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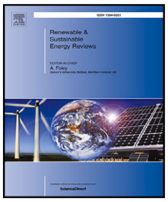

Aggregator's business models in residential and service sectors: A review of operational and financial aspects

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ABSTRACT

Flexibility coming from consumers in residential and service sectors has received significant attention to deal with uncertainty and variability of renewable energy sources. Since these consumers are too small individually to participate in the electricity markets, their assets can be pooled by an aggregator. The aggregator can implement business models by trading flexibility obtained from these consumers' assets in different electricity markets. However, the aggregator and the consumers are only motivated to implement a business model, if it is economically feasible. The economic feasibility of a business model depends on (1) financial aspects: how much profit the aggregator makes, and how much money the consumers save, and (2) operational aspects: how the consumers' assets are operated to increase the financial aspects. This paper aims to provide insights in these operational and financial aspects of the aggregator's business models in residential and service sectors. For this purpose, a literature review is conducted, and a framework is presented to analyze the selected papers on these operational and financial aspects. Based on this analysis, different strategies for the aggregator to implement business models are determined. Moreover, knowledge gaps are identified and several recommendations for future research are provided.

1. Introduction

The reliable operation of the power system relies on a continuous balance between electricity supply and demand. A difference between electricity supply and demand leads to a deviation from the nominal system frequency, and threatens the power system security [1]. However, maintaining this balance becomes more challenging as the penetration of renewable energy sources (RES), such as wind and solar, increases. RES are fundamentally different in comparison to conventional electricity generation, due to their variability and uncertainty. Variability of RES implies that their generation fluctuates over time, and cannot be dispatched, while uncertainty relates to the difficulty to forecast RES generation with high accuracy [2].

The growing RES penetration requires the power system to cope with this variability and uncertainty by means of flexibility, i.e. the ability of a power system to adapt its operation in response to variability or uncertainty, by modifying electricity consumption or generation [3]. Flexibility can be obtained by the following means: dispatchable power plants, demand response, energy storage, and interconnection [4,5]. This paper 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 demand response and energy storage. These flexibility means are obtained by changing the electricity consumption and generation of consumers' assets, and have attracted growing attention both in academia, and in industry [6,7]. *Demand response* (DR) refers to the changes in the consumption of consumers in response to external factors such as electricity prices [8]. *Energy storage* allows to shift electricity consumption and generation in time.

Studies related to the demand side of the power system involve electricity demand in three different sectors: residential (households), service (offices, shops, schools, etc.) and industrial [9–11]. Between 2000 and 2014 in the European Union, 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% [12]. Therefore, this paper chooses to study flexibility from the demand side in the residential and service sectors in this paper.

Flexibility from the demand side is traded in electricity markets. However, the electricity consumption and generation of individual residential and service sectors' consumers are too small to participate in these electricity markets, and to contribute substantially to flexibility. To overcome this, these consumers' assets can be pooled by aggregators. *Aggregators* can trade flexibility obtained from their

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List of abbreviations

RES	Renewable energy sources
DR	Demand response
BESS	Battery energy storage system
EV	Electric vehicle
TCL	Thermostatically controlled load
DAM	Day-ahead market
PTU	Program time unit
TSO	Transmission system operator
DSO	Distribution system operator
BRP	Balance responsible party
FCR	Frequency Containment Reserve
aFRR	automatic Frequency Restoration Reserve
mFRR	manual Frequency Restoration Reserve
CWE	Central Western European
TOU	Time of use tariff
CPP	Critical peak pricing tariff
RTP	Real time pricing tariff
MPC	Model predictive control

consumers' assets by participating in various electricity markets on behalf of them. They have gained significant attention to accomplish flexibility from the demand side, and are relatively new actors in the power system [13].

The aggregator can implement business models by trading flexibility from their consumers' assets in different electricity markets. A business model is "model of the way in which a company creates and delivers value so as to generate revenue and achieve a sustainable competitive position" [14]. Therefore, the aggregator aims to make profit by implementing their business models. However, the consumers involved should also benefit from these business models to be willing to cooperate with the aggregator. In other words, the aggregator and the consumers are only interested in implementing a business model, if it is *economically feasible*. The economic feasibility of a business model of the aggregator is dependent on (1) financial aspects: how much profit the aggregator makes, and how much money the consumers earn, and (2) operational aspects: how the consumers' assets are operated to increase the financial aspects.

In the literature, in [15] a critical review of the value of aggregators is carried out to determine their role in the power system under different technological and regulatory scenarios. In addition, a qualitative research approach is proposed in [16] that identifies barriers and opportunities to enable flexibility through aggregators. Yet, the aggregator's business models, as well as their operational and financial aspects, have not received sufficient attention. Therefore, this paper aims to provide insights on the operational and financial aspects of the aggregator's business models in residential and service sectors. For this purpose, a literature review is conducted on this subject. After that, a framework is proposed to analyze the selected papers in a structured way. Advantages of applying this framework are twofold: (1) different strategies the aggregator can implement a business model can be defined, and (2) knowledge gaps related to this subject that are worth studying can be identified. By this way, economic feasibility of aggregator's business models can be enhanced. The insights gained from this paper are valuable for aggregators, researchers, and policy makers.

The remainder of this paper is organized as follows. Section 2 provides an overview of consumers' assets in the aggregator's portfolio. Aggregator's business models and the framework used in the analysis of business models are introduced in Section 3. In Section 4, the business models are analyzed using the framework. The results and knowledge gaps are presented in Section 5. Finally, conclusions are drawn in Section 6.

2. Aggregator in residential and service sectors

Aggregators are considered essential in the power system since (1) they can provide the power system with flexibility obtained from the consumers, (2) they can represent the consumers as one entity to the actors in electricity markets, and by this way can create market power for the consumers [17], (3) they can help the consumers earn money by offering them financial rewards. Some examples of aggregators and their projects from European countries are outlined in [18].

2.1. *Aggregator's roles*

Different actors in the power system can become aggregators, causing aggregators to have different *roles*. Existing actors in the power system, such as suppliers, and Balance Responsible Parties (BRPs), can become an aggregator. In addition, an independent actor, not associated with a supplier or BRP, can also become an aggregator [19]. Becoming an aggregator means that these actors take up a new function, in addition to their existing roles. For instance, suppliers are normally responsible for purchasing and selling electricity for consumers. Yet, when they become aggregators, they can also trade flexibility in the electricity markets. It should be noted that Distribution System Operators (DSOs) are also discussed to become an aggregator. Nonetheless, based on surveys among European stakeholders in the electricity markets, DSOs are considered least suitable to become an aggregator [20], since they are heavily regulated. More information concerning aggregator's roles can be found in [21].

2.2. *Aggregator's portfolio in residential and service sectors*

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

2.2.1. *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' preference to participate in DR depends to a large extent on the inconvenience caused by DR: discomfort associated with changes in consumers' electricity consumption by DR [22]. 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 [23–25], 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.

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

2.2.2. Assets for energy storage

Among energy storage technologies, highly compact features of *battery energy storage systems* (BESS) enable them to be better suited for volume-limited applications, such as at the residential and service sectors. Within BESS technologies, lithium-ion batteries are widely studied in the literature, owing to their high energy density and energy efficiency [26]. A comprehensive overview of the energy storage technologies and their potential applications is presented in [27]. EVs also show similar characteristics to BESS, when they provide vehicle-to-grid power [28].

2.2.3. Generation units

In addition to the appliances and BESS, the consumers might also possess RES as generation units. Since the consumers are able to produce their own electricity in this case, it might influence their electricity consumption. RES might have a greater impact on flexibility especially when coupled with BESS since this combination enables RES generation to be stored in the BESS and to be used at a later moment [29].

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

3.1. 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, which are out of the scope of this paper, and hence are not explained further. 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, whereas the third market is operated by the Transmission System Operator (TSO).

In the *day-ahead market* (DAM), market participants (like the aggregators) submit their hourly buying and selling bids, for the next day [30]. 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 [31]. 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-programmes) to the TSO, one for each Program Time Unit (PTU) of the next day, which is equal to 15 min in the Netherlands [32]. These e-programmes 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 [33].

In between the submission of e-programmes and the actual delivery of electricity, BRPs are able to update their e-programmes, 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 min before the contract starts [34].

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-programme, and the actual energy exchange with the grid in real-time [35]. Negative and positive individual imbalances occur when BRPs have a shortage, or a surplus, respectively. BRPs are financially responsible for their individual imbalances [36], which implies that these imbalances are settled by means of imbalance prices. The negative imbalance price is paid for negative imbalances, and the positive imbalance price is earned with positive imbalances [37]. The net sum of all individual imbalance of each BRP is called the *system imbalance*.

Table 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

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 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 [38]. 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 [39].

- **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.
- **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 [40].

The regulatory characteristics of each power reserve in the Netherlands are summarized in Table 1 [16,40–43]. The definitions of the regulatory characteristics can be seen in Appendix. A more comprehensive analysis of power reserves in the Netherlands can be found in [16].

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 [44].

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 will be penalized by the TSO.

3.2. Aggregator's business models

The aggregator implements business models by trading flexibility from their consumers' assets in different electricity markets. In this section, business models of the aggregator are identified, based on the existing literature. The 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 [45].
- **Trading flexibility in intra-day market:** The aggregator can update their e-programme in the intra-day market, based on recent information close to real-time [46,47].
- **Providing power reserves:** The aggregator is able to provide power reserves 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 [37]).
- **Managing congestion:** The aggregator can offer flexibility to cope with congestion issues in the grid.

To be able to implement business models using the consumers' assets, the aggregator needs to offer financial rewards to the consumers. These financial rewards are included in the contracts between the aggregator and the consumers. The other terms of these contracts, such as establishment of time intervals, termination fees, start and end dates, access to consumer data, are presented in [48].

Note that aggregators with all the roles explained in Section 2.1, can implement these business models. Yet, they might face different challenges while implementing business models, based on their roles. For example, depending on their roles, aggregators might require different contracts with the other actors. Challenges faced by aggregators with different roles while implementing business models are not discussed further in this paper as it is not main focus of this paper. However, these challenges are identified and described thoroughly in [21].

3.3. The proposed framework

One of the widely used frameworks to analyze business models is the business model canvas framework [49]. 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). This framework is employed in the literature to support energy transition [7,50,51].

In business model canvas framework, even though the financial 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. Therefore, a new framework is required to more explicitly integrate the operational aspects, and to study the operational and financial aspects simultaneously. In order to analyze the operational and financial aspects of the aggregator's business models, the framework depicted in Fig. 1 is proposed.

The proposed framework has four main aspects: Market operational, Consumer operational, Market financial, and Consumer financial. The Market operational and Consumer operational 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 operational involves the following four elements:

- **Which** assets can be operated in the business model.
- **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.

The Consumer operational aspect heavily depends on the regulations of the electricity market involved, i.e., market rules, in particular the elements 'Who' and 'Which'. How regulations influence the operation of the business models is discussed in the next sections in more detail while applying the framework on business models. Market operational represents how the operation of the assets from Consumer operational is translated bids on the electricity markets. Note that a dashed line is given for Market operational since bids on the markets are not present for every business model.

The Market financial and Consumer financial aspects represent the financial relation between the aggregator and the electricity markets, and the financial relation between the aggregator and the consumer, respectively. Market financial relates to how the aggregator earns money from the electricity market. Consumer financial addresses what kind of financial reward the consumers earn for giving the aggregator permission to use their assets. Note that in this paper consumers are assumed to be financially motivated, although different consumer motivations are also studied in literature [52].

In terms of information exchanged between the aggregator and the consumers in the framework, the aggregator acquires and processes data collected from the consumers' assets via Home Energy Management Systems (HEMS). HEMS is defined as the system that allows energy management services so as to access, monitor, and control consumers' assets [53]. In the Netherlands, almost 3 million households had a smart meter installed at the end of 2016 [54]. Furthermore, the aggregator can also send control signals to control the consumers' assets, if the aggregator operates these assets in the business model. The information exchanged between the aggregator and the electricity markets take place in the form of bids submitted by the aggregator.

Note that as mentioned previously, 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 HEMS, in order to obtain data from the consumers, and also to communicate control signals. Moreover, the privacy concerns of the consumers, due to having their data monitored, can be considered an important social aspect [55].

4. Application of the framework

Scientific papers and regulation documents on the aggregator's business models in the residential and service sectors are reviewed in this paper. For this purpose, three electronic databases (ScienceDirect, Google Scholar, Scopus) are searched 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.

After the literature review is carried out, the framework in Fig. 1 is applied to the selected papers to analyze the operational and financial aspects of the aggregator's business models in a structured way. Based on this analysis, different *strategies* the aggregator can implement a business model are identified. This analysis is discussed in this section, following the list of business models given in Section 3.2: trading flexibility in the DAM, trading flexibility in the intra-day market, providing power reserves, balancing portfolio internally, managing congestion.

It should be pointed out that the electricity market regulations in this paper are given for 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 the differences still exist, particularly for the power reserves [38]. Thus,

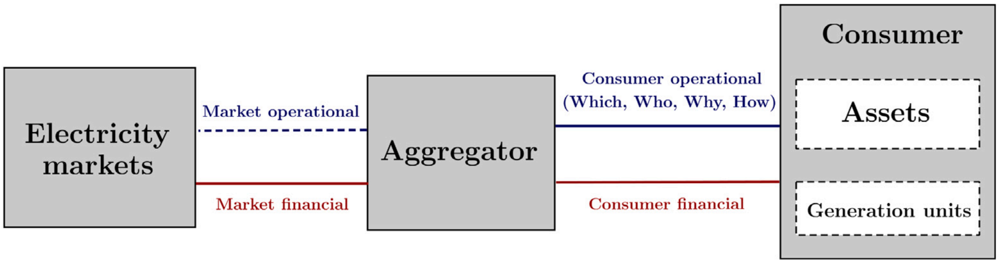

Fig. 1. The proposed framework used to analyze the operational and financial aspects of aggregator's business models.

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.

4.1. 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 financial*). The consumers get a financial reward to permit the aggregator to use their assets (*Consumer financial*). The operation of the assets is transformed to bids on the DAM (*Market operational*).

Three different strategies are identified for the operation of the consumers' assets to trade in the DAM (*Consumer operational*). Appliances, BESS 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 financial 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 [56].

In [57], 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 [58]. An algorithm to determine the operation of EVs is designed in [59], 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 [60]. In [61], 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 [62], while finding the optimal operation of BESS and thermal storage at the residential level. Moreover, a stochastic robust optimization is proposed for an aggregator with EVs in [63], 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 [64], and using of BESS and electric water heaters (EWHs) in [65]. Furthermore, a stochastic optimization model for an aggregator with EVs is given in [66], 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 [67] with a clustering-algorithm and a two-stage stochastic optimization. In [68], 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 financial in the framework. In [69], the aggregator uses flat-rate prices for buying and selling electricity for charging and discharging EVs. [70] 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 [71], 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 [72], the aggregator offers load curtailment and load shifting contracts to the consumers for curtailing and shifting their assets. In [73], time-varying rewards for utilizing BESS 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, [10] calculates the optimal flat-rate price to incentivize the consumers to cooperate with the aggregator, while minimizing the aggregator's DAM cost with appliances. A bilevel optimization is formulated in [74] 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 [75], 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. A game theoretic approach is used in [76] to determine the scheduling of appliances and EVs, while also taking into account consumers' objectives. DAM participation of an aggregator is studied using game theory in [77] to consider the costs of both the aggregator and the consumers.

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) [6]. TOU tariff specifies two or more periods in a day that indicate time periods when the system demand is higher (peak period) or lower (off-peak period), and give higher prices during peak periods. The prices are fixed for each day with TOU tariff. On the other hand, prices in RTP tariff vary for each day, and fluctuate continuously during the day, following the DAM prices. The consumers are generally notified of RTP tariff on a day-ahead or hour-ahead basis. Similar to TOU, in CPP tariff, higher prices are given during peak periods. Nonetheless, CPP is employed solely on a small number of days where considerably high demand is estimated [78]. The consumers are usually informed of these 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 [6,79,80].

However, it should be noted that time-varying tariffs necessitate active participation from the consumers, which might discourage them to engage in the business model. Studies on pricing show that many consumers have a preference for simple pricing tariffs, despite economic disadvantage [81,82]. For example, an online survey in the UK indicates that the consumers choose an operation automated, for instance by an aggregator, with a lower flat-rate tariff and override ability, over TOU and RTP tariff [83]. Similarly, RTP tariff is shown to be not attractive for the consumers, due to the complexity to react to fluctuating electricity prices [83,84], even though RTP tariff is found to be highly effective in reducing the peak demand [80].

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 can reduce the consumers' efforts for active participation.

This strategy is mostly studied with time-varying tariffs in the literature. The optimal schedule of residential appliances and BESS to minimize the consumers' cost is determined in [85], via an aggregator. TOU, CPP and RTP tariffs are incorporated in this paper. Both stochastic and robust optimization models are applied in [86], 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 [87], and for both appliances and BESS in [88].

In addition to time-varying tariffs, some papers also include extra payments. A two-stage optimization model is presented in [89]. 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 [90], an optimization model to schedule appliances is proposed with TOU tariff, as well as an extra time-varying payment, given by the aggregator.

4.2. Trading flexibility in intra-day market

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

Also, the operation of consumers' assets is almost the same in these two strategies (*Consumer operational*). Appliances, BESS 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 financial*). 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-programme, 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-programme in the intra-day market.

In [91], aggregator's optimal bidding to the DAM and the intra-day market is determined to minimize aggregator's DAM and imbalance costs, using BESS, 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 [92]. 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 reduced 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 [93] and [94], residential TCLs are employed to arbitrage intra-day market prices via load control. Moreover, a simulation-based study is presented in [95] to utilize DR from space heating of residential buildings in both DAM and intra-day market trading with lowest operational cost.

4.3. 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 financial)*. The operation decisions of the assets become bids in the FCR, aFRR or mFRR markets (*Market operational*). A financial reward is given to the consumers by the aggregator to get their permission to use their assets (*Consumer financial*). 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 operational*). Mostly EVs, BESS 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 [96], the optimal bid size on the Dutch FCR market is determined using an aggregator's portfolio of heat pumps. Net present value analysis of providing FCR with EVs is studied in [97]. Similarly, [98] focuses on how the future FCR prices might influence the profitability of BESS, also using net present value analysis. The potential economic benefits of providing aFRR with EVs for EV users are assessed in the Netherlands in [99] and [100]. A multi-objective optimization is proposed in [101] 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 [102–106]. The operation of EVs and TCLs to minimize the aggregator's DAM cost in the DAM and aFRR market is studied in [107] with Model Predictive Control (MPC), and in [108] with two-stage stochastic optimization. Moreover, EVs and a single BESS is combined by an aggregator to provide aFRR in [109]. Optimal operation in the DAM and aFRR markets is analyzed with BESS in [110], and HVAC systems in office buildings in [111]. 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 [112].

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 [113], and using a two-stage stochastic optimization with EVs and TCLs in [114]. A heuristic approach is studied in [115], where the aggregator's revenue from mFRR is maximized by operating TCLs.

Some papers also consider the financial relation between the aggregator and the consumers while providing power reserves. An optimal bidding strategy for the aggregator with EVs is proposed in [116], to maximize their profits from participating in the DAM and aFRR markets, while compensating the consumers for degradation. In [117], the aggregator's revenue is maximized when operating EVs in the DAM and aFRR market, while simultaneously considering the consumers' cost. In [118], the financial reward the aggregator offers to the consumers is calculated in an algorithm, to use their EVs in the DAM and aFRR market.

4.4. Balancing portfolio internally

The purpose of balancing portfolio internally, also known as internal balancing, is to minimize the aggregator's individual imbalance cost, by preventing deviations from the aggregator's e-programme, 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 [44] (*Market financial*). The consumers are rewarded to allow the aggregator to use their assets (*Consumer financial*). 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 operational*).

The consumers' assets are operated, to minimize the aggregator's imbalance costs (*Why*) by reducing their individual imbalances (*Consumer operational*). Since internal balancing takes place close to real-time (which could be as close as 15 min), 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, BESS and EVs (*Which*) are suited.

The impact of DR from flexible appliances to reduce the individual imbalances of an aggregator, caused by uncertain solar generation is assessed in [25]. In [119], 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-programme within their portfolio, in order to make profit from imbalance settlement [44,120]. This means that the aggregator creates intentional individual imbalance, contrary to internal balancing. This is out of scope of this paper. More information on passive balancing can be found in [38,44,46].

4.5. 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 DSOs and TSOs by reinforcing the grid, i.e., increasing the capacity of cables, transformers etc. [121], or by redispatching, i.e., altering the power plants' dispatch to resolve congestion [122]. However, these approaches are usually not economically efficient [123,124]. 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 operational, Consumer operational and Market financial, Consumer financial might differ. The only common element seems to be the consumers' assets; appliances, BESS and EVs (*Which*) are suitable for congestion management. The detailed descriptions of these strategies are given as follows:

Strategy 5A: Consumers operating to peak-shave. The aggregator offers time-varying financial rewards, to the consumers, such as TOU, CPP, or RTP. These tariffs are specifically designed to decrease the electricity consumption in peak demand periods, by giving higher prices in these periods. By following these prices, the consumers (*Who*) are able to decrease their peaks, by shifting their consumption to an off-peak period, or curtailing it (*Why*); this is also called peak-shaving [125]. The impacts of time-varying tariffs on peak-shaving are discussed, based on data from pilot projects conducted in [78]. The results show that CPP tariff with automatic curtailment is able to achieve a peak reduction of 30%, while TOU tariff can reach 5%. Due to time-varying tariffs, the operation of in this strategy resembles the operation in Strategy 1B of trading in the DAM. In fact, peak-shaving can be a consequence of the operation in that strategy.

Strategy 5B: Aggregators operating to peak-shave. The aggregator (*Who*) is given permission to control the consumers' assets via HEMS, and to operate them to peak-shave (*Why*). For example, scheduling of consumers' appliances and EVs is studied with RTP and extra time-varying payment in [126] to minimize consumers' cost, and to mitigate the peaks. However, these financial rewards can also be fixed payments. In [127], 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 in this strategy is similar to Strategy 1A or 1C of trading in the DAM.

Strategy 5C: Aggregators operating with market mechanisms with DSO. 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 markets and tariffs to help with congestion management (*Why*).

A market-based mechanism is proposed in [128], 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 [129], 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 [130–134], where the DSO predicts possible congestions for the next day and publishes prices prior to the clearing of the DAM to mitigate possible congestions. Furthermore, a new market structure, called Flexibility Clearing House (FLECH) is proposed in [135,136]. This market enables trading between the aggregator and the DSO, and runs parallel to the existing electricity markets.

A summary of the aggregator's business models and strategies, when analyzed by 'Consumer operational' aspect in the proposed framework is presented in Table 2. Note that 'How' element is not given in this table since more detailed analysis of this can be found in Tables 3–5.

5. Results and discussion

Tables 3–5 present an overview of the papers about the aggregator's business models in residential and service sectors, discussed in the previous section. Table 3 shows the papers that study the business model trading flexibility in the DAM. Table 4 shows the papers that study the business model trading flexibility in the intra-day market and providing power reserves. Table 5 presents the papers that study the business models internal balancing and managing congestion. The papers in these tables are analyzed using the proposed framework. Market financial, Consumer financial, and Consumer operational ('Which' consumers' assets are operated, 'Why' they are operated and 'How' they are operated) are given for each paper in these tables. Note that 'Who' element of Consumer operational 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. Similarly, Market operational is also not given since it is always present, except for balancing portfolio internally. Also, Strategy 1B is not presented in Table 3 since this strategy does not entail the aggregator's control over the consumers' assets; the operation of the assets entirely depends on the consumers' reaction

Table 2
A summary of the aggregator's business models, when analyzed by 'Consumer operational' in the proposed framework. Strategy 3 and 4 are written for providing power reserves and balancing portfolio, respectively, since there is only a single strategy determined for these business models.

	Strategy	Which	Who	Why
Trading in DAM	Strategy 1A	Semi-flexible appliances,	Aggregator	To minimize aggregator cost
	Strategy 1B	Flexible appliances,	Consumers	To minimize consumers' cost
	Strategy 1C	BESS, EVs	Aggregator	To minimize consumers' cost
Trading in IDM	Strategy 2A	Semi-flexible appliances, Flexible appliances, BESS, EVs	Aggregator	To minimize imbalance cost
	Strategy 2B			To arbitrage
Providing power reserves	Strategy 3	Flexible appliances, BESS, EVs	Aggregator	To maximize profit
Balancing portfolio	Strategy 4	Semi-flexible appliances, Flexible appliances, BESS, EVs	Aggregator	To minimize imbalance cost
Managing congestion	Strategy 5A	Semi-flexible appliances,	Aggregator	To peak-shave
	Strategy 5B	Flexible appliances,	Consumers	
	Strategy 5C	BESS, EVs	Aggregator	

Table 3
Papers from business model trading flexibility in the DAM, analyzed by the framework. 'y' indicates yes, and 'n' indicates no.

		Elec. market	Market financial	Consumer operational			Consumer financial	Paper
				Which	Why	How		
Trading flexibility in the DAM	Strategy 1A	DAM	y	Appliances	Max. agg's profit	LP	n	[57]
		DAM	y	EVs	Min. agg's cost	Bilevel opt.	n	[58]
		DAM	y	EVs	Min. agg's cost	Algorithm	n	[59]
		DAM	y	EVs	Min. agg's cost	Bilevel stoc. prog.	n	[60]
		DAM	y	EVs	Max. agg's profit	Robust opt.	n	[61]
		DAM	y	BESS & thermal storage	Min. agg's cost	Robust opt.	n	[62]
		DAM	y	EVs	Min. agg's cost	Stochastic robust opt.	n	[63]
		DAM & imbalance	y	EVs, TCLs & semi-flexible appliances	Min. agg's cost	Two-stage stoc. prog.	n	[64]
		DAM & imbalance	y	BESS & EWHs	Min. agg's cost	Two-stage stoc. prog.	n	[65]
		DAM & imbalance	y	EVs	Min. agg's cost	Stochastic prog.	n	[66]
		DAM & imbalance	y	EVs, TCLs & semi-flexible appliances	Min. agg's cost	Clustering algorithm & Two-stage stoc. prog.	n	[67]
		DAM & imbalance	y	EVs	Min. agg's cost	LP	n	[68]
		DAM & imbalance	y	EVs	Max. agg's profit	Two-stage stoc. prog.	Flat-rate	[69]
		DAM & imbalance	y	TCLs	Min. agg's cost	Two-stage stoc. prog.	y	[70]
		DAM	y	Electric space heating	Min. agg's cost	Optimization	Flat-rate + Extra payment	[71]
		DAM & imbalance	y	BESS	Max. agg's profit	Two-stage stoc. prog.	Flat-rate + Extra payment	[72]
		DAM	y	BESS & Appliances	Max. agg's profit	MILP	Time-varying reward	[73]
		DAM	y	Appliances	Min. agg's cost	MILP	Optimal flat-rate	[10]
		DAM & imbalance	y	EVs	Max. agg's profit	Bilevel stoc. prog.	Optimal flat-rate	[74]
		DAM & imbalance	y	Not specified	Max. agg's profit	Stochastic prog.	Optimal time-varying reward	[75]
	Strategy 1C	DAM	n	BESS & Appliances	Min. cons' cost	MILP	TOU, CPP, RTP	[85]
		DAM	n	Appliances	Min. cons' cost	Stochastic & robust opt.	RTP	[86]
		DAM	n	BESS & Appliances	Min. cons' cost	Algorithm	RTP	[88]
		DAM & imbalance	n	Storage heating	Min. cons' cost	Two LP models	RTP + fixed payment	[89]
		DAM	n	Appliances	Min. cons' cost	MILP	TOU + time-varying reward	[90]

to time-varying tariffs, as discussed in Section 4.1. The aggregator's business models and identified strategies are separated by horizontal lines.

Main observations and knowledge gaps identified as a result of this literature review are given in this section.

5.1. 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 the number of papers that study trading in intra-day market, and balancing portfolio internally is low. 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 [137–139]. In fact, it is indicated in [140] that the traded intra-day volumes are equal to 4% of the traded day-ahead volumes in 2017 in the Netherlands. This number is higher in the aggregated German/Austrian intra-day market, which is nearly 20% of the traded day-ahead volume.

It is discussed in the literature that the design of current intra-day market should be improved to deal with their low liquidity [141]. By this way, more market participants, like aggregators, can trade closer to real time. For instance, Energy Trading Platform Amsterdam (ETPA) is a trading platform, started in April 2016 in the Netherlands, in order to trade electricity in the short-term markets, focusing on the intra-day market [142]. New platforms and approaches, like ETPA, are expected to enhance the liquidity of the intra-day markets, which might lead to a new business model for aggregators.

5.2. 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, 15 min, 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

Table 4

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

		Elec. market	Market financial	Consumer operational			Consumer financial	Paper
				Which	Why	How		
Trading flexibility in IDM	Str. 2A	DAM & Intra-day	y	Appliances & BESS	Min. agg's cost	Probabilistic opt.	n	[91]
		DAM & Intra-day & aFRR	y	EVs	Min. agg's cost	Two-stage stoc. prog.	n	[92]
	Str. 2B	Intra-day	y	TCLs	Min. agg's cost	LP	n	[93]
		Intra-day	y	TCLs	Min. agg's imbalance cost	MPC	n	[94]
		DAM & Intra-day	y	Space heating	Min. agg's imbalance cost	MPC & Simulation	n	[95]
Providing power reserves		FCR	y	Heat pumps	Min. agg's cost	Simulation	n	[96]
		aFRR	n	EVs	Min. cons.' cost	Agent-based model	y	[100]
		aFRR	y	EVs	Max. agg's profit	Multi-objective opt.	n	[101]
		DAM & aFRR	y	EVs	Min. agg's cost	Optimization	n	[102],[103]
		DAM & aFRR	y	EVs	Max. agg's profit	Quadratic prog.	n	[104]
		DAM & aFRR	y	EVs	Max. agg's profit	Two-stage stoc. prog.	n	[106]
		DAM & aFRR	y	EVs & TCLs	Min. agg's cost	MPC	n	[107]
		DAM & aFRR	y	EVs & TCLs	Min. agg's cost	Two-stage stoc. prog.	n	[108]
		DAM & aFRR	y	EVs & single BESS	Max. agg's profit	Stochastic prog.	n	[109]
		DAM & aFRR	y	BESS	Max. agg's profit	Optimization	n	[110]
		DAM & aFRR	y	HVAC in offices	Min. agg's cost	MPC	n	[111]
		DAM & imbalance & aFRR	y	EVs	Min. agg's cost	Two-stage stoc. prog.	n	[112]
		DAM & mFRR	y	EVs	Min. agg's cost	Optimization	n	[113]
		DAM & imbalance & mFRR	y	EVs, TCLs & appliances	Min. agg's cost	Two-stage stoc. prog.	n	[114]
		mFRR	y	TCLs	Max. agg's profit	Heuristic approach	n	[115]
		DAM & aFRR	y	EVs	Max. agg's profit	Optimization	Degradation compensation	[116]
		DAM & aFRR	y	EVs	Max. agg's profit	Optimization	Flat-rate	[117]
		DAM & imbalance & aFRR	y	EVs	Min. agg's cost	Two-stage stoc. prog.	Optimal fixed reward	[118]

Table 5

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

		Elec. market	Market financial	Consumer operational			Consumer financial	Paper
				Which	Why	How		
Balancing internally		n	y	Flexible appliances	Min. agg's imbalances	MPC	n	[25]
		n	y	PHEVs	Min. agg's imbalances	Algorithm	n	[119]
Managing congestion	Str. 5A	DAM	y	Appliances	Min. agg's cost	MILP	RTP & time-varying reward	[126]
	Strategy 5C	DAM & DSO tariffs	y	EVs & heat pumps	Max. agg's profit	MILP	Flat-rate	[128]
		DAM & DSO tariffs	y	EVs	Min. agg's cost	LP	n	[129]
		DAM & DSO tariffs	y	Flexible appliances	Min. agg's cost	LP	n	[130]
		DSO tariffs	y	EVs	Min. agg's cost	LP	n	[131]

well as in other CWE countries. 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. This is also addressed in [143] with respect to temporal granularity of FCR. However, auction frequency of FCR is changed from weekly to daily auctions as of 1st of July 2019 [144]. More frequent auctions might facilitate more participation from the aggregator with consumers' assets, and might thus lead to a new business model for aggregators.

5.3. Financial relations

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

However, the assessment of economic feasibility of a business model needs to involve both financial relations: how much money the consumers earn from the aggregator (Consumer financial), and how much profit the aggregator makes (Market financial and Consumer financial). Not considering both financial 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 financial relations need to be incorporated when evaluating economic feasibility of a business model.

A few papers consider both financial relations, as presented in Tables 3–5. 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 [10,74,75,126]. Moreover, some papers employ game theoretic approaches to deal with financial relations between the aggregator and the consumers [76,77, 145,146]. 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. Yet, it should be noted having different objectives for the aggregator and the consumers might result in multiple equilibria.

5.4. 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 BESS. 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 [147], 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 [148].

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 for the aggregator's business model.

5.5. Consumers' operation to trade flexibility in the 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 [47], 25% of all trades in the intra-day market are carried out maximum 1:42 h before the start of the contract. Only 5% of all trades are carried out more than 15:00 h 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 [149]. 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 [83]. 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.

5.6. Benefit stacking for BESS

BESS can reserve its capacity to provide multiple business models, which is called benefit stacking [150]. Benefit stacking is considered essential to increase the financial attractiveness of BESS [151,152]. Although benefit stacking appears to be financially attractive, it is difficult to satisfy technical and regulatory constraints while controlling BESS to provide multiple business models. A couple of papers study the operation of BESS when combined with FCR or aFRR [153–155]. Yet, benefit stacking for BESS seems to be not studied in detail in the literature, although combining multiple business models is well considered for EVs, such as [102–104]. This may lead to new opportunities for business models for the aggregator. It is also interesting to assess which combinations of business models for BESS can result in a higher profit for the aggregator.

6. Conclusion and further research

This paper provides insights in operational and financial aspects of the aggregator's business models in residential and service sectors. A literature review is carried out, and a framework is presented to analyze the selected papers on operational and financial aspects. Based on this analysis, different strategies to implement these business models are determined. Moreover, several knowledge gaps are identified and the following are recommended for future research: (1) Considering new trading platforms and regulatory changes, business models involving intra-day market, internal balancing, and FCR need more attention. (2) Financial 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 designing the financial rewards aggregators offer to their consumers. (3) Business models involving BESS should be combined.

In a broader perspective, gaining insights in operational and financial 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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[2] More information regarding the non-delivery penalties for power reserves is given in [96].

Appendix

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

Minimum bid size: The minimum acceptable bid to participate in the auction.

Activation method: Whether the bids are activated automatically or manually by the TSO.

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. For FCR, only capacity reserves are procured in FCR auction, which then becomes a contract. 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 [42].

Symmetrical bid — capacity and energy: Whether or not, the bid should offer the same amount in both directions: upward and downward.

Auction frequency — capacity and energy: How frequently the auction is carried out.

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