential and service sectors are defined as consumers. These consumers might be able to produce their own electricity via RES, which is called prosumers [240]. The term prosumers is derived by combining the word producer with the word consumer. It refers to consumers possessing more active role by producing their own electricity. The term prosumers is not used in this thesis, despite the fact that consumers may be able to generate their own electricity.

- **Residential Sector:** refers to a group of households.

- **Service Sector:** includes commercial, educational and governmental buildings, such as offices, shopping malls, schools, restaurants, hotels [195, 241, 242]. However, it excludes agriculture and transportation sectors, street lighting, and waterworks.

- **Aggregator:** a mediator between consumers and electricity markets, as well as actors in these electricity markets, such as Transmission System Operators (TSOs) and Distribution System Operators. They are able to use and operate consumers' assets in order to implement their business models in the electricity markets. By this way, they aim to make money, and provide flexibility to the power system.

- **Electricity demand and electricity consumption:** Electricity demand and electricity consumption are closely related to the consumers' assets. In the field of power system, they are often adopted as interchangeable, and also used as such in this thesis. They refer to the amount of electrical energy used within a given time window by a single consumer, or a set of consumers.

- **Demand response and demand side management:** Demand response (DR) is change in the electricity demand of consumers in reaction to price signals or to specific requests, with the aims of providing flexibility to the power system. The concept of Demand Side Management (DSM) includes both DR and energy efficiency [243]. Energy efficiency aims to use less energy, while still providing the same amount of service or level of comfort [244]. Since energy efficiency is not the focus of this thesis, solely DR is considered, instead of DSM.
- **Program Time Unit:** time unit in the balancing market, which is equal to 15 minutes.
- **Individual imbalance:** difference between the planned energy exchange with the grid on the e-program of a Balance Responsible Party (BRP), and their actual energy exchange with the grid in real-time. Given per Program Time Unit (PTU) in imbalance settlement. The sum of individual imbalances from all BRPs is equal to the system imbalance.
- **Imbalance cost:** cost faced by a BRP resulting from imbalance settlement. Also given per PTU.
- **Imbalance price:** price with which individual imbalances of BRPs are settled.
- **System imbalance:** in imbalance settlement, net difference between total electricity generation and demand per PTU.
- **Power reserve:** activated by TSOs in case of a system imbalance.
- **Upward reserve:** net increase of electricity in the power system by an increase in generation or a decrease in demand.
- **Downward reserve:** net decrease of electricity in the power system by a decrease in generation or an increase in demand.

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Özge Okur was born on the 8th of November 1991 in Ankara, Turkey. After studying Electrical and Electronics Engineering for her Bachelor's degree, Özge has obtained a Master of Science degree in Electrical Engineering from Aalto University in Finland. She graduated with cum laude. During her studies, she became interested in sustainable and renewable energy sources. She completed her Master's thesis on 'Energy Optimization for Nearly Zero Energy Buildings with Electric Vehicles'. While working on her thesis, she was contributing to a research project at Aalto University.

Further motivated by the challenges caused by the integration of renewable energy sources in current power systems, soon after finishing her Master's degree, she started as a PhD candidate at the Energy & Industry section at the Faculty of Technology, Policy and Management at Delft University of Technology in 2016. Her PhD was part of the multi-disciplinary program Smart Energy Systems in the Built Environment by NWO. Throughout her PhD research, she presented her work at several international conferences, as well as for various companies involved in her project. She also gave a lecture in the course Engineering optimization and integrating renewables in electricity markets. In addition, she assisted in several courses on optimization, renewable energy systems, agent-based modeling, and supervised master thesis projects.

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