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Published in:
Energy

DOI (link to publication from Publisher):
10.1016/j.energy.2013.12.041

Publication date:
2014

Document Version
Early version, also known as pre-print

Citation for published version (APA):
Biegel, B., Hansen, L. H., Stoustrup, J., Andersen, P., & Harbo, S. (2014). Value of flexible consumption in the electricity markets. Energy, 66, 354-362. DOI: 10.1016/j.energy.2013.12.041

Energy 66 (2014) 354–362

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Value of flexible consumption in the electricity markets

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ARTICLE INFO

Article history:
Received 9 May 2013
Received in revised form
16 November 2013
Accepted 20 December 2013
Available online 17 January 2014

Keywords:
Smart grid
Flexible demand
Electricity market
Renewable energy
Ancillary services

ABSTRACT

A transition from an oil and coal based energy system to a systems based on renewable and sustainable energy sources has begun in many countries throughout the developed world. As a pioneer, Denmark currently has a wind energy penetration of 30% in the electricity sector and an end goal of 100% renewables in all energy sectors by 2050. The main elements in this transition are an increase in the wind energy production and electrification of main energy sectors such as transport and heating. Activation of flexible consumption in the electricity markets is believed to be one of the means to compensate for the growth of fluctuating renewables and the decrease of conventional power plants providing system-stabilizing services. In this work, we examine the requirements for flexible consumption to be active in the spot market and the regulating power market in the Nordic system and estimate the costs of entering these markets; further, we briefly describe the debated and planned changes in the electricity market to better accommodate flexible consumers. Based on recent market data, we estimate the revenue that flexible consumers can generate by market entry depending on the capacity of the consumers. The results show that consumers should have an energy capacity in the magnitude of 20–70 kWh to break-even in the spot market, while a capacity of 70–230 kWh is required in the regulating power market under current regulations. Upon implementation of the debated and planned market changes, the break-even capacity will decrease significantly, possibly to an energy capacity as low as 1 kWh.

1. Introduction

Many actions have been taken from a political point of view to increase the penetration of renewables throughout the world. A few examples are: renewable portfolio standards or goals that ensure a certain percentage of renewables in almost all states in the US [1], an energy target of 20% renewables by 2020 in the European Union [2], and an increase in wind power capacity in China from 1260 MW in 2005 to 62,000 MW in 2011 [3]. The Danish electric power system, which is the focus of this work, is a particularly interesting case with a wind energy penetration of 30% in 2012 and an expected 2020 penetration of 49.5% [4,5]. The end goal in Denmark is to phase coal out by 2030 and become 100% renewable in *all energy sectors* by 2050 [4].

The implementation of the Danish 100% renewable goal requires actions from the entire energy supply system [6–8]. One of the necessary steps is electrification of consumption from other energy forms [9]. This electrification has already begun: in recent years, 27,000 heat pumps have been installed in Danish homes [10], and additionally 205,000 households have the potential to benefit from replacing their oil-fired boilers with a heat pump [11]. Further, the Danish Government decided in 2012 to lower the taxes on electric heating to expedite electrification of the heating sector [12]. Similarly, electrification of the transport sector is planned: the Danish Department of Transport decided in 2012 on electrification of the railroad in Denmark [13] and a report from 2013 by the Danish Energy Association projects that electrical vehicles will become an attractive alternative to combustion engine vehicles in the following decades leading to an electric vehicle population of 47,000 in 2020 and 221,000 in 2030 [14].

This planned electrification and replacement of conventional power plants with renewables are crucial elements in the future 100% renewable energy system in Denmark. However, when conventional power plants are replaced with renewables such as wind turbines and photovoltaics, the ability to provide power balancing services in the classical sense disappears: the renewable energy sources will often fully utilize the available power and thus not be able to provide balancing ancillary services. Furthermore, conventional fossil fuel power plant generators are synchronous with the

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http://dx.doi.org/10.1016/j.energy.2013.12.041

grid and therefore provide rotating inertia that supports the system frequency against changes [15]. As renewable energy sources typically interface with the grid via power electronics, they do not directly provide inertia to the grid as the conventional synchronous generators [16], which further increase the balancing challenges. Although recent works suggest that wind turbines can provide artificial inertia by regulating the active power output of the generator according to the system frequency [17,18], this type of control is generally not implemented in the wind power plants of today. Moreover, many renewable sources are characterized by highly fluctuating power generation: they can suddenly increase or decrease production depending on weather conditions. These rapid production changes are not always predictable and can therefore imply severe consequences for grid stability [19].

It is therefore evident that the transition towards a Danish 100% renewable energy system will lead to challenges of balancing the electricity supply and demand [7]. Already now, indications of balancing issues are seen in Denmark as evident from the following examples. Negative spot prices occurred in 24 h in 2012 at the electricity day-ahead spot market [20] even reaching the minimum limit of −200 €/MWh. Notice that the negative spot prices occurred in spite of Denmark being well interconnected with Germany (950 + 600 MW), Norway (1040 MW), and Sweden (1900 + 740 MW) [21]. Also, several wind turbines were requested to derate production for several hours on one occasion in December 2012 due to a combination of circumstances where high wind and CHP (combined heat and power) production collided with a holiday with low consumption.[1] These instances are indicators of the increasing balancing issues due to the growth in renewables. As a pioneer in utilizing fluctuating renewables such as wind power, Denmark is among the first places to experience these challenges; however, the rest of Europe can expect similar issues in the coming years [22].

2. Scope and structure of the article

As the wind penetration from fluctuating renewables increases, the need for balancing services will consequently also increase [23,24]. Alternative sources of balancing services must therefore be established as the conventional power plants are pushed out. One of the approaches to obtaining alternative balancing services is the *smart grid* concept, where flexible consumption takes part in the balancing effort [25,26]. This approach is supported by the ENTSO-E (European Network of Transmission System Operators for Electricity), who in a resent paper stated that demand side response is acknowledged as “a main contributor to more effective markets and to system security with a high penetration of fluctuating generation” [27]. Therefore, demand side response is included in the 2012 ENTSO-E network code [28]. In Denmark, the smart grid approach is supported by the Danish TSO (the Danish transmission system operator) and the Danish Energy Association, who have concluded that it is economically attractive to implement the smart grid concept in Denmark as a means to reach the 100% renewable goal. The main stakeholders have recommended a smart grid roadmap with the ultimate goal of having flexible consumption traded on a market place on equal terms with conventional production according to the deliberated electricity market setup in Denmark [29,30].

Control of flexible consumers to support grid stability has been discussed as early as the 1980s [31]. Since, the topic of demand-side management has received much attention from a research perspective [32–34]. Within the deliberated electricity markets, the *aggregator* or *VPP* (*virtual power plant*) concept has likewise been much discussed. The functionality of the aggregator or VPP is to aggregate and control flexible consumption devices whereby the accumulated flexibility can be sold in the electricity markets, as described e.g. in Refs. [35–38]. Examples of flexible consumption devices examined as power balancing resources are: domestic heat pumps [22,39–42], supermarket cooling systems [43–46], domestic refrigerators [47,48], electrical heating elements at CHPs [49,50], and electrical vehicles [51–54]. These existing works describe the effects of including flexible consumers in electric power balancing. Some of the works describe how utilizing flexible consumers will allow larger penetration of renewables, while the focus of other works are the possible electricity savings that can be achieved by selling balancing services. The works do, however, not discuss the requirements for such devices to enter the electricity markets, which is a crucial element in the Nordic liberalized system. Further, these works do not consider the costs associated with being active in the electricity markets.

In this work, we take the aggregator’s point of view and examine the Nordic electricity markets and describe the requirements for market participation of flexible consumption. In particular, we describe the requirements and identify the barriers for participation in the two largest markets: the day-ahead spot market and the regulating power market. Moreover, we estimate the costs of making devices able to participate in these markets. The main contribution of this part of the work is a short overview intended for potential aggregators and smart grid researchers in the Nordic countries, describing the core regulations that apply for market participation of flexible consumers. The background for this market overview is the existing regulations, technical documents, reports, and interviews with the Danish TSO.

Following, we describe how an aggregator can generate revenue via the flexibility of consumers by participating in the two examined markets, namely the spot market and the regulating power market. We present concrete methods for utilizing flexibility in the markets and estimate the revenue that can be generated depending on the power and energy capacities of the consumers. This revenue is compared to the previously found costs of enabling devices to be active in the markets. Hereby we are able to examine the capacity of a consumer required to make market participation attractive. To complete the conceptualization, we briefly describe the potential of some specific flexible devices: domestic heat pumps, supermarket refrigeration systems, and water purifying plants.

Notice, that this paper does not analyze the social benefit of utilizing demand response or examine how flexibility is best utilized. This while social benefit analysis is a most important topic [55–58], we instead take the aggregator’s point of view and examine the costs and potential benefits an aggregator can expect when entering the main electricity markets. This aspect gives an indicator of the state of the current markets with regards to the ability to accommodate aggregated flexible consumers. Also, it provides an easy overview to potential aggregators of the barriers and costs that can be expected upon market entry.

The structure of this work is as follows. First, in Sec. 3, a brief overview of the considered markets is presented; following in Sec. 4 and Sec. 5, we describe the requirements for participating in the day-ahead spot market and the regulating power market, respectively. In Sec. 6, we describe the main barriers for market entry and show the estimated costs of market participation. Following, in Sec. 7, we estimate the revenue flexible devices can obtain by being active in the spot market and the regulating power market and complete the comparison between expenses and revenue of market participation. Finally in Sec. 8, we conclude the work.

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[1] Information based on e-mail correspondence with the Danish transmission system operator (TSO), Energinet.dk on March 22, 2013.

3. Market overview

Three electricity markets exist at an overall level: a day-ahead market, an intra-day market and an ancillary service market. In the day-ahead market, electricity is traded for each hour of the following day. If the market players are not able to realize the volumes traded day-ahead, bids can be placed in the intra-day market which closes an hour before the delivery hour. In the delivery hour, ancillary services are activated to accommodate for any system imbalances [59].

The largest turnovers in the Nordic system are in the day-ahead market and the ancillary service market for regulating power; only very small volumes of electricity are traded in the intra-day market. This work therefore focuses on the day-ahead and regulating power market.

4. The day-ahead spot market

This section describes the requirements for flexible consumption devices to optimize the electricity consumption towards the spot market prices. First we describe how the hourly spot prices are derived, then how the prices are settled, and finally how devices can achieve settlement at the spot prices via hourly sampled electricity meters.

4.1. Spot prices

Each day before gate closure at noon (12.00 p.m.), the BRPs (balancing responsible parties) for both consumption and production place bids in the day-ahead market for each hour of the following day specifying the volumes they are willing to trade given the hourly electricity prices [60]. 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 p.m., all BRPs are informed of the traded volumes and hourly prices for the following day [59].

4.2. Settlement methods

Two different methods are used for consumption settlement in Denmark: load-profile settlement and hourly settlement. Further, the Danish TSO 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.

4.2.1. Load profile settlement

All consumers with an annual consumption lower than a threshold of 100,000 kWh will by default be settled using load profile settlement. By comparison, the average annual energy consumption of a Danish household is in the order of 4500 kWh [61]; consequently, all private consumers and smaller industrial consumers will fall into the load profile settlement category. 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 [62,63]. Spot price optimization is thus *not possible* for load profile customers, which today account for almost all private consumers in Denmark.

4.2.2. Hourly settlement

Hourly settlement is mandatory for consumers with a consumption exceeding 100,000 kWh/year but can voluntarily be chosen for smaller consumers. This settlement method requires daily collection and validation of hourly-metered values [63,64]. The subscription fee varies for different distribution companies as illustrated by the following two examples: Dong Energy Distribution with a subscription of 1368 DKK/year[2] and TREFOR with 4940 DKK/year.[3] The subscription fee covers both the installation of the hourly sampled electricity meter (smart meter) and the extra data handling associated with collecting data on a daily basis instead of a yearly basis.

4.2.3. 3rd settlement method

The Danish TSO Energinet.dk and the Danish Energy Association have suggested the implementation of a third settlement method. The concept of this method is that the consumption is metered hourly but only read and communicated once every month [65]. This has the advantage that hourly consumption settlement is possible while the communication costs are kept small. Distribution companies estimate that the subscription fee for this monthly metering will be in the order of 20–50 DKK/year additional to the load profile settlement fee [66]. The Danish Government has made a plan to roll out hourly sampled electricity meters to all consumers by 2020 making it possible to fully enable this settlement method 9.

4.3. Balancing power

After the delivery hour, the balance of the BRPs is found. This is done by adding the hourly-metered electricity consumption of the hourly-metered customers with the electricity consumption determined for the load profile customers. The difference between these hourly values and the purchased electricity is by definition traded with the TSO (transmission system operator) as *balancing power* at the RP price (*regulating power price*) [67]. The origin of the RP price will be described in detail in the next section.

It is important to notice that the spot prices therefore *cannot be seen as a price signal* that all consumption will be traded at, as done in many works describing control of flexible consumers. This is evident as the spot prices only apply to the electricity purchased day-ahead.

4.4. 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 for example allow an aggregator to manage a portfolio solely consisting of flexible 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 1368 to 4940 DKK/year, as described in Sec. 4.2.0.2 [65]. The Danish Energy Association and the Danish TSO are, however, currently in the process of developing methods to handle separate electricity measurements with separate billing from within the same household [9].

5. Regulating power market participation

This section describes the requirements for consumers to optimize their flexibility towards the regulating power markets. First we briefly describe the regulating power market, then how demand-side devices can participate.

5.1. Regulating power

The TSO is responsible for maintaining balance between production and consumption in the delivery hour. If BRPs for

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[2] 1 DKK approximately equals 0.13 €.

[3] Prices available online, www.trefor.dk and www.dongenergy.dk.

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 flexible consumption are able to place bids. Players can place bids for upward and downward regulation in the regulating power market up to 45 min before the delivery hour [67]. The TSO's expenses for regulating power are financed via the balancing power traded with the BRPs that caused the imbalances.

The regulating power bids are sorted in merit order after price in a list often referred to as the NOIS list (Nordic operational information system list) [68]. If upward or downward regulation is needed, the TSO will activate the required regulating power by selecting the cheapest bids first (the merit order) [67]. The price paid to the providers of regulating power is the RP price which is found as the bidding price of the most expensive regulating power bid activated in the delivery hour [59,67].

5.2. Requirements for demand-side participation

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

5.2.1. 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 [69,70,59].

5.2.2. Volumes, duration, and response time

Regulating power is bought and sold 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 in Denmark (values may vary in the Nordic countries). Bids greater than 10 MW can be activated in part. Regulating power bids can be placed until 45 min before the delivery hour and it must be possible to activate the full delivery within at most 15 min from receipt of the activation order [67,71].

5.2.3. 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. It is, however, not allowed to include both production and consumption devices in a combined delivery [71].

5.3. Day-ahead communication requirements

In this subsection, the required day-ahead communication is described; following, in the next two subsections, the requirements to intra-day and online communication are described. Three main elements that will be described in the following are: notifications, operational schedules, and adjusted operational schedules, see Fig. 1.

5.3.1. Notification

A BRP for consumption must submit a notification for trade in MWh per hour prepared for the 24 h of the following day with an accuracy of one decimal. The deadline for notifications is 3 p.m. the day before the day of operation [59,67,72].

5.3.2. Operational schedule

A BRP for flexible consumption must in addition to the notifications also submit a 24-h operational schedule with a 5-min 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 p.m. the day before operation. For flexible consumption 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 [73,72]. Notice that the time resolution of 5 min applies in the Danish system but may vary from country to country in the Nordic system.

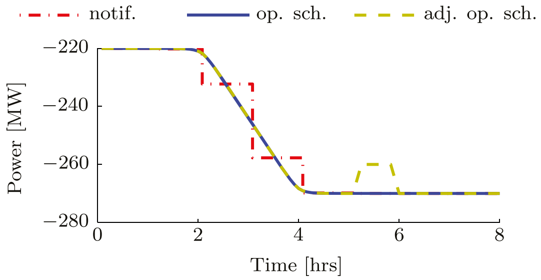

Fig. 1. Illustration of the hourly notification (red, dash-dot) and a 5-min operational schedule (blue, solid). Finally, an activation order of 10 MW upward regulation is illustrated in form of an adjusted operational schedule (yellow, dashed). The adjusted operational schedule is identical to the original operational schedule except for the activation in hour 5 to 6. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.4. Intra-day communication

In the following it is described what type of information the BRP must provide to the TSO during the day of operation.

5.4.1. Regulating power bids and activation

A BRP for flexible consumption can place and alter bids for upward or downward regulation up to 45 min before the delivery hour. Upon activation of regulating power, the TSO will send a 5-min power schedule to the BRP in question; this schedule will describe how the regulating power should be delivered. Following, the BRP must submit an adjusted operational schedule that includes the activated regulating power (see Fig. 1) and finally, the TSO will confirm the adjusted schedule [72].

5.4.2. Notification

A BRP for consumption can send an adjusted notification to the TSO if intra-day trades 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 min before each delivery hour [73].

5.4.3. Operational schedule

A BRP for flexible 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-min operational schedule. Further, 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 [73]. The regulations do not specify any cost for updating the operational schedules.

5.4.4. Real time communications

Using flexible consumption for regulating power deliveries requires independent metering. The metered data collector must acquire active power measurements from *each device* in the portfolio comprising the flexible consumption except if the devices are behind the same point of connection and have a total capacity below 1.5 MW. The real time data must be communicated via certain protocols to the TSO [74]. It is the responsibility of the BRP to make the necessary metering data easily accessible for the metered data collector. Further, the BRP must finance the establishment and operation of the metering equipment. The metered data collector is responsible for the physical metering task and for the data communication to Energinet.dk [74]. The equipment and installation costs will vary depending on the consumption device. The typical costs are in the order of 10,000–50,000 DKK per device in installation costs and a running expense of 2000 DKK/year for communication and maintenance.[4]

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 debated whether these requirements should be made more favorable towards smaller flexible consumption 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 be 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.

6. Market barriers

In this section we summarize the barriers for market entry of flexible consumers and present estimates of the costs per device to enter these markets.

The main barriers of enabling a device to be active in the day-ahead spot market are as follows.

1. The high annual costs of being read on an hourly basis. This will, however, be resolved with the planned 3rd settlement group possibly in 2020.
2. The requirement of a separate new electricity meter to enable a single device to receive separate settlement. The Danish Energy Association and the Danish TSO are working on resolving this issue.

The main barriers of being active in the regulating power market are as follows.

1. The high annual and one-off costs of real time equipment. Although it is debated to loosen this requirement, no plans are currently made.
2. The threshold of 10 MW requires a large number of flexible devices. Currently, there are no plans to reduce this value.
3. The requirement of 5-min operational schedules sent the day before operation. The stochastic behavior of many consumers will make it difficult to make such schedules. The current regulations, however, allow the schedules to be updated at no costs.

To complete the conceptualization, we summarize the costs of making a single device able to honor the requirements of market participation in the current and future electricity markets. This is presented in Table 1. A number of comments to this table are necessary. First, notice that we do not include the costs of making the devices themselves controllable, we only consider the costs of honoring the regulations. Second, notice that since we take the aggregator's view, and not a socioeconomic view, we only consider the costs that the consumers will face and not the global society costs. For example, we consider the cost the consumer will have pay to the distribution company for being hourly-metered instead of considering the actual costs the distribution company will have to pay for installation of a smart meter, etc.

7. Market participation of flexible consumers

In this section, we examine the profit a flexible consumption device can obtain by being part of a portfolio that is optimized towards the day-ahead spot market and regulating power markets. Hereby we can determine the possible profit per device and compare this value with the cost of market entry presented in Table 1. Notice that we consider the devices individually to find the profit per consumer; however, in practice the devices' flexibility would be aggregated before market entry. The reason we examine the cost per consumer is that the aggregator should be able to cover the cost of each device included in the portfolio.

We assume that each flexible consumption device is able to shift consumption in time at no additional cost and with no additional energy loss; further, we assume that the load on each device is constant over time. This model is presented in more detail in Appendix A.

Obviously, this model is very simplified: flexible devices such as thermal storage, electrical batteries, etc., are all associated with losses that depend on how the device flexibility is utilized. Further, the load will vary over the day, often with a stochastic behavior depending on user behavior, weather conditions etc. Finally, shifting consumption in time may for some devices be associated with a given cost such as a *disutility* or a *discomfort* cost. Some consumers will require an economical compensation for utilizing their devices' flexibility while other consumers will not experience any loss of quality or comfort and consequently not necessarily require compensation. These issues are, however, neglected as our objective is to illustrate how revenue can be generated and what the magnitude of this revenue is – the objective is not to accurately model consumers or design implementable control strategies.

Strategies for flexibility optimization towards the day-ahead spot market and the regulating power market are found in Appendix B and Appendix C, respectively. To obtain an estimate of

Table 1
Marginal expenses per device active for spot optimization (Spot.) and regulating power provisions (Reg.) under current (Cur.) and future (Fut.) regulations.

	Investment costs		Running costs per year	
	Cur.	Fut.	Cur.	Fut.
Spot.	0	0[a]	1–5000	20–50[a]
Reg.	10–50,000	0[b]	2000	0[b]

[a] Expected costs when the 3rd settlement group will be implemented around 2020, see Sec. 4.2.

[b] The marginal cost can be 0 if the future market will allow the aggregator to utilize standardized equipment that already is embedded in the devices for other purposes and assuming we can communicate at no additional costs via the internet, see Sec. 5.3. This is, however, the most positive projections and may be far into the future.

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

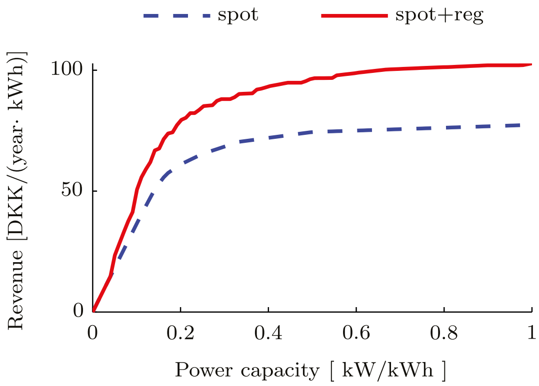

Fig. 2. Revenue per kWh in 2011 for an energy storage when optimizing towards the spot market and when optimizing to both spot and regulating power market as a function of the consumer power capacity.

the revenue that can be generated based on participation in the spot market and in both the spot market and the regulating power market, we simulate market participation over one year. We do this for a storage with normalized energy capacity but varying power capacity. Historical spot and regulating power prices from 2011 are used and the work of [75] is utilized to provide spot price forecasts.

7.1. Results

The results of a one-year simulation are shown in Fig. 2 and should be interpreted as follows. The *y*-axis indicates the revenue per year in DKK per kWh of energy capacity available. We assume a liquid market where we do not influence the spot and regulating power prices, hereby the revenue will simply scale linearly with the energy capacity. The *x*-axis indicates the power capacity of the device ranging from 0–1 kW/kWh. It is not required to examine higher power capacities than 1 kW/kWh: when the capacity is 1 kW/kWh we are able to fully fill/empty the energy storage in each hour.

As the figure shows, the revenue curve is very steep from 0 up to around 0.3 kW/kWh, indicating that if the storage capacity for example is 1 MWh, then it is very profitable to increase the power capacity up to around 300 kW. Increasing the power capacity further will only slightly increase the possible revenue.

We are now able to compare the revenue with the costs of being active in the market as specified Table 1. The following is observed.

1. *Spot price optimization*. An energy capacity of 20–70 kWh is required to break-even when considering the annual costs of for hourly metering and assume a power capacity of 0.3 kW/kWh.
2. *Spot and regulating power optimization*. An energy capacity of 70–230 kWh is required to break-even over a 5-year period when considering the investment costs and costs for the required equipment and communication. We assume a power capacity of 0.3 kW/kWh and an interest rate of 5%.
3. *Future scenario*. If the revenue graph in Fig. 2 is considered valid for the future scenario[5] and if the marginal expenses from Table 1 are used, an energy capacity in the magnitude of 1 kWh is required to break-even.

Notice that the revenue-graph and the estimates above are made for the Nordic electricity system and for a specific year; however, the methods for making the graph are general and can readily be implemented to other electricity markets to form the background for similar analysis. Alternatively, the revenue-graph can be generated based on data from several years to examine how stable the revenue is over time.

Further, notice that the electricity system of today is rapidly changing, possibly affecting the spot and regulating power prices. For example, the rapid growth of renewables in Denmark will likely give rise to more fluctuating electricity prices. On the other hand, new interconnectors from Denmark to Norway are being constructed which possibly will compensate this effect to some extend. Likewise, integration of demand response might smooth out fluctuating electricity prices. As these effects point in different directions for the market prices, it is difficult to say anything definite about the future electricity prices and consequently difficult to find better estimates than looking at today's prices which are the basis of the analysis in this work.

Finally, let us examine the results presented in Fig. 2 further by considering a number of specific flexible devices. We examine three consumption devices: an electric heat pump, a supermarket system, and a water purifying plant, see Table 2. The power and energy capacities for the heat pump are based on [22], for the supermarket they are based on [76] (idealized and scaled up to a larger supermarket), while the capacity for the water plant is based on DONG Energy's experiences in flexibility optimization of water plants. Again, we remind the reader that we consider these consumers as ideal storage with constant load, which clearly is a simplification as such devices will be characterized by stochastic consumption and possibly a consumption coupled with the storage level. However, the presented values will reflect the magnitude of the revenue that can be generated base on the devices' consumption flexibility. The table shows that both heat pumps and supermarket refrigeration systems will generate a profit that is too low compared to the costs of enabling spot market and regulating power market participation in the current market; however, it may prove as a desirable business case in the future system that is better at accommodating flexible consumers. The water plant generates sufficient profit to perform spot price optimization. The revenue increase of DKK 20,100 for activating regulating power will cover the running costs and allow a payback period of 1–3 years for the installed equipment making such investments very attractive.

Notice, that the business case presented in Table 2 is only concerned with selling services in the regulating power market and the spot market. However, some works emphasize that the real value of flexible consumers might lie in the distributed nature of these devices [56] making it possible to deliver services on the distribution level such as voltage control [77] or congestion alleviation [78]. Other works further mention energy efficiency and ancillary services participation as possibilities to generate revenue. These services are not included in the business case presented here, but might be able to further increase the value of the flexible devices.

Table 2
Marginal expenses per device active for spot optimization (Spot.) and regulating power provisions (Reg.) under current (Cur.) and future (Fut.) regulations.

	Device capacity		Annual revenue	
	Energy [kWh]	Power [kW]	Spot [DKK]	Spot + reg [DKK]
Heat pump	60	2	900	1200
Supermarket	200	10	5100	6700
Water plant	1000	300	67,900	88,000

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[5] It is difficult to predict how the market volatility will evolve: increasing penetration of renewables and increasing oil prices suggests higher and more fluctuating prices while increasing volumes of flexibility and new transmission cables suggest the opposite.

8. Conclusion

In this work we made a thorough survey of the Nordic regulations for flexible consumers to participate in the current and future day-ahead market and the regulating power market. Based on this, a list of main barriers for market entry was presented and estimates of the costs for enabling flexible consumers to enter the considered markets were made. Following, the possible revenue of participating in these markets was estimated based on the consumer energy and power capacity limitations. The market entry costs were compared with the possible profit of market participation, which resulted in an estimate of the capacities required to make market participation profitable. The estimates showed that market entry for flexible consumers had a break-even capacity in the magnitude of 20–70 kWh and 70–230 kWh, respectively, for day-ahead and regulating power market entry under the current regulations. Further, the results showed that the future regulations (around 2020) will remove many of the market barriers; possibly reducing the break-even capacity to a magnitude of around 1 kWh.

Acknowledgments

The work is completed as a part the *iPower* project which is supported by the Danish government via the DSR-SPIR program 10-095378.

Appendix A. Ideal flexible consumer model

The idealized consumption device is modeled as a consumer with constant load which the overall consumption can be varied around. As both the spot market and the regulating power market are based on hourly bids, we use a discrete time model with a sampling time of 1 h. Let k index the hours and let $x(k)$ denote the energy level; further let $\overline{p}$ be the constant load. Finally, let $p(k)$ be the total consumption of the device. By using units kWh for $x(k)$ and kWh for $\overline{p}$ and $p(k)$ (energy delivered over an hour) we obtain

$$x(k+1) = x(k) + p(k) - \overline{p}. \tag{A.1}$$

This simply expresses that if the total consumption equals the constant load $p(k) = \overline{p}$, no energy is stored; however, if the consumption increases above the constant load, energy is stored accordingly and vice versa. The storage is limited in energy capacity and power capacity which can be expressed as

$$0 \le x(k) \le \overline{x}, \quad 0 \le p(k) \le 2\overline{p} \tag{A.2}$$

where $\overline{x}$ is the energy capacity in kWh and where we assume the device is able to vary its total power consumption with $\pm\overline{p}$ around the constant load of $\overline{p}$. This model is a much simplified version the consumer model presented in Ref. [79].

Appendix B. Spot market optimization

Various strategies can be envisioned when participating in the spot market. In this work we utilize the following strategy: before gate closure at noon, we collect spot price forecasts by using data from the work in Ref. [75]. Based on the storage energy level just before midnight (which is known from the optimization done the previous day), the flexibility is optimized towards the spot price forecasts and electricity is purchased accordingly. During the day, the purchased electricity is consumed such that we avoid trading balancing power with the TSO at possibly unfavorable prices.

Formally, this can be formulated as shown in Algorithm 1. We use k to indicate the hour number. Further, we use $\mathcal{K} = \{k+12, \ldots, k+35\}$ to describe the 24 h of the following day at the point in time just *before* gate closure which is at 12 noon (the first hour of the following day is 12 h ahead).

Algorithm 1 Spot Optimization

```
for hour $k = 1, 2, \ldots$ do
  if Current hour is 12 p.m. (just before gate closure) then
    Collect spot prices forecasts $\tilde{\pi}(\kappa), \kappa \in \mathcal{K}$;
    Collect the predicted storage level at midnight $x(k+12)$;
    Solve the optimization problem

        minimize     $\sum_{\kappa \in \mathcal{K}} p(\kappa)\tilde{\pi}(\kappa)$
        subject to   $x(\kappa+1) = x(\kappa) - \overline{p} + p(\kappa)$          (B.1)
                     $0 \le p(\kappa) \le 2\overline{p}, \quad \underline{x} \le x(\kappa) \le \overline{x}$
                     $\kappa \in \mathcal{K}$

    where the variables are $p(\kappa), x(\kappa+1), \kappa \in \mathcal{K}$ and the data is $x(k+13), \overline{p}, \overline{x}, \tilde{\pi}(\kappa), \kappa \in \mathcal{K}$;
    Denote the solution $p^\star(\kappa), \kappa \in \mathcal{K}$ and purchase these volumes for following day;
  end if
  Consume electricity $p^\star(k)$;
end for
```

Appendix C. Regulating power optimization

Optimization towards the regulating power market is a delicate task and many strategies can be imagined: regulating power price forecasts can be utilized, alternative day-ahead purchase strategies can be used to allow more flexibility in bidding in the regulating power market, etc. In this work we utilize the following simple strategy. After gate closure at 1 p.m., the spot price realizations will be published. Based on these spot price realizations, we reoptimize the consumption of the portfolio. Following, for each hour of the day, we bid the difference between the purchased electricity and the volume gained from the reoptimization, if feasible, with a bidding price equal to the spot price. If activated, we will get a regulating power price equal to or better than the spot price (our bid). Hereby we still avoid trading balancing power with the TSO, but enable ourselves to get access to regulating power prices when they are favorable.

Formally, this is presented in Algorithm 2. Again, we use k to indicate the hour number but now let $\mathcal{K} = \{k+11, \ldots, k+34\}$ describe the 24 h of the following day just *after* gate closure which is 11 h ahead in time.

Algorithm 2 Spot and Reg. Power Optimization

```
for hour $k = 1, 2, \ldots$ do
  if Current hour is 12 p.m. then
    Purchase electricity $p^\star(\kappa)$ as in Alg. 1;
  end if
  if Current hour is 1 p.m. (first hour after gate closure) then
    Collect spot price realizations $\pi(\kappa), \kappa \in \mathcal{K}$ and storage level $x(k+11)$;
    Reoptimize by solving (B.1) using $\pi(\kappa)$ instead of $\tilde{\pi}(\kappa)$;
    Denote solution $p^+(\kappa), \kappa \in \mathcal{K}$;
  end if
  Bid feas$(p^\star(k) - p^+(k))$ as regulating power at price $\pi(k)$ where feas$(y)$ returns the value closest to $y$ that does not violate the energy constraints (A.2) throughout the rest of the day;
  Consume electricity $p^\star(k) - p^\dagger(k)$ where $p^\dagger(k)$ is the activated regulating power;
end for
```

Notice that more advanced strategies can be utilized to further increase the value of the available flexibility. An example is to withhold flexibility in the electricity spot market if forecasts indicate that it might be more profitable to trade on the regulating power market. This requires forecasts of the regulating power prices as well as sophisticated optimization algorithms and is consequently outside the scope of this work.

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