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Adjustable Consumption Participating in the Electricity Markets

Benjamin Biegel   Lars Henrik Hansen   Jakob Stoustrup   Palle Andersen   Silas Harbo

Abstract— **We consider a player managing a portfolio of flexible demand-side devices and examine the requirements for such a player to become an active player in the Nordic electricity system. In particular, we examine the regulatory requirements that must be satisfied to perform spot price optimization and to participate in the regulating power market. To conceptualize these requirements, we estimate the costs per consumer for honoring the given requirements, both under the current regulations but also under the planned future regulations. Finally, we consider a specific case study where domestic appliances are aggregated and utilized for spot price optimization and to participate in the regulating power market. In this case study we examine in detail the implications of the given regulatory requirements for market participation in the Nordic system and compare this with estimates of the revenue that can be generated via market participation. The case study shows that the profit in the current system is very limited but that planned regulatory changes will make market participation significantly more attractive.**

I. Introduction

With an increasing focus on climate-related issues and rising fossil fuel prices, the penetration of renewable energy sources is likely to increase in the foreseeable future throughout the developed world. As the conventional power plants are outdone by renewables such as wind turbines and photovoltaics, the ability to provide balancing services in the classical sense disappears. One of the approaches to obtaining such balancing is the *smart grid* concept, where demand-side devices with flexible power consumption take part in the balancing effort. The basic idea is to let an *aggregator* manage and optimize a portfolio of flexible demand-side devices on behalf of the balancing responsible party (BRP) for this consumption. This allows the BRP to utilize the accumulated flexibility in the unbundled electricity markets on equal terms with conventional generators [1].

The topic of demand-side management has received much attention from a research perspective. In particular, optimization of flexible consumption has received much attention in Denmark due to the high penetration of wind. A few examples from Denmark are: optimization of domestic heat pumps [2], [3], supermarket cooling systems [4], [5], domestic refrigerators [6], [7], and electrical vehicles [8], [9].

B. Biegel, J. Stoustrup, and P. Andersen are with the Department of Electronic Systems, Automation and Control, Aalborg University, Denmark; e-mail: {bbi,jakob,pa}@es.aau.dk.

L. H. Hansen is with DONG Energy A/S (largest Danish power producer), Copenhagen, Denmark; e-mail: LARHA@dongenergy.dk.

S. Harbo is with the Danish Energy Association (Professional Organization for Danish Energy Companies), Copenhagen, Denmark; e-mail: SIH@danskenergi.dk.

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The focus of these existing works is to use the demand-side devices for power balancing by performing spot price optimization or providing ancillary services. These works and many more describe the revenue that can be generated via market participation but do not discuss the requirements for entering these markets. This is, however, a most relevant topic as these requirements must be honored before any revenue can be generated. Further, it will have a certain cost to enable each individual demand-side device to honor the requirements, which must be taken into consideration when developing such smart grid strategies.

In this work we examine the requirements for market participation in the Nordic system based on the current regulations and the planned future regulations. Further, we estimate the costs of utilizing the accumulated flexibility of a portfolio of flexible devices towards the spot price and in the regulating power market. With these cost estimates it is possible to examine whether different smart grid strategies for spot price and regulating power optimization have economic grounds in the Nordic electric power system under current and planned future regulations.

This work hereby serves as a survey and reality check of the regulatory framework for flexible consumers to participate in the current and future Nordic market. The basis is the existing regulatory documents, technical reports describing details for market participation, and interviews with the Danish transmission system operator (TSO) Energinet.dk. The end result is a thorough description of the requirements for flexible consumers to perform spot price optimization and for participation in the regulating power market. Further, we present a specific case study to conceptualize the implications of these requirements for flexible demand-side devices.

The structure of the paper is as follows. First, in Sec. II, we discuss the requirements for enabling flexible demand-side devices for spot price settlement; following, in Sec. III, we discuss the requirements for participation in the regulating power market. In Sec. IV, a case study on household devices is presented discussing in detail the requirements, costs, and possible revenue associated with enabling market participation. Finally, in Sec. V, we conclude the work.

II. Spot Price Optimization

This section describes the requirements for flexible demand-side devices to optimize the electricity consumption towards the spot market prices. It is based on the following TSO regulations and technical reports: [10], [11], [12], [13]. First we describe how the spot prices are found, then how the prices are settled, and finally how spot price settlement can be achieved via hourly sampled electricity meters. It is

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important to notice that these are the requirements that determine to what extend it is possible to construct controllers that optimize the flexibility towards the electricity spot prices.

A. Spot Prices

Each day before gate closure at noon (12.00 pm), the BRPs for both consumption and production place purchase bids in the Elspot market for each hour of the following day specifying the volumes they are willing to trade given the hourly electricity prices. The spot prices for each hour of the following day are found as the intersection between the accumulated bids for supply and demand. At 1 pm, all BRPs are informed of the traded volumes and hourly prices for the following day.

B. Settlement Methods

Two different methods are used for consumption settlement in Denmark: load-profile settlement and hourly settlement. Further, Energinet.dk and the Danish Energy Association have proposed a third settlement method that is planned to be implemented in the Nordic system. These three methods are described in the following.

1) Load Profile Settlement: All consumers with an annual consumption lower than a threshold of $100,000$ kWh will be settled using load profile settlement; however, hourly settlement can voluntarily be chosen for smaller consumers. For load profile settlement, the accumulated consumption is read typically once a year. As a result of this infrequent metering, the hourly consumption is unknown and identical consumption profiles are used for all consumers within the same grid area for settlement purposes. It is therefore clear that spot price optimization of flexible consumers is not possible for load profile customers, which today account for almost all private consumers in Denmark.

2) Hourly Settlement: Hourly settlement is mandatory for consumers with a consumption exceeding $100,000$ kWh/year but can voluntarily be chosen. This settlement method requires daily collection and validation of hourly-metered values. The hourly-metered values will be used in the balancing settlement of the consumers' BRP. Consumers with hourly settlement are hereby able to be used for spot price optimization, as their hourly electricity consumption is recorded and communicated. The subscription fee varies for different distribution companies as illustrated by the following two examples: Dong Energy Distribution with a subscription of 180 €/year and TREFOR with 660 €/year [1]. The subscription fee covers both the electricity meter and the extra data handling associated with collecting data on a daily basis instead of a yearly basis.

3) 3rd Settlement Method: Energinet.dk and the Danish Energy Association have suggested the implementation of a third settlement method denoted "3. afregningsgruppe" (meaning: 3rd settlement group). The concept of this group is that the consumption is metered hourly but only read and communicated once every month. This has the advantage that hourly consumption settlement is possible while the communication costs are kept small. Many households already have smart meters installed and therefore are able to perform this hourly metering. Distribution companies estimate that the additional subscription fee for this monthly metering would be in the order of 2.5 to 7.0 €/year additional to the fee in load profile settlement [14]. Hereby, the 3rd settlement method allows for spot price optimization of flexible consumers at a low annual fee.

C. Regulating Power

The TSO is responsible for maintaining balance between production and consumption in the delivery hour. If BRPs for consumption or production cause imbalances in the system, the TSO will compensate by activating regulating power. The TSO will procure this regulating power from the regulating power market where generators or consumers with adjustable consumption are able to place bids. The regulating power bids are sorted in merit order after price such that the cheapest bids that fulfill the requested regulating power demand are activated first. This merit order list of regulating power is often referred to as the Nordic Operational Information System list (NOIS list) [15].

The price paid to the providers of regulating power is denoted the "RP price" and is found as the bidding price of the most expensive regulating power bid activated in a delivery hour. The RP price will be used to settle all the provisions of regulating power in that given hour.

D. Balancing Power

After the delivery-hour, the consumption of each BRP can be calculated by adding the metered electricity consumption of the hourly metered customers with the electricity consumption determined for the load profile customers as described in Sec. II-B.1. Any difference between the calculated hourly consumption of a BRP and the electricity this BRP has purchased at the spot market is by definition traded with the TSO as *balancing power* and settled as such. If the imbalance of a given BRP is in the same direction as the overall system imbalance, the BRP will trade balancing power with the TSO at a price equal to or worse than the spot price[2]. On the contrary, if the imbalance of a given BRP is in the opposite direction of the overall system imbalance, BRP will trade the balancing power with the TSO at a price equal to or better than the spot price.

Let us describe this more formally. If a BPR has purchased the electricity volumes $u_{\text{spot}}(k), k = 1, \dots, 24$ at the spot market for the 24 hours of the day and if the sum of the hourly metered consumption and the load profile consumption is given by $u(k), k = 1, \dots, 24$, then the total cost J on this day will be

$$J = \sum_{k=1}^{24} \left(u_{\text{spot}}(k)\pi_{\text{spot}}(k) + \left(u(k) - u_{\text{spot}}(k)\right)\pi_{\text{RP}}(k) \right) \quad (1)$$

[1]Prices available online, `www.dongenergy-distribution.dk`, and `www.trefor.dk`.

[2]By *worse* we mean a price higher than the spot price when we purchase from the TSO and a price lower than the spot price when we sell to the TSO.

where $\pi_{\text{spot}}(k)$ and $\pi_{\text{RP}}(k)$ are the electricity spot price and regulating power price, respectively, in hour k. This price model is denoted the one-price model.

Based on this, it is important to understand that the spot prices *cannot be seen as a price signal*, as the spot prices only apply to the electricity traded day-ahead.

E. Multiple Electricity Meters

It might be desired to have several electricity meters assigned with different electricity retailers within the same household or company. Such a setup will allow an aggregator to manage a portfolio solely consisting of flexible demand-side devices without managing the remaining inflexible consumption. Currently, such a setup is only possible by installing a separate meter and having a separate subscription plan for this meter, which will cause a subscription fee in the magnitude of 180 to 660 €/year as described in Sec. II-B.2.

III. Regulating Power Market Participation

This section describes the requirements for flexible demand-side devices to optimize the electricity consumption towards the regulating power markets. It is based on the following TSO regulations and technical reports: [16], [17], [18], [19], [12], [20], [21]. First we briefly describe regulating power and manual reserves and then how demand-side devices can provide these services.

A. Regulating Power and Manual Reserves

Players can place bids for upward and downward regulation in the regulating power market up to 45 minutes before the delivery hour. If upward or downward regulation is needed, the TSO will activate the required regulating power by selecting the cheapest bids first (the merit order) from the NOIS list. To ensure that sufficient reserve capacity is available on the regulating power market, the TSO can conclude manual regulation reserve agreements with suppliers (reserve capacity) day-ahead. This takes place on a daily auction that closes at 9 am. The suppliers who win these auctions will receive an availability payment for having reserves available in the given hours of the following day.

B. Requirements for Demand-Side Participation

In the following, the requirements in terms of balance responsibility and volumes are discussed.

1) Balance Responsibility: Regulating reserve bids are made through a BRP. Consumers must therefore rest with the same BPR in order to collectively provide regulating reserves; further, this BRP must be approved by the TSO and conclude an agreement on balance responsibility.

2) Combined Delivery: It is allowed to make a regulating reserve bid by aggregating a portfolio of consumption units as long as the aggregated (combined) portfolio response satisfies the requirements to upward and downward regulation. It is, however, not allowed to include both production and demand-side devices in a combined delivery.

3) Volumes, Durations, and Response Time: Regulating power is bought and sold day-ahead on the manual reserve market and intra-day in the regulating power market for each hour of the day. The minimum volume of a regulating power bid is 10 MW and the maximum is 50 MW for both upward and downward regulation. Bids greater than 10 MW can be activated in part. Regulating power bids can be placed until 45 minutes before the delivery hour and it must be possible to activate the full delivery within at most 15 minutes from receipt of the activation order. Notice that the presented volumes etc. are taken from the Danish system but may vary from country to country in the Nordic system.

C. Communication Requirements

In the following, the requirements in terms of day-ahead, intra-day, and real time communication are discussed. Three main elements that must be communicated are notifications, operational schedules, and adjusted operational schedules. This is elaborated in the following and illustrated in Fig. 1.

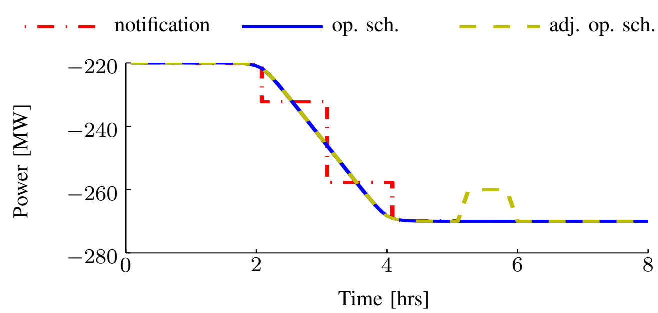

Fig. 1. Illustration of the hourly notification (red, dash-dot) and a 5-minute operational schedule (blue, solid). Finally, an activation order of 10 MW upward regulation is illustrated in form of an adjusted operational schedule (yellow, dashed). The adjusted operational schedule is identical to the original operational schedule except for the activation in hour 5 to 6.

1) Day-ahead Communication: In the following we describe the type of information the BRP must provide to the TSO day-ahead (the day before operation).

a) Notification: A BRP for consumption must submit a notification for trade in MWh/h prepared for the 24 hours of the following day with an accuracy of one decimal. The deadline for notifications is 3 pm the day before the day of operation.

b) Operational Schedule: A BRP for adjustable consumption must in addition to the notifications also submit a 24-hour operational schedule with a 5-minute resolution for the planned consumption the following day. The operational schedules are specified with the unit MW and the accuracy is one decimal. The deadline for these operational schedules is at 5 pm the day before operation. For adjustable demand-side devices with a capacity less than 10 MW it is sufficient to provide an operational schedule with the total consumption for the entire portfolio of devices. Notice that the time resolution of 5 minutes applies in the Danish system but may vary from country to country in the Nordic system.

c) Regulating Power Bids: If the BRP has entered into agreement with the TSO on keeping manual reserves available, the BRP must place the first regulating power bids by 5 pm the day before operation with volumes at least equal to the volume agreed upon. New regulating power bids can be placed up to 45 minutes before the delivery hour.

2) Intra-hour Communication: In the following it is described what type of information the BRP must provide to the TSO during the day of operation.

a) Notification: A BRP for consumption can send an adjusted notification to the TSO if intra-day bilateral trades or trades on the intra-day market Elbas are made. The adjusted notification is the original notification with changed time series for consumption and trade. The deadline for the adjusted notification is 45 minutes before each delivery hour.

b) Operational Schedule: A BRP for adjustable consumption must be prepared at any time to provide the TSO with information about the anticipated operation of the devices in the form of a 5-minute operational schedule. The BRP must submit an adjusted operational schedule if deviations occur exceeding 10 % of the installed capacity and is above a threshold of 10 MW. Such an adjusted operational schedule must be submitted as soon as possible after the deviation is detected.

The current regulations do not specify any penalty for updating the operational schedules. This gives adjustable consumption the large benefit, that updates of the operational schedule can be made if needed without penalty. This is a clear advantage for aggregation and control of flexible consumers with stochastic loads where it may be very difficult or even impossible to produce perfect day-ahead operational schedules.

c) Regulating Power Bids: A BRP for adjustable consumption can place and alter bids for upward or downward regulation up to 45 minutes before the delivery hour. Upon activation of regulating power, the TSO will send a 5-minute power schedule to the BRP in question. The BRP will then plan the regulation and submit an adjusted operational schedule that includes the activated regulating power, see Fig. 1.

3) Real Time Communications: Using adjustable consumption for regulating power deliveries requires independent metering. The metered data collector must acquire active power measurements for *each device* in the portfolio comprising the adjustable consumption [21]. The equipment and installation costs depends on how difficult the installation is, but typically the costs are in the order of $1,300-6,700$ € per device in installation costs and a running expense of 270 €/year for communication and maintenance which must be paid by the BRP [3].

It is important to notice that the strict regulations for real time measurements were composed in a system where regulating services from smaller units were of no interest. Currently, it is discussed whether these requirements should be made more favorable towards smaller flexible demand-side devices to increase the volume of available balancing services. Some suggestions are: that the metered data collectors will accept standardized equipment installed by aggregators, that real time measurements on portfolio level instead of individual device level can be accepted, and that real time communication can replaced with ex-post communication. In a future scenario, the high costs might therefore be significantly reduced – possibly even to a marginal cost of zero if it eventually will be possible to use the same equipment as is required between the aggregator and the devices for control purposes. Note that such regulatory changes are currently not planned only discussed.

[3]Numbers are based on a private interview on the 4th of March 2012 with a Danish BRP for adjustable consumption with experience in this field.

IV. Case Study: Aggregation of Flexible Demand-Side Devices

To conceptualize the implications of the described regulations, we consider a concrete case study where smaller flexible consumers are aggregated and utilized in the markets. First, we examine the requirements for such aggregation, and second, we estimate the costs associated with enabling devices to be active in the markets.

A. Balancing Responsibility, Hourly Settlement, and Real Time Measurements

As different households in Denmark will have different electricity retailers, they will by default rest with different BRPs. However with the current legislations it is necessary that the flexible household devices in the portfolio rest with the same BRP to enable spot price optimization and provisions of regulating power. One way to accommodate this requirement is to install an additional electricity meter. The additional meter only measures the consumption of the flexible devices in the household and is assigned with a separate electricity retailer belonging to a specific BRP.

This additional electricity meter also serves another purpose than assigning the household devices to a certain BRP. Many consumers are still load profile customers, which does not allow hourly settlement. But by installing a new hourly read electricity meter, it is possible to obtain hourly settlement as desired. Such a meter is, however, associated with a higher monthly fee. In a future setup it will be possible to obtain inexpensive hourly settlement based on the 3rd settlement method as previously described.

In order for an aggregator/BRP to not only perform spot price optimization, but also provide regulating power, it is necessary that the metered data collector installs and operates certain required real time measurement equipment for each household. The expense for this equipment is by far the largest barrier for small consumers to participate as regulating reserves. As previously described, it may be possible to use inexpensive ex-post settlement equipment in a future setup.

B. Market Threshold

The portfolio must exceed the regulating power participation threshold of 10 MW to be able to deliver TSO service. Household devices such as domestic heat pumps and electrical vehicles have nominal power consumption in the magnitude of 1 kW to 10 kW and the devices are not always available as flexible resources; hence, a portfolio in the magnitude of $10,000$ household devices is needed in order to reach a volume that exceeds the regulating power threshold. Notice that this huge number constitutes a real barrier for market participation of flexible consumption as this means that an aggregator is required to contract with thousands of households before a bid can be placed in the regulating power market.

C. Consumption forecast

In order to optimize for spot prices, the aggregator must forecast the BRP consumption of the portfolio at noon (12.00 pm) the day before operation and procure electricity accordingly; hence, a 36-hour load forecast must be made. If the actual consumption deviates from the procured electricity, the deviation will by definition be traded with the TSO as balancing power at the RP price.

In order to enable provisions of regulating power reserve, 5-minute operational schedules must be provided to the TSO at 5 pm day-ahead. During operation, the BRP must ensure that the aggregated consumption of the portfolio tracks the operational schedule. The aggregator must therefore steer the domestic appliances to collectively track the operational schedule. In case of activation for upward or downward regulation, the aggregator must update the operational schedule and ensure tracking of the updated schedule. If it is not possible to follow the operational schedule, the BRP must submit an adjusted operational schedule to the TSO. Notice that this option to adjust the operational schedules with no charges is a big advantage for the BRP, as it allows correction of prediction errors.

D. Estimation of Expenses

To complete the conceptualization, Table I shows the costs for enabling demand-side devices within the same household to be activated for spot price optimization and to provide regulating power. The table only shows the costs associated with the TSO regulations – not the costs for enabling the device itself to be flexible.

Exp./dev. [€]	Investment costs		Running costs per year	
	Cur. reg.	Fut. reg.	Cur. reg.	Fut. reg.
Spot opt.	0	0[1]	$130-670$	$2,5-7.0$[1]
Reg. opt.	$1,300-6,700$	0[2]	270	0[2]

TABLE I

EXPENSES PER DEVICE FOR MARKET PARTICIPATION.

E. Estimation of Possible Profit

To illustrate how Table I can be used, we construct a control strategy that optimizes the electricity consumption of a house with electric heating towards the electricity spot prices. We perform this optimization for a single house to examine the possible profit per household; however, in reality this optimization would be done by an aggregator on an entire portfolio.

Spot price optimization can be done in a simple way, as illustrate in the following. Participation in the regulating power market is, however, more complicated and requires certain bidding strategies and possibly predictions of regulating power prices; hence, it is outside the scope of this work.

The control strategy developed in this work is very simple and should not be seen as directly implementable, but rather as an example of how revenue can be generated based on flexible consumption and how this profit compares to the expenses of participating in the electricity markets.

1) Household Flexibility Model: We assume that the household is electrically heated and acts as a thermal storage. It is assumed that the average consumption of the heating system is 1 kW; further, the house has concrete floors which serve as a thermal storage with a capacity of 3 kWh. The maximum power consumption of the heater is 4 kW. These parameters are chosen as they correspond to typical values of Danish households, see [3]. For simplicity, we describe the flexibility of the house as an ideal energy storage limited in power and capacity and describe this with a discrete time model.

Let k index the hours of the day and define $x(k) \in \mathbf{R}$ as the electrical equivalent of the stored thermal energy (i.e., we scale with the COP to obtain a simpler formulation). Further, let $v(k) \in \mathbf{R}$ be the load and let $p(k) \in \mathbf{R}$ be the power that we store or collect from the house's thermal energy storage. Then we have

$$x(k+1) = x(k) + T_{\mathrm{s}}\left(p(k) - v(k)\right) \tag{2}$$

where we assume the time constant is $T_{\mathrm{s}} = 1$ hour and use kW and kWh as units. The heat pump power limits and energy limits can be described as

$$0 \leq p(k) \leq \overline{p}, \quad \underline{x} \leq x(k) \leq \overline{x} \tag{3}$$

where $\overline{p} = 4$ and $\underline{x} = 0, \overline{x} = 3$ according to the assumed parameters of the house. Note that these parameters depend much on the type of house including the construction and the insulation. For larger houses with concrete floors, the thermal capacity can be significantly larger than the 3 kWh used in this example. Further, we assume a constant load of 1 kW, hence $v(k) = 1$. Notice that this thermal model is very simplified: disturbances and prediction errors etc. are not taken into account as we only seek a rough estimate of the value of consumption flexibility.

2) Spot Price Optimization: The flexibility in power consumption is utilized to optimize the consumption of the household towards the electricity spot prices. It is assumed that the electricity needed to meet the daily load of 1 kW is purchased day-ahead at the spot market. By utilizing the flexibility, the household will deviate from the electricity

[1] Expected costs when the 3rd settlement group will be implemented, see Sec. II-B.3.

[2] The marginal cost is 0 if the future market will allow the aggregator to utilize standardized equipment, see Sec. III-C.

purchased day-ahead and cause imbalances which are settled with the TSO as balancing power at the RP prices according to Sec. II-D. The control strategy developed in this work utilizes the spot prices as predictions of the RP price.

As described in Sec. II-A, the spot prices for the following day are published each day at noon; hereby we always know the spot prices at least 12 hours ahead which we use as prediction of the future RP prices. This allows us to design a receding horizon controller with a horizon of 12 hours, see Algorithm 1.

Algorithm 1: Spot Price Optimization

for $k = 1, 2, \ldots$ **do**
  Collect current state $x(k)$ and spot prices $\pi(\kappa), \kappa \in \mathcal{K} = \{k, \ldots, k+11\}$;
  Solve the optimization problem
$$\begin{array}{ll} \text{minimize} & \sum_{\kappa \in \mathcal{K}} p(\kappa)\pi(\kappa) \\ \text{subject to} & x(\kappa+1) = x(\kappa) + p(\kappa) - v(\kappa),\ \kappa \in \mathcal{K} \\ & \underline{p} \le p(\kappa) \le \overline{p}, \quad \underline{x} \le x(\kappa) \le \overline{x},\ \kappa \in \mathcal{K} \end{array}$$
  with variables $x(\kappa+1), p(\kappa), \kappa \in \mathcal{K}$ and where we denote the solution $x^\star(\kappa+1), p^\star(\kappa), \kappa \in \mathcal{K}$;
  Consume power $p^\star(k)$;
end

We simulate this controller using the spot prices from 2011 and use the RP prices from the same year for settlement according to (1). As a benchmark we consider a strategy where we do not shift the load but simply purchase and consume 1 kW for each hour of the year.

This simulation reveals that an annual saving in the order of 360 € is achievable using this method. Simulating the previous years reveals similar results. By comparison with the values presented in Table I it is evident that an annual profit can be made in the grid areas where the cost of hourly metering is as low as around 130 €/year; however, in some regions these costs are around 670 €/year ruining the business case. However in a future setup with hourly metering costs in the magnitude of $2,5 - 7,0$ €/year, spot price optimization could prove as a desirable business case. The annual profit of participating in the regulating power market is not calculated; however, the high market participation expenses reveal that it is impossible to generate profit based on household devices in the current setup. Depending on the development in the regulations, regulating power participation might become attractive in a future setup even for small demand-side devices.

V. Conclusion

In this work we made a survey of the possibilities for flexible consumers to participate in the Nordic electricity markets. The regulatory requirements for optimization of the electricity consumption towards the spot prices were examined and the costs to achieve this were estimated. Likewise, the requirements for participation in the regulating power market were examined and the costs to honor these requirements were estimated. Further, the planned changes in the regulations were presented and the implications on the costs of market participation were discussed. Finally, a case study was presented illustrating the requirements for aggregation and market participation of a portfolio of households with flexible consumption. The study showed that the possible consumer revenue was very low compared to the expenses of market participation under the current regulations but that the future regulations might make it possible to generate profit.

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