Activating electricity demand as regulating power

FLEXPOWER – TESTING A MARKET DESIGN PROPOSAL

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Contents

Foreword

FlexPower

The FlexPower project investigates the possibility of using broadcasted dynamic electricity prices as a simple and low cost means to activating a large number of flexible small-scale power units. The aim is to provide regulating power via an aggregated response from the numerous units on a volunteer basis. The power units could for example be electrical heating and cooling units, electrical vehicles, industrial demand and micro generation. Each power unit can have its own local controller and individual business model and objective function. The optimisation of the local controls may involve forecast services requested by the customer (such as heat for a house, or charging power for an electrical vehicle) – in terms of quantity, timing and flexibility – and forecasts of the electricity prices.

The responses from the individual units to variations in the electricity prices can be difficult to predict, but the aggregated response from a large number of units is expected to be relatively predictable.

Based on international 'real-time' power market experiences, new dynamic FlexPower market mechanisms to deliver regulating power are designed and tested via simulations, under laboratory conditions, and in the field. A dedicated simulation tool is developed for this purpose. The FlexPower regulation can never be perfect, but is expected to be able to meet some of the present and future growing demand for regulating power.

As a starting point, a 5-minute power price signal, based on the actual regulation power prices, is tested.

The project expects to address the following questions:

- How could a system with a one-way price signal be designed? How can the FlexPower mechanism be integrated into the present electricity market, including the market for regulating power? (WP 1)
- To what extent, and under which conditions, can the aggregated response from many units be predicted? (WP 2)
- Is the use of local electricity prices an efficient way of regulating the power flow in the power distribution system? (WP 3)
- Which part, and how much of the power system's need for regulating power can be provided by FlexPower mechanisms? How can individual technologies be controlled under FlexPower? (WP 4, WP 5)

- How should communication be designed to support the FlexPower idea? (WP 7)
- Is the FlexPower mechanism stable and robust enough to handle disturbances? Is the use of broadcasted, dynamic electrical prices an efficient way of activating small-scale regulating power? Does it work in practice? (WP 6, WP 8, WP 9)

The project involves the following partners: Ea Energy Analysis (coordinator), the Technical University of Denmark (DTU), Enfor, Actua, Eurisco, EC Power, SEAS-NVE and NEAS (formerly Nordjysk Elhandel). The work is divided into the following work packages: WP 1: Market design (Ea), WP 2: Prediction of aggregated response (DTU Compute), WP 3: Advanced options (DTU CEE), WP 4: Control algorithms (Risø DTU), WP 5: Forecasts (Enfor), WP 6: Simulation (Actua), WP 7: Communication (Eurisco), WP8: Laboratory tests (Risø DTU) and WP 9: Field tests (DTU CEE).

More information at: **www.flexpower.dk**.

1 Introduction and background

1.1 Regulating power today

The Transmission System Operator (TSO) is responsible for the overall security of supply of the electricity system by maintaining the electrical balance in the power system, as well as ensuring a well-functioning electricity market by developing market rules.[1] Electricity production and consumption always have to be in balance, and 45 minutes before the operating hour the task of balancing these two in Denmark is left to the TSO (Energinet.dk). It maintains this balance via the regulating power market, and other markets for automatic reserves.

In the hour of operation, Energinet.dk utilises several types of reserves to ensure the stability of the system. The reserves can be grouped into automatic and manual reserves. Generally speaking, the system criteria are initially managed by the automatic reserves, which are activated in accordance with frequency deviations and/or deviations in the actual, compared with the planned, exchange with neighbouring areas. These automatic reserves are expensive and have limited capacity.

Regulating power

To anticipate excessive use of automatic reserves, and in order to re-establish their availability, regulating power is utilised. Regulating power is a manual reserve and is defined as increased or decreased generation that can be fully activated within 15 minutes. Regulating power can also be demand that is increased or decreased, as is highlighted in Table 1 below. Activation can start at any time, and the duration can vary.

	Generation	Demand
Up-regulation	More	Less
Down-regulation	Less	More

Table 1: Definition of Up and Down regulation

In the Nordic countries there is a common regulating power market managed by the TSOs with a common merit order bidding list. The balance responsibles (for load or production) make bids consisting of amount (MW) and price (DKK/MWh). All bids for delivering regulating power are collected in the common Nordic NOIS-list and are sorted with increasing prices for up-regulation (above spot price), and decreasing prices for down-regulation (below spot price). These bids can be submitted, adjusted, or removed until 45 minutes before the operational hour. In Denmark, the minimum bid size is 10 MW, and the

[1] For more on the current regulating power market please see (Bang, Fock, & Togeby, 2012).

maximum is 50 MW. Taking into consideration the potential congestions in the transmission system, the TSOs manage the activation of the cheapest regulating power. An example of the NOIS-list is displayed below in Figure 1.

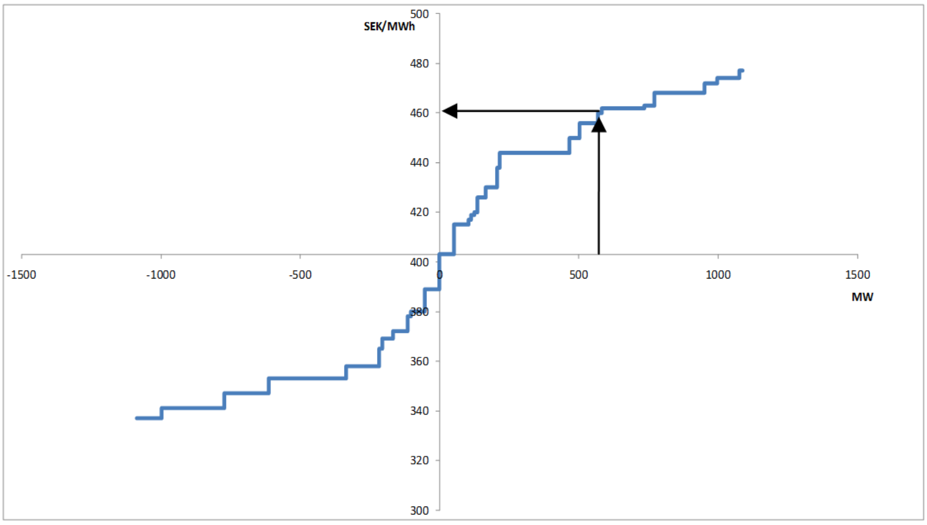

Figure 1: Example of the NOIS list, from 17.6.2009, CET 07-08. 583 MW of up regulating power was activated, corresponding to a price of 460 SEK/MWh (Data provided by SvK).

After the day of operation, the costs of activating regulating power are passed on to the balance responsible agents whom were responsible for the imbalances. Both production and demand can cause imbalances, but currently it is primarily production units that can benefit from acting in the regulating power market. The only Danish examples for demand used as regulating power are electric boilers in district heating networks. In 2009, 54 MW of electric boilers participated in the regulating power market with down regulation, a figure that is expected to increase to 300 MW.

1.2 Limitations of current regulating market

The current design has some drawbacks that if removed could make the regulating power market more efficient in the future. For example, small-scale demands and small-scale generations are, in practice, excluded from the market. Current requirements that hamper demand side involvement in the regulating power market include:

- A 10 MW minimum bid size
- A plan for the controllable load: The plan must be followed and must exist with 5-minutes values
- Demand must be re-established after activation: In some cases, this may be difficult if special staff are needed for re-establishing demand, for example, some forms of industrial production (Johansson, 2008).

- Real-time measuring of regulation units: Real-time metering is relevant in relation to consumers in the +10 MW class. However, for small consumers, the cost of such a requirement is prohibitive (Regional Group Nordic, 2013).
- The bidding process in itself requires several active actions. First, a bid must be made, then if chosen the supplier notified, and finally the actual regulation must occur. This is an undesirably bureaucratic process for smaller resources and a simpler design might attract more participants (Van der Veen & De Vries, 2009).

1.3 Aspects of current regulating power market

A central reason behind integrating demand response into the regulating market (as opposed to in the spot market) is that there is a greater need for it, and therefore more potential profit to be made in the regulating market. One way of investigating this hypothesis is to review the historic differences between hourly regulating power and spot prices. Figure 2 below displays duration curves of the absolute hourly differences between the spot price and regulating power prices for DK1 (West) and DK2 (East) from Jan 1st, 2005 till August 10th of 2010. The average spot price over the period was 309 DKK/MWh in DK1, and 325 DKK/MWh in DK2.

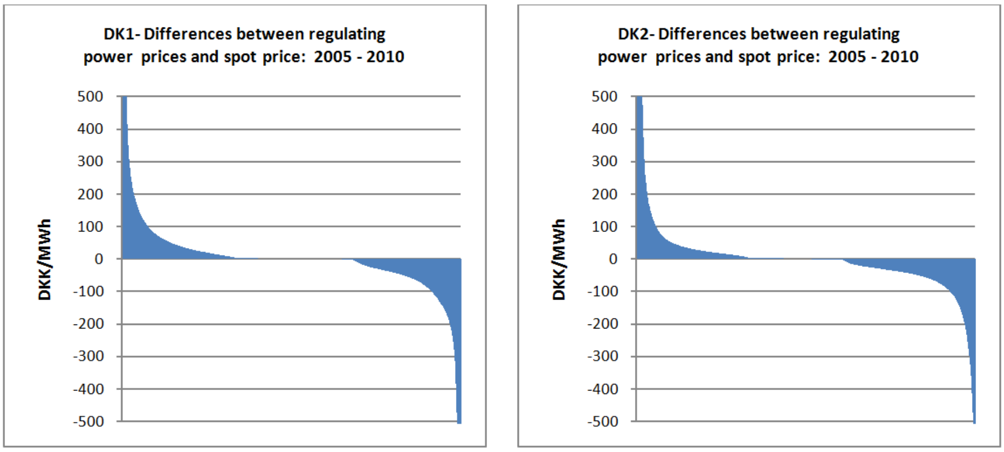

Figure 2: Historical differences between spot and regulating power prices in DK1 (West) and DK2 (East) from Jan 1st, 2005 till August 10th, 2010. For ease of illustration, the vertical axis has been limited to +/- 500 DKK/MWh, thus excluding roughly 2% of hours in both of the graphs (see Table 2 below).

As can be seen from Figure 2 and Table 2, for both DK1 and DK2, on average the absolute difference between the spot price and regulating power price has been 66 DKK/MWh. However, there is a great deal of variation in the data, as more than 1/3 of the hours had an absolute total difference of less than 10 DKK/MWh, and roughly 1/7 of the hours had an absolute value greater than 100 DKK/MWh.

	DK 1	DK 2
Average spot price (DKK/MWh)	309	325
Hours with differences greater than 500 DKK/MWh	1.5%	1.1%
Hours with differences less than - 500 DKK/MWh	0.5%	1.0%
Hours with a difference greater than 100 DKK/MWh	7.5%	5.6%
Hours with a difference less than - 100 DKK/MWh	8.5%	7.3%
Hours with a difference less than +/- 1 DKK/MWh	32.6%	24.8%
Maximum difference (DKK/MWh)	7,034	14,712
Minimum difference (DKK/MWh)	- 6,566	- 10,136
Average absolute difference (DKK/MWh)	65.5	65.5

Table 2: Historical differences between spot and regulating power prices in DK1 (West) and DK2 (East) from Jan 1st, 2005 till August 10th, 2010.

Lastly, it is interesting to note that the tips at either end of the duration curves are very steep, and as such while rare in number, those hours with large variations (e.g. very low prices) can be very interesting for the end-user.

1.4 Future developments

Increased need for regulating power & fewer providers

With the introduction of more intermittent power generation in the Nordic power system, it is anticipated that there will be an increased demand for regulating power. In the Danish system, regulating power is currently provided primarily by central power plants, in combination with import/export to Norway and Sweden where there is a high share of hydropower. As a greater portion of the electricity provided comes from intermittent sources (i.e. wind power), less will come from these central plants, thus further increasing the need for regulating power from new sources.

Demand as regulating power

One way of supplying regulating power capacity from new resources is to activate the demand side. This could be resources such as industrial or commercial electricity demand, as well as household electricity demand such as heat pumps, direct electric heating, electrical vehicles and other types of demand that can be controlled with little or no consequences to the end-users. Electricity consumption for heating or air conditioning could for example be converted into thermal energy (heat or cold) during one hour, to provide the service (desired temperature) at another hour; thus involving storage of heat or cold and the shifting of electricity demand from one time to another.

For more on the current and future potential use of demand response, please see “Benefits and Challenges of Demand Response: A Critical Review” (O’Connell, Pinson, Madsen, & O’Malley, 2013).

Nordic TSO's concept paper

In the fall of 2012, the Balance Regulation Group (BRG) of the Nordic TSOs prepared a draft discussion paper to address demand side bidding in the Regulation Power Market (RPM). The paper recognised the fact that:

> "A larger share of renewable energy sources and the sequential replacement of conventional production will increase the need for new balancing resources in the Regulation Power Market (RPM). To meet this need, new types of suppliers of balancing energy have to be found, since the traditional suppliers of balancing energy might not be able to increase their supply in the coming years. The potential of demand side bidding in the RPM has been recognised but the complexity of the issue and the technical challenges in implementation have delayed substantial demand side bidding in the RPM."

The draft paper contained a number of potential alterations that would facilitate greater demand side participation in the regulating power market, including:

- Reducing the minimum bid size.
- Relaxation of the requirement for real time measurement by allowing for ex-post verification.
- Implementation of automatic bids.
- Allowing a resource owner to change the relevant consumption bid for the next hour in the case of activation.
- Giving the owners of consumption resources a possibility to update the bid volumes before the operational hour.
- Introduction of some relief from firmness requirements for consumption units.

All of the above changes would be beneficial for a FlexPower type system, and as such, it is extremely positive that the BRG is attempting to address many of the obstacles that currently prevent demand side resources from participating in the RPM. Even if all these changes are not implemented in the immediate future, the paper in of itself indicates the direction that the BRG intends to take going forward.

Profiling system

The electricity demand for Danish end-users with a demand below 100,000 kWh/year is recorded only once per year, or once a month. Their hourly demand is thereby not known, and therefore has to be 'constructed'. This is done by first subtracting the large end-user's known hourly demand from the total demand, resulting in what is referred to as the residual demand for each hour. This process is carried out by each grid company. Each small end-user within a grid company's area is then assigned an hourly demand proportional to their demand for the entire year. For example, if an end-user has an *annual* demand equal to 0.01% of the total *annual* residual demand, then in *each hour* of the year they would be assigned 0.01% of the residual *hourly* demand. This is referred to as a *profiling system* and results in all users without hourly metering sharing the same profile (also known as the residual profile). As such, the constructed profile will be used for the settlement, regardless of the individual demand.[2] The result for a small end-user under the profiling system is that there exists no economic motivation to adapt their demand to hourly electricity prices.

Interval meters in Scandinavia

In Sweden, most households have a remotely read meter and demand can be settled hourly. In Finland, practically all consumers will be hourly read and settled by 2014. In Norway, all consumers will have an interval meter by 2017.

In Denmark, half of all end-users have a meter with remote reading, however it is not used as an interval meter. It has been politically agreed that all households shall have an interval meter, and these are expected to be in place by 2020.[3] While the other Nordic countries have, or are in the process of planning, standard hourly settlement for households, the electricity sector in Denmark is negotiating a different plan. Currently, hourly settlement of data, e.g. for end-users with a demand above 100,000 kWh/year, requires that all data must be ready after five working days. The Danish grid companies claim that this will be too costly for the millions of small end-users. Instead, they suggest a special system with a longer timeframe for verification of data and completion of transactions.[4]

This proposed system will make it possible for end-users to buy electricity at hourly spot prices, or use other time varying tariffs. However, the suggested system has the consequence that demand cannot be used as regulating power. This is due to the fact that unbalances and regulating power are settled a few days after the operating day. It is expected that the new system will be operational by October of 2014.

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[2] In Finland and other countries, the profiles are defined for different types of end-users. E.g., single-family houses with electric heating is one such profile. The profiles are based on detailed measurement of a sample of representative end-users. This setup may distribute the electricity more accurately between different groups, but gives (such as in the Danish system) no economic motivation for demand response.

[3] 1) "Vækstplan DK" (Finansministeriet, 2013). 2) "Bekendtgørelse om fjernaflæste elmålere og måling af elektricitet i slutforbruget". (Danish Energy Agency, 2013) 3) "Pseudo-forskrift D1: Afregningsmåling" (Energinet.dk, 2013).

[4] The new system is called "3. afregningsgruppe" or "flexafregning" in Danish. See also"Systemplan 2012" (Energinet.dk, 2012).

2 The FlexPower concept and design

2.1 Market and prices

FlexPower objective – Design and testing of a market

The objective of FlexPower is to develop and test a real-time market for regulating power that will attract a large number of small-scale resources (demand and distributed energy resources) to the regulating power market. This real-time market can be created by maintaining the current spot market as the basis for planning of the system operation, and then expanding the current regulating power market with a new system: *A one-way price-signal for regulating power*. The fundamental idea behind the FlexPower concept is that the market should co-exist with the current market structure, be simple and straightforward for the end-user, and be technologically neutral.

Co-exist with the current market structure

Under FlexPower the current regulating power market will exist and function as today, and as a starting point larger power plants will still contribute with the main volume in the regulating power market. As was highlighted above, when the system operator selects a bid from the sorted NOIS list, the marginal price is the most expensive bid activated. The fundamental idea behind FlexPower is that if a Load Balance Responsible (LBR) is activated in the regulating power market to deliver regulating power by increasing/decreasing the consumption from end-users, the marginal price (or a form of it) could then be sent out as a one-way price signal to end-users participating in FlexPower.

Every five minutes this price signal could be sent out to all participants with controllable loads that elect to subscribe to FlexPower. Based on historical consumption data, a Balance Responsible would bid in as per today, with this bid incorporating the anticipated FlexPower demand response (left side of Figure 3 below). At the same time, the Balance Responsible would also send out a price signal to its FlexPower end-users (right side of Figure 3 below).

Under the current market structure, regulating power bids submitted by the LBR must have a minimum bid size of 10 MW. In a FlexPower proposal comprised of many small end-users, if the minimum bid size restriction was loosened, to for example 1 MW, this could allow for a number of smaller bids of varying prices as opposed to one larger bid, and therefore smaller ‘steps’ in the left side of Figure 3.

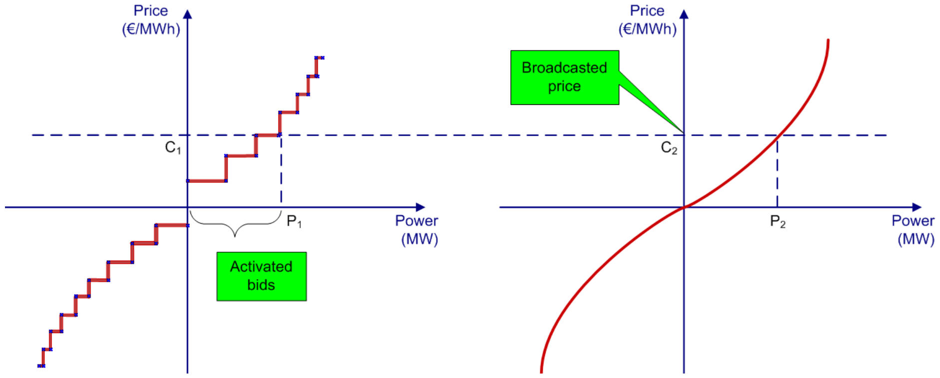

Figure 3: The current market for regulating power (left) and the suggested one-way price signal sent to the end-user from the LBR/retailer (right). The price curve is based on the latest activated regulating power price. This example represents an up regulation.

Simple for end-user

Response to the price signal is voluntary and the price signal acts as the final settlement price. As such, the system is very simple seen from the end-user perspective, as it does not require bidding, a promised reaction, or a complicated settlement procedure. In addition, it is assumed that no manual reaction is needed, as a typical end-user set-up will include equipment that controls demand side appliances' electricity use, and records the price. Through this local controller, customer preferences are respected via predetermined set points and/or parameters.

The end-users that could be interested in participating in this system would have some electricity uses that are suitable for control. This could be electricity in relation to heating (e.g. heat pumps, direct electric heating, or industrial processes), cooling (e.g. industrial cooling, retail, air condition etc.), pumping (e.g. a water treatment plant) or charging of electric vehicles. In addition, micro generators could also be active in this market. This could be small CHP-units or other controllable generation.

Technologically neutral

The design of the FlexPower concept is intended to be technologically neutral, in the sense that the same price signal is sent to each unit regardless of whether it is a heating/cooling unit, electrical vehicle, industrial process, or local generation unit. However, local parameters and settings for the various units can of course differ and be regulated by the local control device.

FlexPower time plan and interplay between actors

The figure below is one way of presenting the interplay between the actors in FlexPower.[5] In principle, the description of the "loop" can start at any of the

[5] For more on the FlexPower concept, market design, interplay between actors, etc., please see (Bang, Fock, & Togeby, 2011).

points, but since FlexPower is focused on introducing more end-users to the regulating power market, the following description will start with the 5-minute metered data at the end-user.

Data metering and collection

For all customers participating in FlexPower, the end-user's consumption is read in an interval meter each 5 minutes. Once a day, this data is sent to the distribution system operator (DSO), whom forwards it to the LBR. To improve the LBRs price signal computation process, it is envisioned that a small percentage of FlexPower end-users will send unverified 5-minute data directly back to the LBR, thus providing the LBR with immediate feedback, and allowing the LBR to continually update their price signals accordingly.

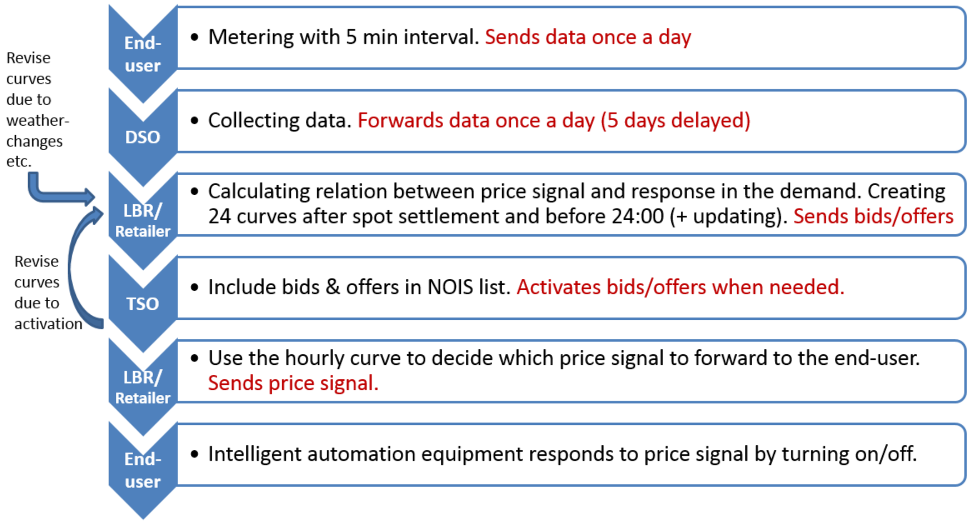

Figure 4: The FlexPower process, starting with the end-user's data being measured and sent daily.

Bidding on spot market

Based on historical consumption data, the LBR forms a prognosis for each hour of the next day (hourly values), and this is used to bid on the spot market (before 12:00). The LBR also creates 'relation curves' for each hour showing the relation between the power available for up or down regulation and the price.

Bidding on regulating power market

After the spot market settlement for the following day has been released around 13:00, the LBR incorporates this information into its continuous value curve calculation. These expected demand side reactions to the regulating power price signals (the hourly curves) are converted into a series of stepwise bids and offers for each hour. The LBR sends the series of bids and offers for each hour to the TSO to participate in the regulating power market. One hour before each operating hour, an updated final version of these stepwise bids and offers for regulating power (based on the curves) are sent to the TSO. The bids and offers, and resulting price curve could resemble those depicted in Figure 3 above.

Activation of bids and offers

The bids and offers for delivering up or down regulation are collected in the common Nordic NOIS list. All bids and offers from load balance responsible and generation balance responsible actors are sorted in the list with increasing prices for up-regulation (above spot price), and decreasing prices for down-regulation (below spot price). When an imbalance in the system occurs, bids or offers from the list are activated by the transmission system operator (TSO) and the corresponding LBR is contacted.

Activation of end-users

Based on the activation price and the relation curves, the LBR then sends a price signal to the end-users participating in the FlexPower system. At the FlexPower end-user, equipment with automation will include the new price in their internal optimisation.

The local equipment may acquire a prognosis for the regulating power price to reduce risk. If electricity demand can for example only can be disconnected for a limited time, the expected future price is important.

FlexPower data and money streams

The financial interaction and some of the data streams between different players can be illustrated as below in Figure 5.

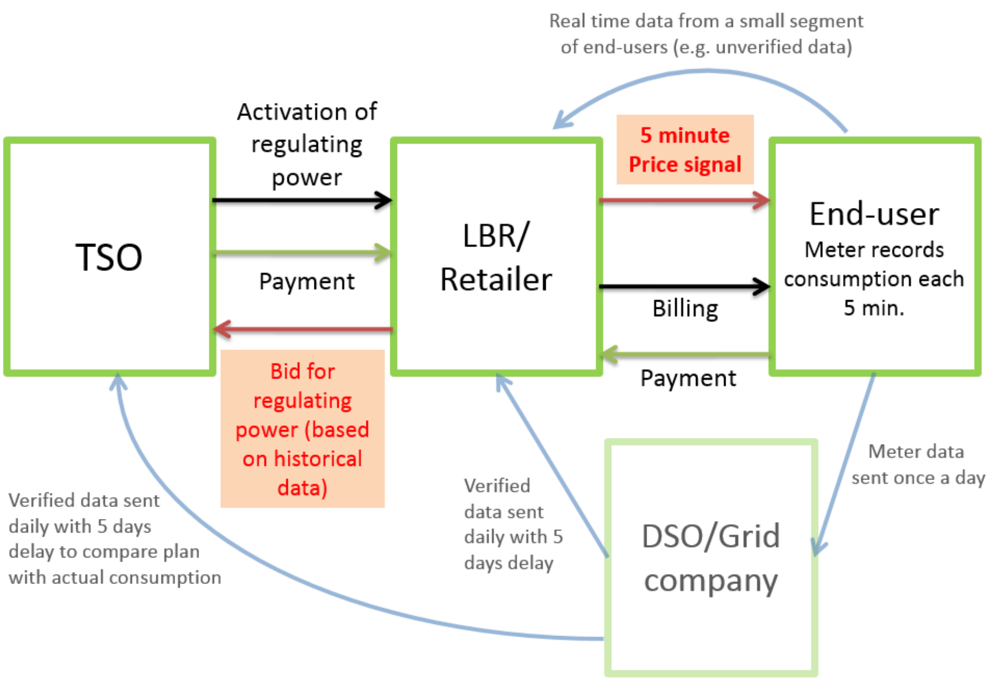

Figure 5: Overview of the financial and data interactions between different players.

Starting in the centre of Figure 5 and following the arrows:

- LBR/retailer sends bids/offers to TSO based on historical consumption data.
- When there is a need for regulating power the TSO activates bids and offers, and there is a payment to the LBR/retailer afterwards.
- The LBR/retailer reads the curves calculated based on the historical consumption data to determine what price signal is adequate for obtaining the demanded response. This price signal is sent to end-users.
- The end-users respond automatically to the price signal by changing consumption. The resulting consumption is read in the meter and data is sent once a day to the DSO.
- DSO forwards the meter data to the LBR/retailer after quality assurance.
- The LBR/retailer bills the end-user.
- The end-user pays the LBR/retailer.

Simulated prices

The FlexPower price sent from the TSO to the balance responsible described above already exists today. This price is the cost associated with the most recently activated regulating power bid, which as noted above, become increasingly expensive with each activated bid. However, this price is considered confidential and therefore only the balance responsible whom receives an activation of a bid knows what the current regulating power price is. Afterword, it is only hourly prices that are published, and these prices indicate the cost of the most expensive bid that has been activated during each hour.

For the purpose of this project, artificial FlexPower prices have been generated. The five-minute prices consist of two elements:

1. The hourly spot price, and
2. An element indicating the difference between the bid for regulating power and the spot price (this element can be positive or negative).

The spot prices are known for the next 11-35 hours in advance. The second element is however not known. The need for regulating power (in MW) has a stochastic nature, however, some autocorrelation exists; If up-regulation is required in one five-minute interval (positive price correction), the demand in the next five-minute interval is likely to be similar. This fact was the starting point for constructing a first order auto correlated model and a Markow model.

Markow model

Based on real market data (from 1.1.2002 to 19.1.2009), a Markow model was estimated. The difference between the balancing prices and spot prices were grouped in 29 intervals of 100 DKK/MWh (10 øre/kWh) from less than -1,400 DKK/MWh, to more than 1,400 DKK/MWh. The cells in the Markow matrix define the probability of going from one interval to another interval in the next time step.

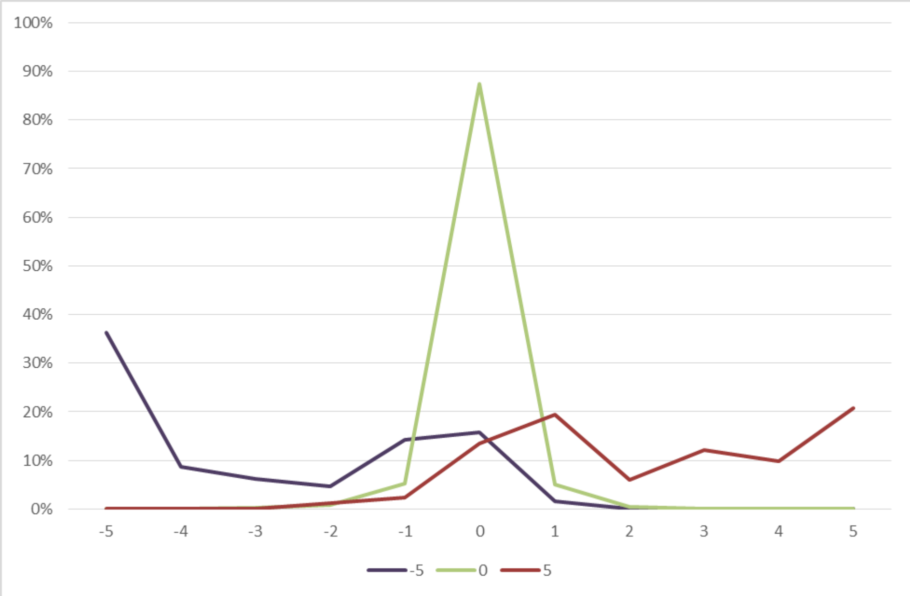

Figure 6. The probability of being in different intervals in the next time step, when the regulating power corresponds to -5, 0 or +5 in the time step before. The scale is from -14 to +14. Only the central part is shown here. E.g. if the regulating price is close to the spot price (interval 0), then the price will increase to interval +1 in 5% of the cases.

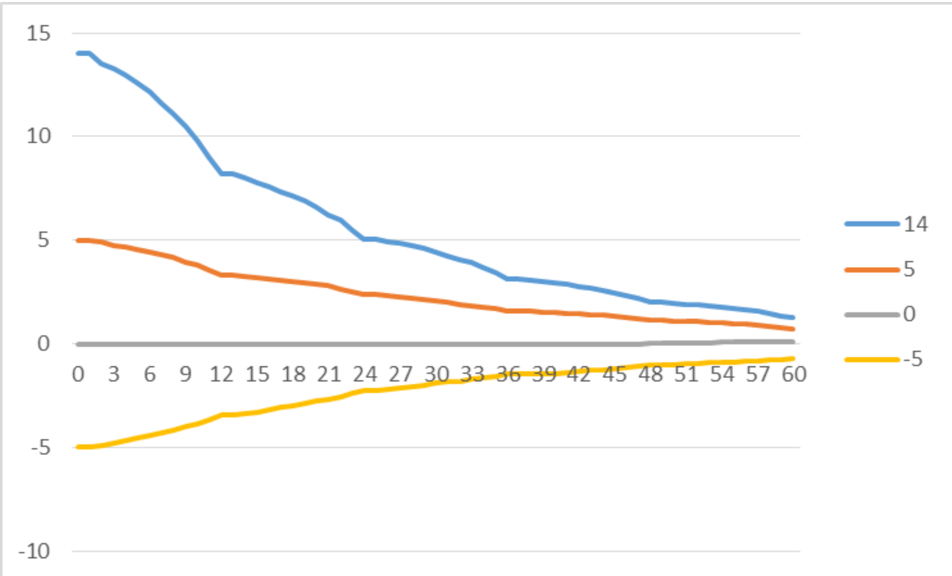

Figure 7. The development (in 60 time steps) of the median in four cases of the starting point: +14, +5, 0, -5. The development towards 0 is clear.

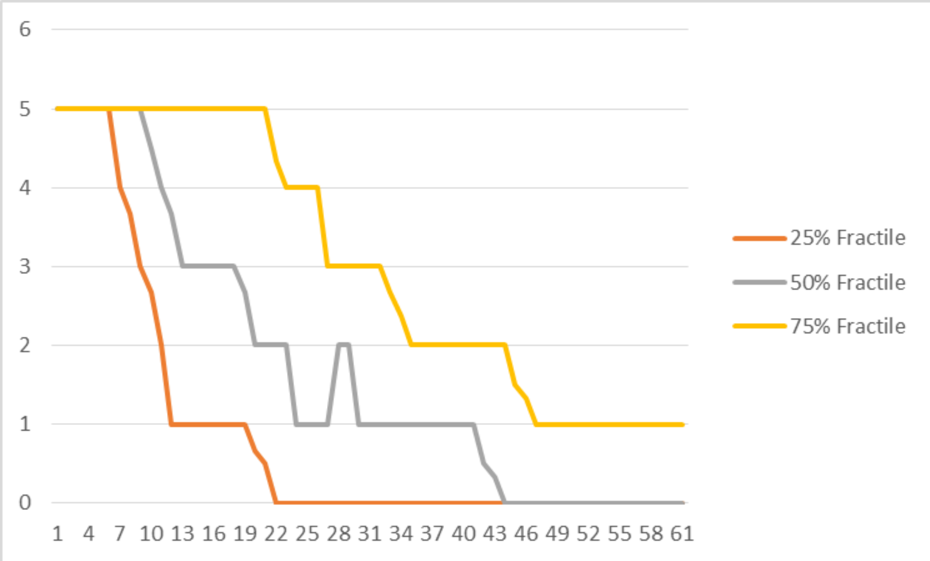

Figure 8. The development of different fractiles (60 time steps) when the starting point is +5.

Simulation of 5-minute prices in line with historical prices

The first step in simulating 5-minute regulating prices was investigating how spot and regulating power prices had developed in Denmark from 2001-2011.[6] The data forming the basis for the simulated 5-minute prices are actual spot and regulating prices for the two Danish Nord Pool price areas DK1 (West of the Great Belt) and DK2 (East of the Great Belt). The hourly historical regulating power prices were then adjusted so that:

- Each hourly price is repeated 12 times in order to construct 5-minute datasets.
- Each simulated 5-minute power price lies between the spot price and the activated regulating power price, or is equal to the spot price in cases of no regulation.
- The simulated 5-minute price equals the regulating price at least once every hour since the regulating hourly prices are the extremes (maximum in case of up-regulation and minimum in case of down-regulation) of the actual activated bids for the particular hour. In order to achieve this for every hour the twelve 5-minute simulated prices are moved by a common amount so that at least one equals the actual regulating price.

A number of other parameters were also introduced, with one of the most relevant being the number of times during an hour there was a price shift (represented by r0 below). A simulation of historical regulating power prices was carried out, and a sample of the results are displayed in Figure 9. The figure displays an example of actual spot and regulation prices for DK2, together with the simulated 5-minute prices for two different simulation setups.

[6] The description of the simulation of 5-minute prices herein is summarised from (ENFOR, 2013 a). Please see this report for more detail. For a summary of the WP5 work, please see (ENFOR, 2013 e)

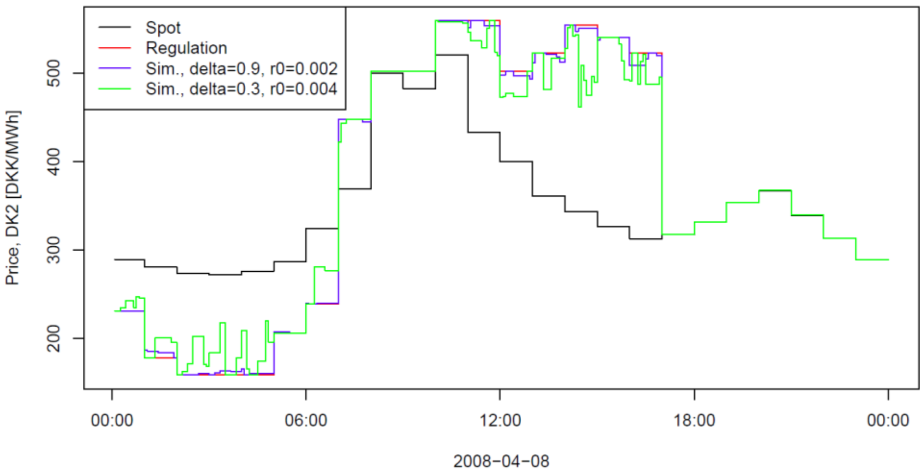

Figure 9: Example of actual spot and regulation prices for DK2, together with the simulated 5-minute prices for two different simulation setups (ENFOR, 2013 a).

Note that in the simulation depicted by the green line, the number of shifts from the regulating power price each hour (the red line), is much higher than under the blue scenario. This is due to the higher r0 value. In addition, the extent of the shift is also greater in this scenario.

Simulation of 5-minute prices for field study

For the demonstration phase of the FlexPower project, 5-minute regulating power prices were required. However, as was highlighted above, while the actual hourly spot prices are known 11-35 hours in advance, the inter hour regulating power prices (those associated with the cost of activating the latest bid) sent from the TSO to a balance responsible are confidential. As such, it was necessary to use the process outlined above to simulate 5-minute prices based on actual spot prices and hourly regulating power prices. Hourly regulating power prices are however first published a few hours after the hour of operation, and as such, the simulated prices were based on spot and regulating power prices that had been shifted 6 hours in time. As the end-users in the study were not paying for electricity on an hourly basis this 6-hour shift did not have any effect on their electricity bill or the study results. The operational setup for the 5-minute prices simulation portion of the field study is outlined in Figure 10.

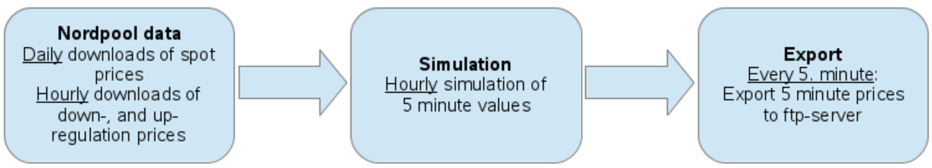

Figure 10: Outline of the operational procedure applied in order to export simulated 5-minute prices. Since the actual regulation prices are delayed, the export shifts 6 hours in time in order to be able to export prices for the upcoming 5-minute interval (ENFOR, 2013 a).

2.2 Technical requirements

Communication

For a system such as FlexPower, which is reliant on reactions to continual 5-minute price signals, to work in practice, a number of communication issues must be solved. Within the project, EURISCO was the leader of the communication work package, which concerned the technical specifications, design and implementations of the data communication services.

One of the first communication tasks was to generate a mutual consensus regarding the actors, data communication interactions, and basic structure for the design of the FlexPower data service.[7] This structure is displayed below.

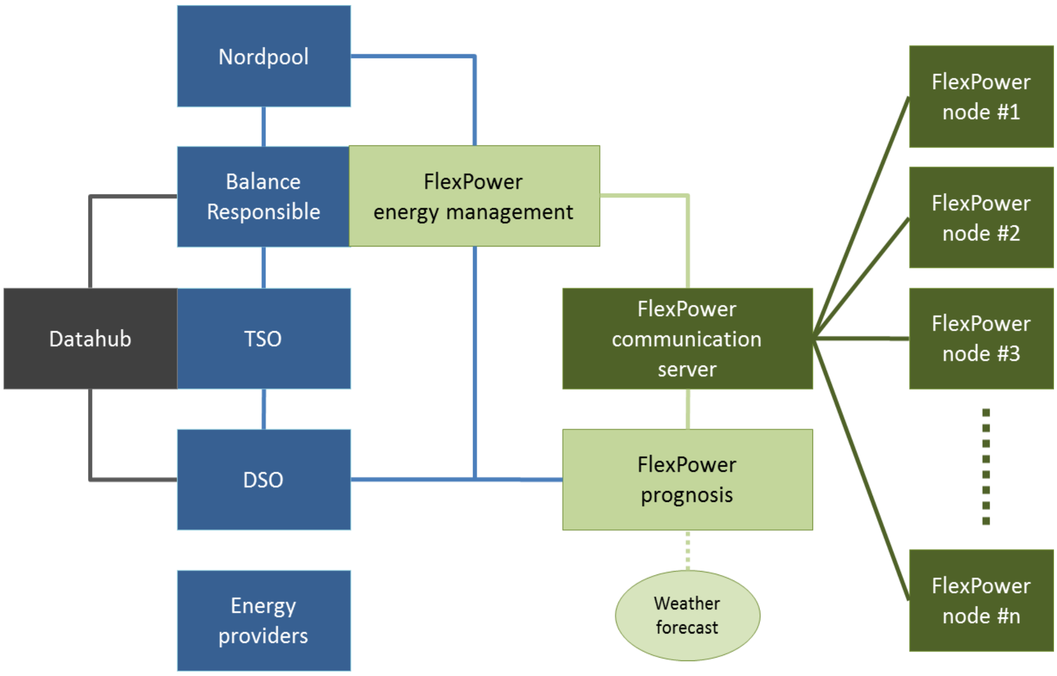

Figure 11: Communication overview (EURISCO, 2013 a)

The conceptual FlexPower design consists of a price server that fetches information from:

- The ENFOR FTP-server, which included simulated prices (as described above) as well as price forecasts,
- The Energinet.dk price service, and
- The FlexPower nodes (DFR nodes) in the field.

[7] A more detailed description of the FlexPower technical interfaces can be found in: Interface specification (D7.1) and Information Exchange specifications (D7.2) (EURISCO, 2013 a), Concept design report (EURISCO, 2013 b), and 'FlexPrice – the definition' (EURISCO, 2012).

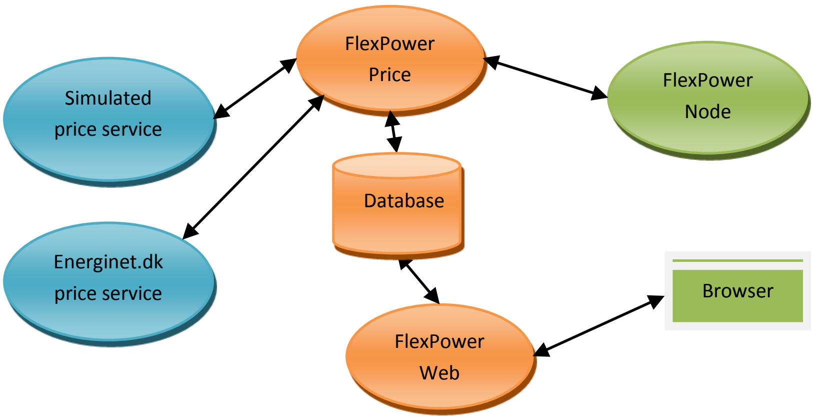

Figure 12: System illustration (EURISCO, 2013 b)

A database between the Price server and the FlexPower webserver holds the information to be distributed between the parties involved. Information regarding the current status of the FlexPower nodes can be viewed with a standard web-browser, which also includes the predicted and historical price signals.

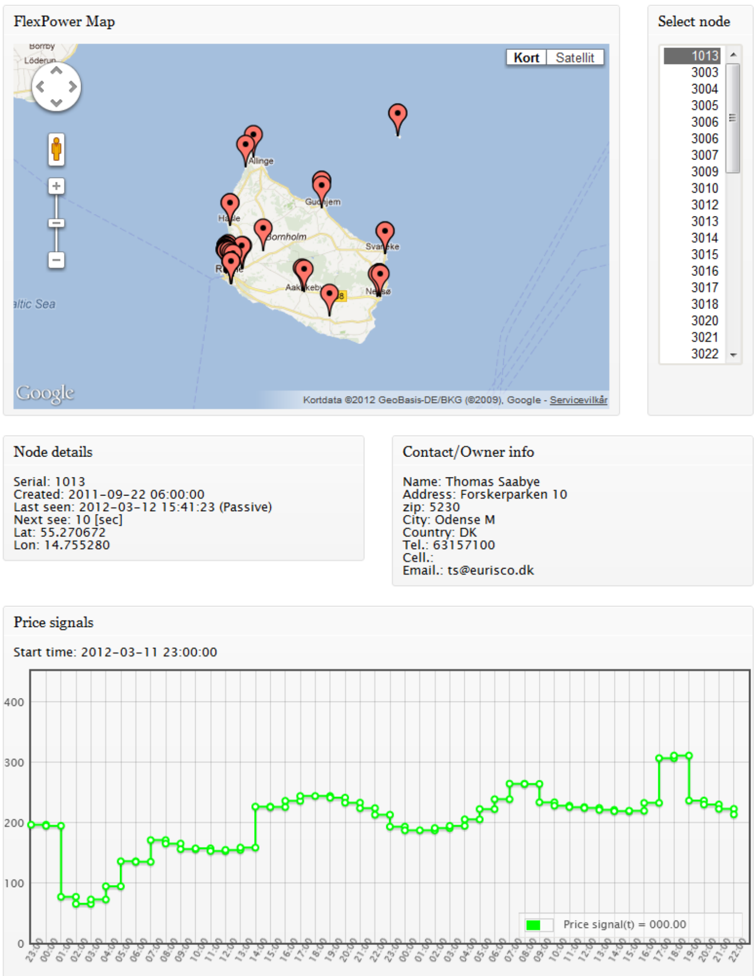

Figure 13: Web user interface. Note the upper map displays the Danish island of Bornholm where the demonstration phase of the project took place (EURISCO, 2013 b).

The web interface uses Drupal 7 as the Content Management System (CMS), and the web interface itself is developed as a module for easy installation in Drupal. When the module is installed, extra rights are needed for users to log in and see the map.

FlexPrice

One of the most important aspects of FlexPower is the actual price signal that is sent out to the end-users. A 'Control-by-price' signal can be defined as Information sent to electricity producers and consumers, as an incentive to maintain, increase or reduce production or consumption.

In order for this to work in a broad context, a well-defined format has to be agreed on by the parties involved, one that is generic and simple to understand and implement.

The following requirements have been the basis for definition of the 'FlexPrice' format:

- A structure that will support both real market price (e.g. SPOT price) and an index level (e.g. high, medium, low)
- A simple uncertainty value (high, low) for each price value to support forecasts.
- A unique ID for each price signal for traceability.
- A timestamp for each entry in the price signal.
- A unit definition according to ISO 4217 incl. multiplier (Wh, kWh, MWh)

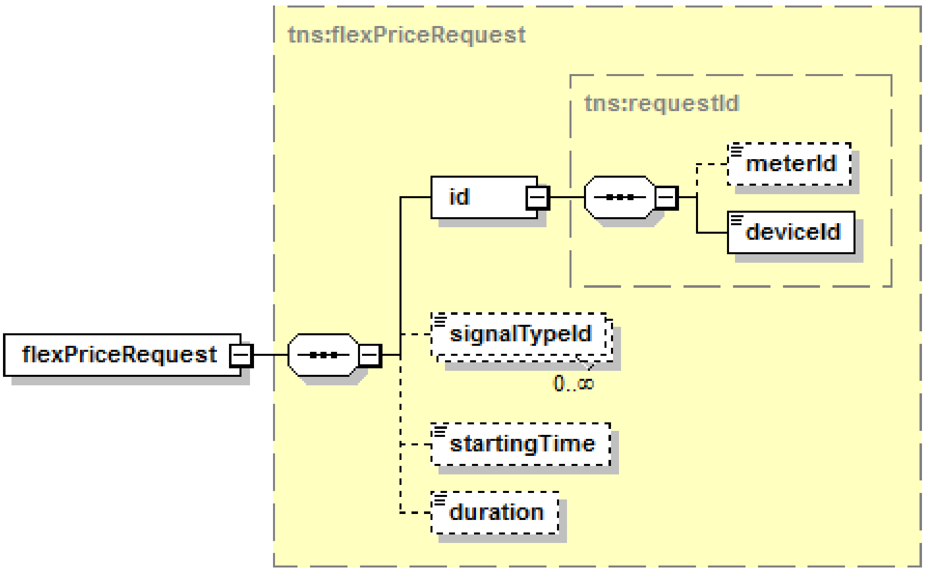

Figure 14: FlexPrice request structure (EURISCO, 2012)

The request can be as simple as just specifying the ID for the requesting client, and based on a table of known clients and their settings the server can respond with the right signal(s). If the client is somehow limited, or the project structure is not configured to store the client settings, the client can request a specific signal for a given period. If more than one signal is needed, the client has to do multiple requests, or the project could use a comma-separated string to send multiple signalTypeId's.

The response structure is very flexible and allows for:

- Sending a bundled signal which includes (all in one response)
  - A price signal
  - A prognosis
  - An upper and a lower limit (using either fractiles, percentage or a high price)
  - A grid cost
- Sending only the requested signal (for a given period)
  - Useful for limited clients, such as microcontrollers, which are low on memory resources.
- Sending a list of available signals
  - Useful for new clients and more intelligent clients that can automatically subscribe to new servers.

2.3 Control Strategies

Having received the above-described FlexPrice signal, it is then up to the local controller to determine how the local device(s) should respond to this signal. Within the FlexPower project, these control strategies were investigated at two levels, both in a more complex fashion, which will be relevant for a more advanced version of FlexPower, and in a more simple fashion that was needed for the field test.

Complex control strategies

Advanced control strategies were studied and a number of papers were published:

- "Indirect regulation of many DER units through broadcasted dynamic price signal" (Nørgaard, Sossan, & Nielsen, 2011),
- "Evaluation of the performance of indirect control of many DSRs using hardware-in-the-loop simulations" (Sossan & Bindner, 2012 a),
- "A comparison of algorithms for controlling DSRs in a control be price context using hardware-in-the-loop simulations" (Sossan & Bindner, 2012 b).

- “Scheduling of Domestic Water Heat Power Demand for Maximizing PV Self-Consumption Using Model Predictive Control” (Sossan, Kosek, Martinenas, Marinelli, & Bindner, 2013),
- “Identification of the flexibility and control strategies for indirect controlled flexible demand” (Sossan, 2013).

Heating of the DTU FlexHouse was one example of a control strategy that was tested in practice. FlexHouse is a 100 m^2 office building with 10 kW electric heating elements. The control problem has two main challenges. There is uncertainty regarding the heat demand (e.g. because of solar influx and the use of the office space) and the exact future electricity price is unknown. Therefore, in practise it is impossible to perform an optimal control.

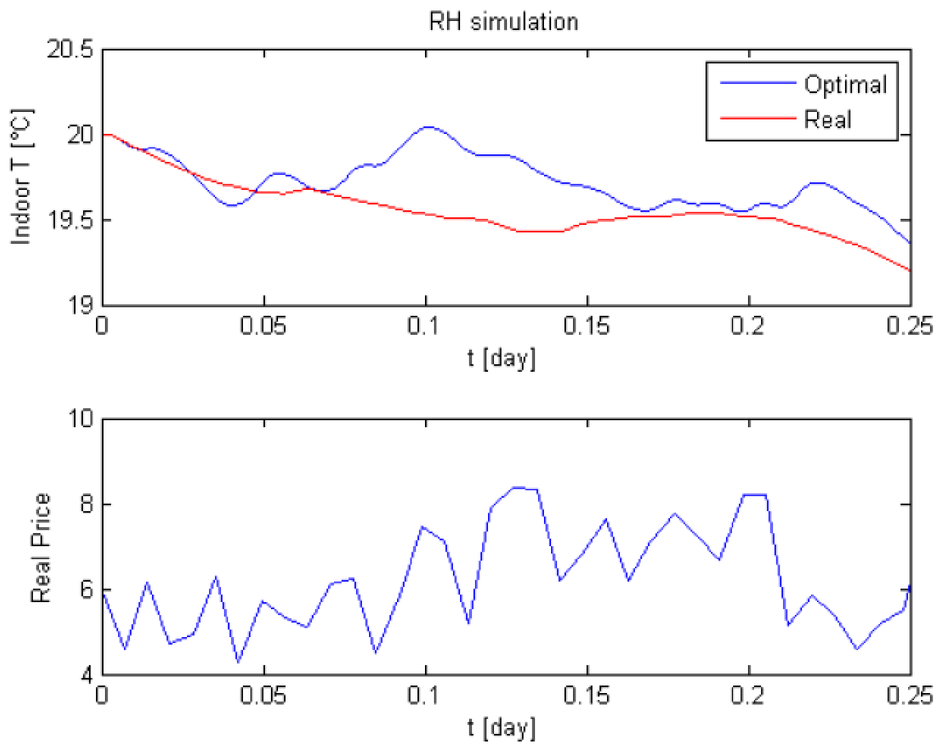

Figure 15. Control under uncertainty. In the upper graph, the blue line represents a theoretical optimal solution, while the red line is the practical solution with uncertainty regarding the future electricity price.

Field test control strategy for temperature controlled devices

Due to technical constraints and for the sake of simplicity, for the WP9 field test a more simple control strategy was required.

Most appliances can only shift their electricity usage for a maximum of a few hours, and therefore the local controller must determine whether to use electricity now, or postpone this usage. In a situation without any knowledge about upcoming prices, the only way of judging whether the unit should react now or wait, is to look at past prices, and determine whether the current price is high or low relative to these past prices.[8] If for example the current price is much higher than past prices, then there is a higher probability that the current price is also higher than future prices will be, and therefore the unit should postpone its usage.

As such, an algorithm was installed in the SmartBoxes, and this algorithm converted the received 5-minute absolute prices, into a *relative price*.[9] In essence, this algorithm determined if the latest price signal was high or low relative to the price signals it has received in the recent past. The SmartBox then reacted to these relative prices according to the pre-defined settings and the state of the device.

Each time a price was received a new relative price was calculated with equations (1.1) to (1.4) presented in (Nyeng & Østergaard, 2011). If the price is normally distributed, these equations standardise the values so the resulting relative values P_{rel} follow a standardised normal distribution.

$$P_{rel} = \frac{P - P_{avg}}{P_{dev}} \tag{1.1}$$

$$P_{avg,i} = P_{avg,i-1} + \frac{\Delta t}{\Delta t + \tau}\left(P - P_{avg,i-1}\right) \tag{1.2}$$

$$P_{var,i} = P_{var,i-1} + \frac{\Delta t}{\Delta t + \tau}\left(\left(P - P_{avg,i}\right)^2 - P_{var,i-1}\right) \tag{1.3}$$

$$P_{dev,i} = \sqrt{P_{var,i}} \tag{1.4}$$

Δt is the time between price updates and Tau (τ) is a time constant with a default value set to 3h (36 time steps).

For the temperature control, an offset from the target temperature is needed. To calculate this, four variables are used as shown in Figure 16.

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[8] It should be noted that forecasted prices were available along with the simulated prices. They covered 12 hours in 5-minute steps, were updated every 5 minutes, and converged towards the spot prices for the longer horizons. However, for the sake of simplicity, these forecasted future prices were not used in the field test.

[9] The SmartBoxes were lacking in computational power, and therefore a rather simple algorithm was required. The algorithm did not require many inputs and delivered a first order approximation of a weighted rolling average. For more details on the algorithm, see (Nielsen, Zimmermann, Rasmussen, & Pedersen, 2013).

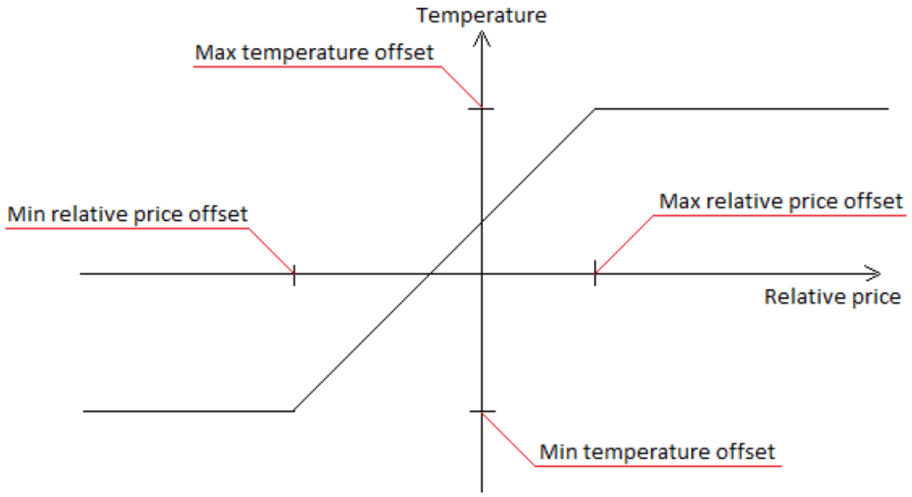


Figure 16: Mapping between relative price and a temperature offset (Nielsen, Zimmermann, Rasmussen, & Pedersen, 2013)

As indicated above, the computation of the relative price is based on historical prices and the parameter τ is used adjust the time horizon. In the field test, a τ of 36 was used (corresponding to a time constant of 3 hours, 36 x 5 min. = 3 hours).

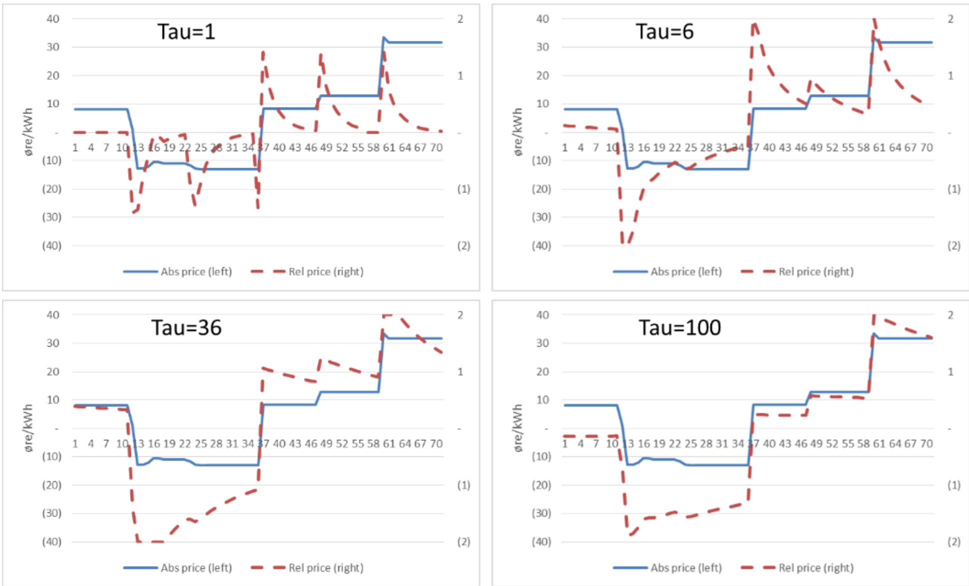


Figure 17. Illustration of how the absolute price is transformed to the relative price with different values of Tau. The axis for the relative price is restricted to +/-2.

Figure 17 shows how different values of τ change the relative price. Further study is required to determine optimal values of τ for different types of appliances.

2.4 Advanced options

Within the current FlexPower project, the sole ancillary service that is looked at is regulating power. However, looking further down the road, one could envision a 5-minute real time electricity price system being able to deliver a number of services.

Frequency control

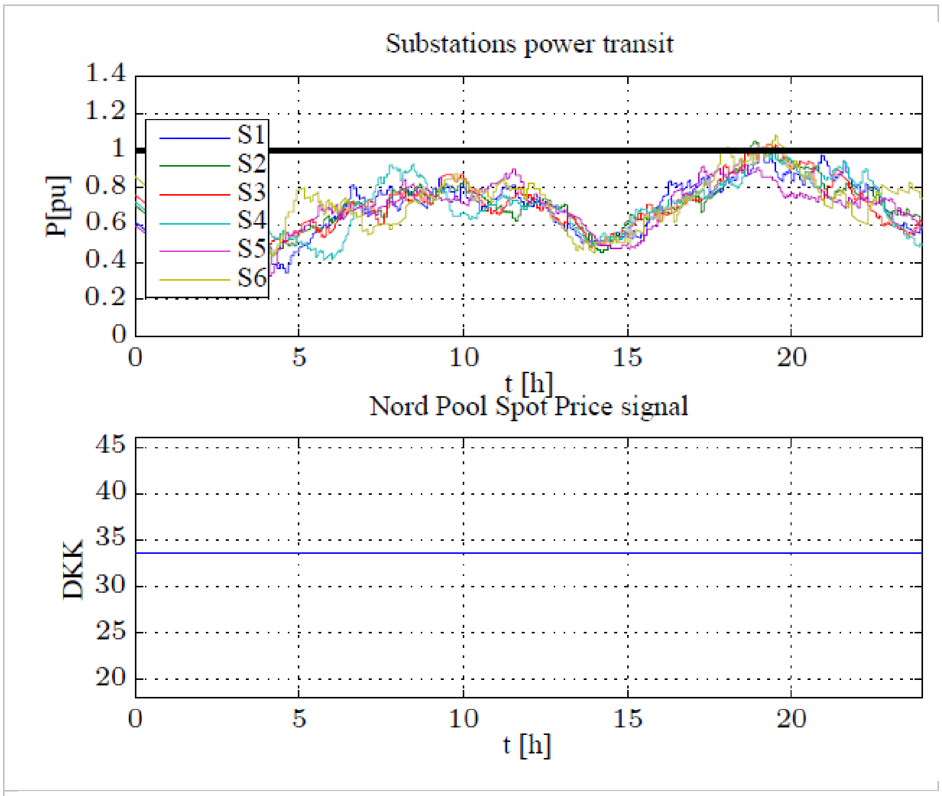
It is the responsibility of the local TSO(s) to maintain the frequency of a synchronous area and it does so via purchasing automatic reserves in the market. Depending on the type, these services can receive both a reserve payment, and an energy payment if activated. As the name would indicate, they are activated automatically in accordance with frequency deviations, but are expensive and have limited capacity. A balance responsible and/or aggregator with a number of FlexPower end-users with local control devices could have frequency monitoring devices installed in these local control devices as well. In addition to providing regulating power according to 5-minute price signals, these end-users could also (again, according to pre-determined set points) have particular devices automatically increase or decrease their electricity demand.

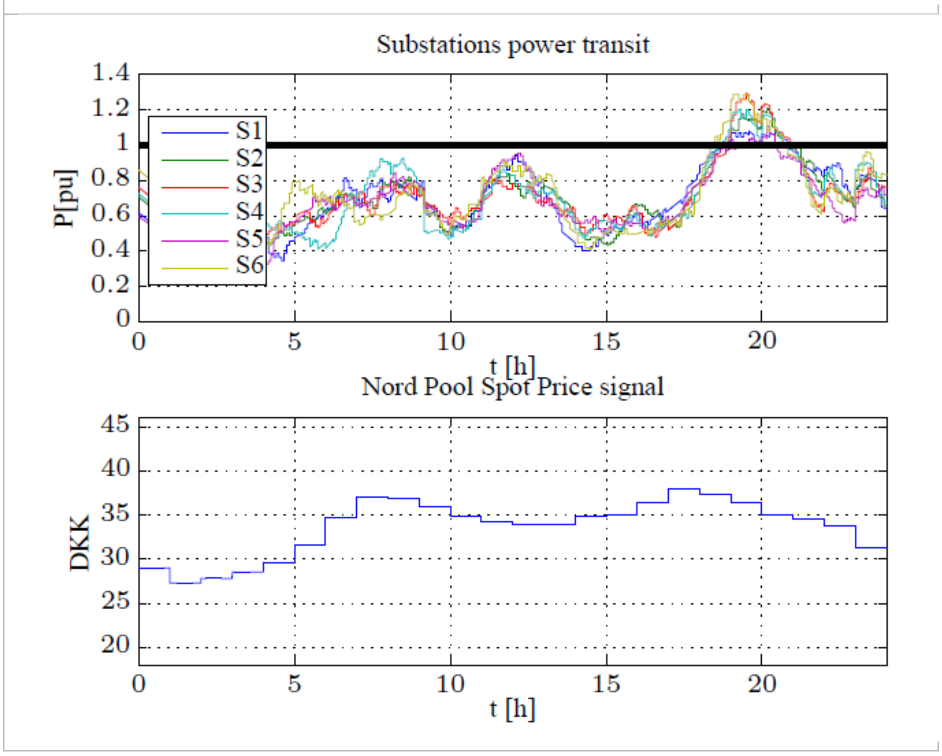
Avoid overloading of local grids

In a future with large numbers of heat pumps and electric vehicles drawing additional electricity, there could be the potential for the overloading of local grids during peak times, and/or when there are low spot prices for electricity, particularly if the prices in the preceding hours have been high. One way of relieving these potential local grid congestions in a dynamic fashion would be to send an additional distribution tariff to all end-users within the affected area, thereby giving them a financial incentive to reduce their consumption. This additional congestion tariff could be added on to the existing 5-minute price, thereby allowing the local control system to incorporate this additional information into its local control calculations.

In Figure 18, results of a computer simulation is shown. Six substations are simulated and the total capacity (depicted by the thick black line) is such that the existing demand can be accommodated in the standard case with no demand response. When time varying prices are introduced, the peak is increased, thus exceeding the capacity. This is driven by the fact that in this case the highest prices occur a few hours before the demand peak. This can be realistic because the prices are determined at the price area level (i.e. DK1 or DK2), while specific substation may be dominated by e.g. residential consumers. As illustrated in the last panel of Figure 18, introducing individual real-time prices per substation largely solves the problem of overloading.

In the study, the tested price mechanism is reactive in the sense that it can only increase the price when overloading of a substation is found. This results in the postponement of some electricity demand. However, in this test, moving demand forward in time by lowering the price in not considered. For more details, see (Sossan, Marinelli, Costanzo, & Bindner).





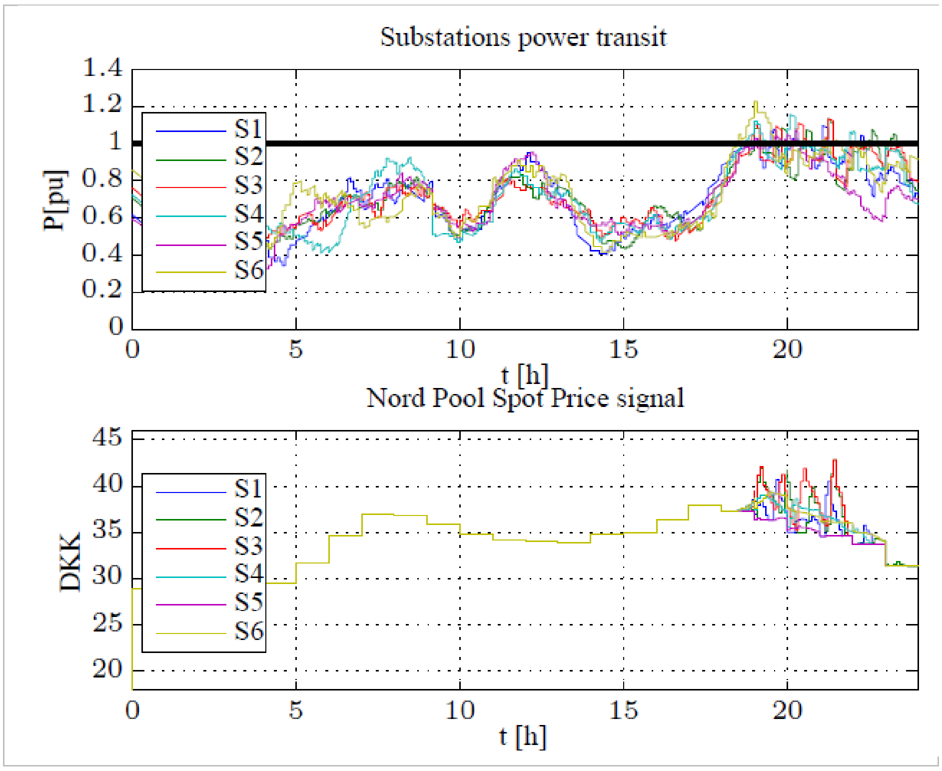


Figure 18. Loading of six substation in three cases: a) Top: Flat prices, b) Middle: Time varying prices, c) Bottom: Time varying prices with real time dynamic pricing to minimise overloading of substations.

Voltage quality in local grids

For some local grids, keeping the voltage within the acceptable limits (+/- ca. 6%) is more critical than the potential overloading of cables and transformers. If a DSO or balance responsible has sufficient knowledge about the real-time loads of its end-users, and sufficient computing power, it is possible to compute the voltage at various points in the grid. If any levels become critical, the 5-minute broadcasted price could be adjusted accordingly for the relevant end-users.

Market for energy and reserve capacity procurement

Another more advanced option that was investigated within FlexPower was the development of a market for energy and reserve capacity procurement. These findings were detailed in "Development of simultaneous energy and reserve dispatch model and corresponding pricing mechanism" (Delikaraoglou & Ding, 2012).

New potential market designs

The FlexPower market design as described above is largely based on the current electricity markets setup. Within the project, potential new electricity market designs were also investigated in a report entitled "New organisations in electricity market" (Li, Zhang, Ding, & Østergaard, 2013).

3 Practical results

3.1 Bornholm testing

The purpose of the FlexPower field test was to assess how the set-up worked in practice, both from a technical and practical viewpoint, and in terms of how end-users react to 5-minute simulated regulating power prices. The field test took place on the Danish island of Bornholm, and involved four types of end-users: Bootle coolers, houses with direct electric heating, industrial applications at a wastewater treatment plant, and diverse on/off devices. Inputs included simulated 5-minute prices (see ENFOR, 2013 a) and control stragtigies that determined how the local controller should react to these prices (as described in section 2.3 previously). The practical and technical aspects are described in detail in a WP 9 report (Nielsen, Zimmermann, Rasmussen, & Pedersen, 2013). The figure below provides a simplified overview of the elements involved in the FlexPower field test.

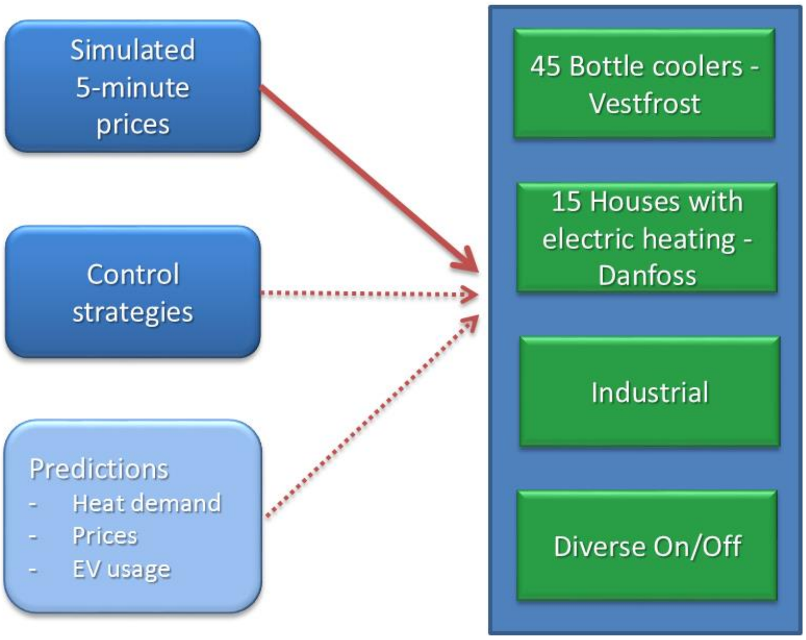


Figure 19: Overview of the elements involved in the FlexPower field test. Aspects in the light blue box were investigated in the FlexPower project, but were not direct inputs in the field test.

Simulated 5-minute prices

As was discussed previously in section 2.1, updated inter-hourly regulating power prices are not made public, and therefore the field test utilised simulated 5-minute regulating power prices that were based on actual hourly spot prices and regulating power prices.[10]

[10] For a more detailed description of how these simulated 5-minture prices were produced, please see (ENFOR, 2013 a).

Control strategy

Via the FlexPrice[11] price signal, 5-minute prices were sent out to local control devices installed at end-users. These controllers are referred to as a SmartBoxes[12], and they are capable of controlling the power consumption of the connected appliance in accordance with the price signal and pre-established parameters. In addition to receiving an updated price every 5 minutes, the SmartBox can also receive updated configuration files, which allow for updates to the pre-determined parameters, as well as new firmware, etc. Upon receiving the FlexPrice signal, the control algorithm described in section 2.3 converts this price signal to a relative price. The SmartBox then reacts to these relative prices according to the pre-defined settings and the state of the device.

Predictions

Weather forecasts, price forecasts, and forecasted future driving requirements for EVs, are all examples of predictions that can be utilised by the local controller to better optimise the electricity usage of end-user devices. In a commercial version of FlexPower, such forecasts would very likely be employed by the end-user and/or balance responsible. These aspects were all studied within the FlexPower project, and price and heat forecasts were available, but for simplification purposes, they were not implemented in the field test.

Bottle coolers

Within the field test, 45 Vestfrost bottle coolers on Bornholm were each attached to SmartBoxes. For these units the absolute price signal was converted to a relative price signal, and then according to pre-defined settings the thermostat set points were altered by the SmartBox. Under normal conditions, a bottle cooler may for example have an upper temperature set point of 7°C and a lower set point of 5°C (as such the cooling unit would start each time the temperature reached 7°C, and would turn off again when it had fallen to 5°C). If the SmartBox received a price that the algorithm deemed to be a relatively high price, then both temperature set points were increased, so the bottle cooler would now be allowed to reach for example 8°C before the cooling unit was activated, and would turn off at 6°C. In case of a relatively low price, then the opposite would take place, i.e. the temperature set points would be lowered.

The amount that the set points were adjusted up or down depended on the magnitude of the relative price. If for example the latest received relative price was extremely high or low (i.e. much higher or lower than in the previous periods), then the set points would be altered by their maximum pre-defined amount, which was 2°C. On the other hand, if the latest received relative price was only marginally larger or smaller than the previous prices, then the set-points would only be adjusted slightly. The 'relative price algorithm' along with

[11] For more on the FlexPrice signal, please see (EURISCO, 2012).

[12] For a detailed explanation of the SmartBox and other hardware aspects, please see (Nielsen, Zimmermann, Rasmussen, & Pedersen, 2013).

the pre-defined parameters thus determine how much, and in which direction the temperature set points should be adjusted. Pre-defined parameters include for example minimum run times (i.e. the compressor should not start and stop too often).

In adjusting the set points up (i.e. upon receiving a high price), electricity demand will be shifted into the future, while adjusting the set points down will result in utilising more electricity in the near term. The left side of the figure below displays a number of bottle coolers at various stages in their cooling cycle under a normal price situation, and the right side shows how the picture changes after an upward shift in the temperature set points takes place due to the SmartBox having received a higher price. As will be discussed below, not all bottle cooler compressors will immediately turn on or off due to an adjustment to the temperature set points.

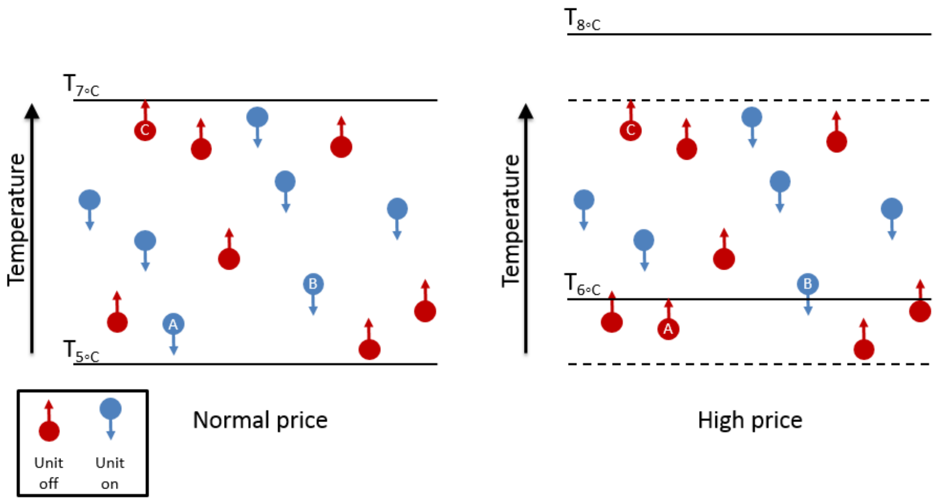


Figure 20: A number of bottle coolers at various stages in their cooling cycle under a normal price situation (to the left), and after a higher price signal is received (to the right).

In reviewing Figure 20, there are a number of interesting aspects worth noting. Firstly, due to the various stages at which the bottle coolers find themselves in, only one of the 14 units turns off immediately, namely unit 'A', which had a temperature between 5°C and 6°C at the time the new price signal was received. Unit 'B' is also noteworthy because under the normal price situation, it would have continued to cool for a while, but now it will very quickly reach 6°C and thus stop cooling. Unit 'C' is in a somewhat similar situation, as it was just about to start its cooling cycle, but now it will be postponed until its temperature reaches 8°C.

Seen from an overall system viewpoint, the advantage of adjusting the temperature set points in this fashion is that a change in the price signal will be unlikely to induce an immediate change in electricity consumption from all units at once, but instead it will be more of a steady progression.

Electric heating

Fifteen houses with DEVI Danfoss electric space heating attached to SmartBoxes also and took part in the field test. The set up for the electrical heating units was the same as for the bottle coolers in that changes in the relative price resulted in shifts of the temperature set points. The only major difference was that because these units provided heating instead of cooling, a higher price resulted in temperature set points being decreased (as opposed to being increased for the bottle coolers), and vice versa for lower prices.

End-user retains control

The electric heating end-users (as well as the bottle cooler end-users) still have complete control over the thermostat in that they are free to control what is termed the ‘user defined set point’. If for example the end-user sets their thermostat a 21°C, then the upper and lower set points under a ‘normal’ price could be 22°C and 20°C respectively (the heater starts when the temperature reaches 20°C, and stops again when it warms to 22°C). If a very high relative price is received, this could result in shifts to 21°C and 19°C. If the end-user found this resulting temperature to be too cold, they could adjust their thermostat to 22°C and the resulting set points during this high price would become 22°C and 20°C respectively.

Industrial

Bornholms Forsyning’s wastewater treatment plant was also involved in the field test as various pumps, circulation mechanisms, etc. were incorporated. These non-critical loads were in the form of induction motors that pumped water or moved cleaning brushes. The SmartBoxes did not directly control these devices, but instead one dedicated SmartBox provided a price signal to the plant’s Supervisory Control and Data Acquisition (SCADA) system. The SCADA used this signal to interrupt processes that tolerated interruption, while giving first priority to ensuring that process constraints were not violated. Meanwhile, measurement SmartBoxes, with firmware identical in the control SmartBox but without an output signal, were installed at each load to gather data (Rasmussen, 2013).

Miscellaneous On/Off

That last group of devices involved in the field test were miscellaneous on/off units and consisted of devices such as electric heating, ventilation, saunas, etc. They were also attached to SmartBoxes, but unlike the bottle coolers and electric heating devices, they were not regulated via the altering of set points. Instead, these devices reacted to the relative price by simply turning on, off or maintaining their current state.

Field-test results

Example for electric heating

The figures below display some of the results of the field test for electric heating.[13] The first figure displays how two electric heating end-users reacted in relation to the above-described relative price. This data was collected during a 3-month period between 2013-03-07 and 2013-07-07. As the rated power consumption of the electrical heaters varies from unit to unit, the power consumption has been normalised in such a way that the two boxes have a normalised rated power consumption of 100% of full the load.

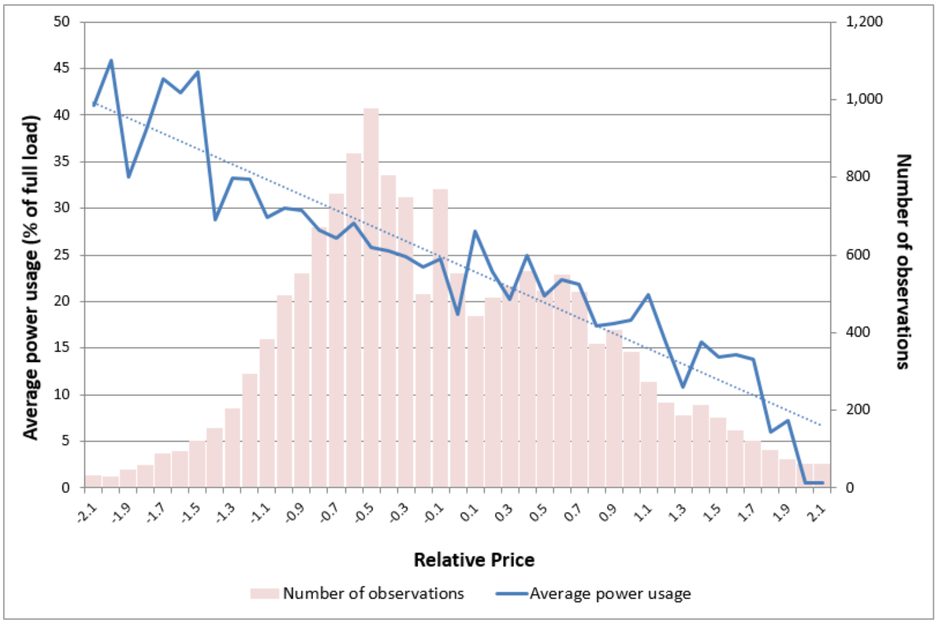


Figure 21: Average power usage according to the relative price for two electric heating end-users during the trial period. The right vertical axis indicates the number of observations given the relative price. Observations were grouped into relative price categories that were 0.1 in size. Observations with a price higher and lower than +/- 2.1 are not included in the graph as there are few such observations.

As can be seen in the figure, there exists a clear tendency for higher electricity usage when the relative price is low, and very little when the relative price is high. This is a positive result as it indicates that units react to a price signal in the desired manner.

While the previous figure showed that electric heating end-user units respond very well to the input price signal (i.e. the relative price), what is most interesting for an end-user that is eventually billed according to the 5-minute price signals, is how they react to the absolute price. The figure below displays the elec-

[13] For a comprehensive review of the results from the Bornholm field study please see (Bang, Togeby, & Brus, 2013) regarding bottle coolers and electric heating, and (Rasmussen & Petersen, 2013) regarding industrial and various on/off devices.

tricity demand for the same end-users, however this time as related to the absolute price. Note that the small number of observations greater than 53 øre, and less than 29 øre, have been excluded.

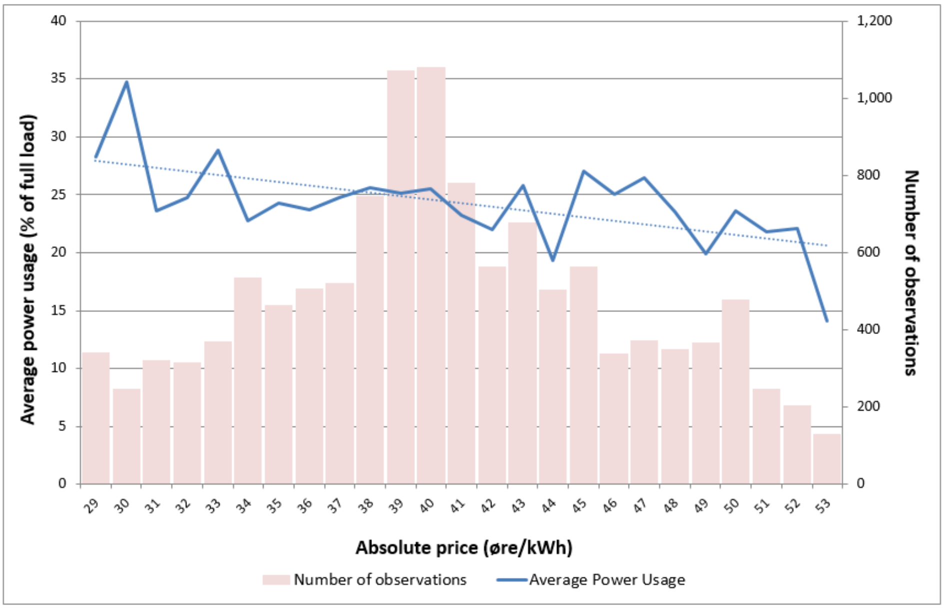


Figure 22: Average power usage according to the absolute price for two electric heating end-users during the trial period. The right vertical axis indicates the number of observations given the absolute price. Observations were grouped into absolute price categories that were 1.0 øre in size. Observations with a price higher than 53, and lower than 29 are not included in the graph as there are few such observations.

Figure 22 shows that while there is still a trend for greater electricity usage when prices are low and vice versa, this trend is not as significant as it was for the relative price. Part of the reason for this weaker trend has to do with how stable prices have been in the recent past, as well as what the state of the individual device was in when it received the latest price signal. Please see (Bang, Togeby, & Brus, 2013) for a more detailed example of an individual user during a specific time period.

Bottle coolers

While the power consumption was normalised for the electric heating units because the rated power consumption of the electrical heaters varied from unit to unit, this was not the case for bottle coolers studied, which all had the same rated power usage. The figure below displays how the bottle cooler end-users reacted in relation to the relative price.

While not quite as prevalent as for electric heaters, Figure 23 indicates that there is a strong (negative) correlation between the relative price and electricity usage. Part of the reason that the reaction is not as strong is due to the constant minimum electricity usage, which is larger for bottle coolers than it was for the electric heating units.

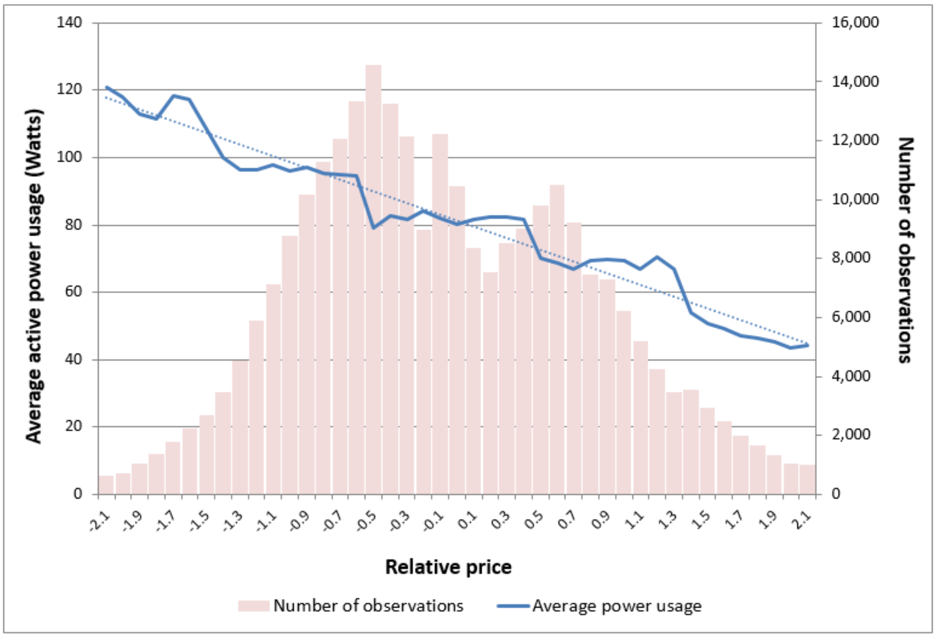


Figure 23: Average power usage (in Watts) according to the relative price for 21 bottle cooler end-users during the trial period. The right vertical axis indicates the number of observations given the relative price. Observations were grouped into relative price categories that were 0.1 in size. Observations with a price higher and lower than +/- 2.1 are not included in the graph as there are few such observations.

When the reaction of the same end-uses is now plotted with respect to the absolute price, there is still a negative correlation between the absolute price and electricity usage (see figure below).

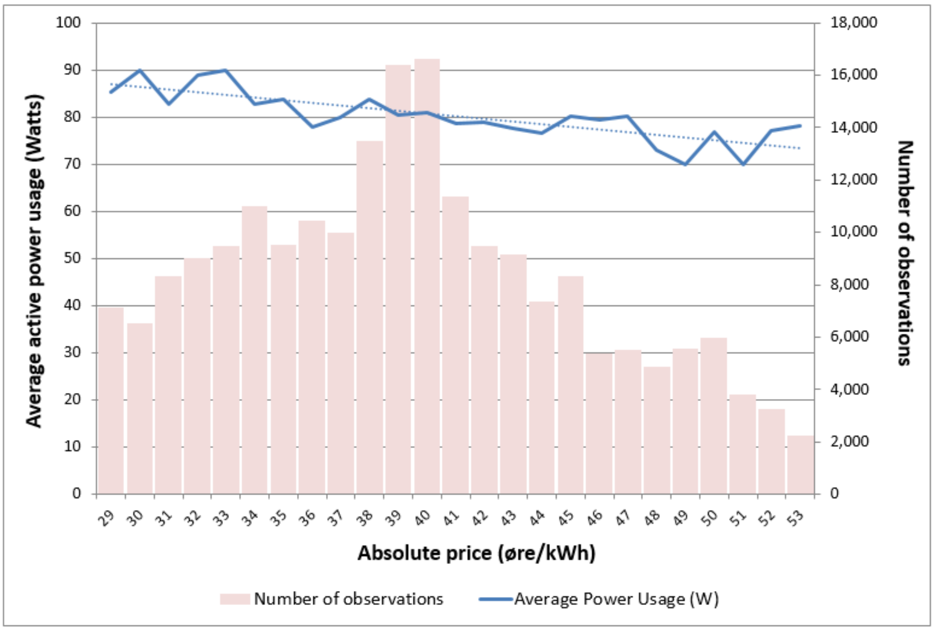


Figure 24: Average power usage (in Watts) according to the absolute price for 12 bottle cooler end-users during the trial period. The right vertical axis indicates the number of observations given the absolute price. Observations were grouped into absolute price categories that were 1.0 øre in size. Observations with a price higher than 53, and lower than 29 are not included in the graph as there are few such observations.

When looking at Figure 24, at first glance the negative correlation is once again less significant than for electric heating, but when the fixed minimum usage is subtracted this increases the slope of the trend line.

Results summary

Electric heating

For electric heating, the field test demonstrated that the local controller and thermostat react well to the relative price. Given the outdoor temperature and price, the results are rather predictable.

Meanwhile, the controller reacts less well to the absolute price. This can be explained by the simple nature of the test (the local control algorithm is quite simple), and the fact that no additional forecasts or data are utilised in the local control calculation. Despite this, it was estimated that the end-user realised cost savings of 7.4% of the electricity price cost (excluding tariffs and taxes). These savings are relative to what the end-user would have paid for electricity on a 5-minute basis had they not altered their electricity demand.

In a hypothetical test carried out by WP9, it was concluded that the economical savings could be doubled, if the price of the next 5-minute period was known. The same equation was used, just with a future price. With this formula, the best results were found if only the next price was included. Including more future prices (with the simple formula) reduced the savings. More advanced methods would be required if more than one extra price was known (or estimated).

Bottle coolers

For bottle coolers, the field test once again demonstrated that the local controller and thermostat react well to the relative price. However, the controller again reacts less well to the absolute price.

As was the case for electric heating, this can be explained by the simple nature of the test, and the fact that no additional forecasts or data are utilised in the local control calculation. Despite this, it was estimated that the end-user realised cost savings of 6.7% of the electricity price cost (excluding tariffs and taxes). These savings are relative to what the end-user would have paid for electricity on a 5-minute basis had they not altered their electricity demand. The calculations were performed on a subset of the data with continuous observations of nine bottle coolers covering the period 11-17 March 2013.

The data indicates that increased economical savings could be achieved if Tau was increased above 36 time steps (please see equations 1.2 and 1.3, Figure 17 and the accompanying discussion of the effect of utilising differing values of Tau.) As with electric heating, the economic results could be doubled if the next future price was known. For a more thorough discussion of the electric heating and bottle cooler results please see (Bang, Togeby, & Brus, 2013).

3.2 Other practical results

Industrial units + diverse on/off units

With respect to field test results for industrial units and diverse on/off units please see (Rasmussen & Petersen, 2013).

Simulation

Within FlexPower there were also a number of simulation studies carried out by Actua and DTU. It was decided to focus on open loop algorithms, and simulations were made within the existing power market price structures. Scenarios were simulated for both electric vehicles (EVs) and house heating. For more detailed reporting on the EV and house heating results, please see (Ebert, 2013 a) and (Ebert, 2013 b).

4 Tools for improved performance

The field test highlighted the fact that there exists significant potential for improvement for regulating power based on price signals.

This could be done by utilising some or all of the following:

- Including known spot prices in the control algorithm
- Including forecasts for regulating power prices in the control algorithm
- Fine tuning the algorithm
- Including historical data in the control algorithm
- Including known weather data in the control algorithm
- Including weather forecast data and heat demand forecasts in the control algorithm
- Including known delivery/stocking times data in the control algorithm

The following chapter will explore a number of these aspects.

4.1 Prediction of prices

Though not utilised in the field test, the FlexPower FlexPrice also has the capability to include a forecast for future prices that would assist the local controller in improving the optimisation of its end-user device(s). As such, a number of investigations were made with respect to the forecasting of future prices.

Reports entitled 'Modelling the Danish real-time electricity market' (ENFOR, 2013 b), and 'Forecasts of actual imbalance unit costs and simulated 5 minute prices for the two Danish Nordpool Spot price areas' (ENFOR, 2013 c), address forecast performance for actual prices. Focus was on the difference between each of the regulation prices and the spot price. This quantity is referred to as the *imbalance unit cost*.

The first report considers separately the tasks of forecasting the probability of a particular imbalance sign (down, up, or no regulation penalty) and the magnitude of the regulation penalty given that it is strictly positive. The last value is called the *conditional expectation*, i.e. the expected value conditional on the penalty being positive. However, for decision-making based on expected revenues, the unconditional expectations of the down and up regulation penalties are required. The report describes how these unconditional expectations can be found from the imbalance sign probabilities and the conditional expectations. (ENFOR, 2013 b).

The data reveals that the imbalance penalties, especially the up regulation imbalance penalty, contain large spikes. Nevertheless, the imbalance penalties seem to contain a diurnal variation both with respect to the sign, and with respect to the magnitude. Furthermore, the sign-probabilities show some dependence on the wind power forecast for the region. (ENFOR, 2013 b).

Within the second report, it is argued that where the production is a random variable which cannot be controlled (as e.g. for the case of wind power), then it is the conditionally expected values, i.e. the imbalance unit costs, and not the expected spot prices, that are of main interest when seeking optimal bids (ENFOR, 2013 c). Although, the noise level is high, the forecasts seems to be capable of reproducing correct expected values. This is most predominant for the shorter horizons relevant for the FlexPower setup.

For the FlexPower setup, where we can assume the spot prices to be known, we just add/subtract the expected imbalance unit costs in order to arrive at the expected final price. Based on (ENFOR, 2011), this is the most important price forecast for the control case considered in FlexPower.

4.2 Other predictions

Prediction of heat load

There are a number of other predictions that could help to improve an end-users electricity utilisation. For end-users with electric heating, one of the most relevant is a prediction of future heat demand. As such, one FlexPower output was a report that described modelling and forecasting of heat load for single-family houses (Bacher, Madsen, & Nielsen, 2013). In addition, (ENFOR, 2011) investigated forecast requirements for house temperature control with flexible energy prices. Another document (ENFOR, 2013 d) describes the API for communicating with the PRESS web-service, which can be utilised for operational forecasting of heat load.

Prediction of aggregated response

Another prediction aspect that was investigated within the FlexPower project was what the aggregated response to a change of price signals was likely to be. For more on this topic please see two published papers: “Controlling Electricity Consumption by Forecasting its Response to Varying Prices” (Corradi, Ochsenfeld, Madsen, & Pinson, 2013) and “Chance-constrained optimization of demand response to price signals reports” (Dorini, Pinson, & Madsen, 2012); as well as a FlexPower report: “FlexPower – Work Package 2” (Dorini, Corradi, Ochsenfeld, Nielsen, & Madsen, 2013).

4.3 Discussion

The previous chapter described the FlexPower field test and the rather 'simple' nature of the test. This chapter has therefore discussed options for improving upon this original setup. The figure below incorporates both, and displays a future potential development for a FlexPower system involving heating units.

Figure 25: From the simple to the advanced, future potential development paths for electric heating guided by price signals.

The tools in the top three boxes of Figure 25 are likely to be utilised by the end-user via their home automation equipment. Meanwhile, the prediction of aggregated response would likely be used by the aggregator in determining what level of price signal to send out to its FlexPower subscribers (i.e. a tool to answers questions such as 'If price X were sent out to the end-users, what response Y can be expected?').

5 Perspectives

5.1 VPP vs. price

There is ongoing debate whether demand response is best served via price signal based systems or virtual power plant (VPP) systems. Those whom favour price signal based systems (commonly referred to as indirect control) often point to the end-user autonomy under such systems, will proponents of VPP systems (commonly referred to as direct control), highlight the fact that the response under a direct control system is more reliable.

VPP advantages

In a VPP system where the aggregator has complete control over the end-users devices, it is quite likely that the demand response will be more certain than in an indirect control system because the aggregator has the ability to control the devices as they see fit, and therefore deliver the exact amount of regulating power desired.

In a VPP, the aggregator may also have more information about the state of the various devices, therefore allowing them to better optimise the overall portfolio of devices. For example, the aggregator may be provided with all their EV's current state of charge and anticipated driving requirements the next day.

Price control advantages

While a VPP system may provide a more exact response, there may be some end-users that do not wish to participate in a system where they confer control of their devices to an aggregator. For these end-users a price control system could be attractive because while their home automation systems will respond optimally to price signals most of the time (and therefore result in lower electricity cost savings the majority of the time), at other times they will simply pay a little more for their electricity. For a number of end-users it may be desirable to suffer some cost savings in exchange for complete freedom.

The fact that a VPP operator has more information regarding the state of the end-user units is clearly an advantage. However, the required monitoring and communication software and hardware for the utilisation and maintenance of this data also incurs a cost, and as such, an indirect control strategy is likely cheaper and more simple to operate.

Field test findings

The field test with electric heating and bottle coolers has demonstrated that a quite reliable demand response reaction is achieved in response to the relative price signal. While less reliable, a demand response reaction was also realised in response to the absolute price signal. Via the implementation of a number of improvements (i.e. incorporating various known and forecasted data) into the conversion from the absolute to relative price it is therefore deemed that a price signal based demand response system could provide a new source of reliable regulating power.

Combination

Given end-users varying appetites for direct control, and the field test findings that a price signal can attain a reliable response, it is suggested here that there is room for both types of systems to provide regulating power. In addition, it is also foreseeable that the two systems could complement each other exceptionally well. A single balance responsible could for example have a portfolio of end-users where some were controlled by price, while others were controlled directly. Such a system would allow for the balance responsible to have more end-users in their portfolio, while at the same time supplying an exact response. This exact response could be achieved by the online measurement of the response received by its price controlled users (via installations in ca. 5-10% of end-users), and then adjusting the directly controllable loads accordingly.

5.2 Taxes and tariffs

FlexPower is unlikely to be financially viable under the current tax and tariff structure, however with dynamic taxes and/or tariffs it could prove much more interesting.

For small-scale end-users in Denmark, the wholesale electricity price (i.e. the spot price) only accounts for roughly 20% of the final electricity cost. The other major components are (Bang, Hay, Togeby, Søndergren, & Hansen, 2010):

- Transport (ca. 12%) which covers the costs of transport of electricity from the production unit to the end-user, and includes grid tariffs to the TSO and the DSO.
- Public service obligations (ca. 8%) which are legal obligations paid by all consumers for subsidies for wind energy and CHPs, and research and development.
- Various taxes (ca. 40%) which covers CO_2 taxes, electricity taxes, distribution taxes, and electrical heating taxes.
- VAT (20%) which is a 25% tax paid on the total electricity bill.

The transport, public service obligations and various taxes above are all fixed proportionally to the amount of kWh consumed by the end-user, and thus are not affected by changes in the wholesale electricity price. As a result, only 25%[14] of a Danish end-user's electricity bill is directly related to the wholesale price of electricity. This has large implications for end-user willingness to participate in demand response activities. If a commercialised version of FlexPower (or a VPP) could for example deliver electricity cost savings of 10%, the actual net cost savings seen by the end-user under the current tax and tariff structure would only be 2.5%.

[14] The 20% of the electricity bill that is the wholesale electricity cost, + 25% VAT = 25% of total electricity bill.

As a result, if society is serious about enticing a large number of small-scale end-users to assist in providing regulating power, then an important step would be revamping the tariff and tax system so that they become more dynamic in nature.

Dynamic taxes and tariffs vary according to the load on the system, and as such are generally higher when electricity prices are high, and lower when electricity prices are low. As was noted above, transport, public service obligations and various taxes are today all flat per kWh costs. Alternatively, by linking their cost to the wholesale electricity price (i.e. instead of having a cost that is 50 øre/kwh, have a cost that is 1.5 times the hourly spot price) this would increase the incentive for end-users to participate in demand response programs. These changes would require hourly meeting and billing, but these requirements are already part of the FlexPower set up. Dynamic tariffs meanwhile could become particularly interesting in the local grids, where additional loads from EVs, heat pumps, etc., could stress local grids in upcoming years.

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