EcoGrid 2.0

Main Results and Findings

September 20th 2019

EcoGrid 2.0 is a research and demonstration project funded by EUDP (Energiteknologisk Udviklings- og Demonstrationsprogram). The 9 partners in the project are:

1 Project Details

Project:	EcoGrid 2.0
Funding:	EUDP
Project managing company:	Dansk Energi
Project partners:	Dansk Energi IBM Danmark ApS Danmarks Tekniske Universitet Bornholm's Energi og forsyning Copenhagen Business School Insero Krukow Uptime-IT ApS We do democracy

2 Table of Contents

3 Executive Summary

EcoGrid 2.0 is unique because we have not only developed a market and the necessary tools for identifying and utilising flexibility from 800 private households and summer houses. We have demonstrated it with real consumers for three years – from the involvement of private consumers, management of flexible consumption, design and implementation of a market on which flexibility is traded, to development and implementation of tools for power system operators, as well as the aggregators, who identify flexible consumption, pool it and manage it in accordance with market demand. The results we have achieved are among the best seen in a demonstration project.

In EcoGrid, we have developed and demonstrated a possible solution for the green electricity market of tomorrow where flexible electricity consumption is traded as a commodity. We have managed flexible consumption in private households and municipal buildings and provided services to the power system, so that we can help the power system to:

- integrate more renewable energy and reduce CO2 emissions.
- reduce costs through better utilisation of power system capacity, by keeping consumption below the load limits in the transmission and distribution grids, and thereby reducing the need for investments in the power system.
- maintain a balance between production and consumption.

We have demonstrated:

- that we can control heat pumps and electric heating panels without compromising comfort limits in households and sell it as flexibility to the power system.
- that we can deliver upward and downward adjustment of electricity consumption, both as planned services and conditional services:
  - we have reduced the consumption by 300 kW for an hour, equal to 124 MW at national level[1].
  - we have increased consumption by 559 kW for an hour, equal to 560 MW at national level.
- that we can control the rebound effect, so that start-up of heating, after it has been 'forced off', does not create new voltage or bottleneck problems in the power system.
- that we can trade, activate and verify the flexible consumption using a market platform
  - 209 trades and activations with services to the transmission grid.
  - 36 trades and activations with services to the distribution grid.

[1] Scaling to the national level is done scaling the results from our 800 participants to the entire population of heat pumps and electric heating panels in Denmark.

- that we can use data from the smart meters, together with machine learning, to make reliable forecasts for consumption, and use these for verification of delivered flexibility.

The project's findings are:

- Digitalisation and machine learning give new opportunities for monitoring and utilising the capacity of the power system.
- Green transition and flexibility on the electricity market from private households can be achieved if consumers become involved. Private households are willing to let others manage their heating to provide flexibility, but confidence in those managing the consumption plays a key role. Relinquishing control over the heating in your house is partly relationship driven.
- It is difficult for consumers to relate to the role of aggregators and trading of flexibility. Consumers are generally interested in their own consumption, comfort and finances, and not in the needs of the power system. In order to convince consumers to sell their flexibility, they must be offered something that has value for them, for example professional help with configuration and optimisation of their heat pump.
- Utilisation of existing data through new software and technology (e.g. machine learning) is an important factor in the digitalisation. With data from smart meters, machine learning and digitalisation we can utilise data to do more than we initially believed – move consumption, integrate more renewable energy production, monitor consumption, optimise grid operation, identify future bottlenecks and improve the utilisation of power grid capacity.

Many people talk about harnessing flexibility from private households. In EcoGrid 2.0, we have demonstrated that it is possible to use flexible electricity consumption in private households to integrate more renewable energy production, reduce CO_2 emissions and reduce costs in the power system. We reached the stage where the market and the developed tools are ready for commercialisation. Our objective has been to develop solutions that can be integrated into the current market model using existing technology. We have succeeded in developing such a solution. We have not relied on solutions that could become available 10 years from now, but on solutions that are commercially available today.

4 Project Objectives

Power plants have historically regulated the production of electricity to follow demand. With the transition to green energy resources, fluctuating renewable energy production will replace traditional power plants. This creates a challenge when renewable energy production is low and demand is high. One obvious solution is to regulate electricity consumption to follow production, a technology called demand-side flexibility. A large part of the electricity consumption is not flexible, but the charging of electric vehicles and heating in houses can be managed and moved to follow electricity production and thereby demand-side flexibility can be harnessed.

In the EcoGrid 2.0 project we wanted to develop a system to manage heat pumps and electric heating panels as a flexible component of the power system, without compromising consumers' comfort. Moreover, we wanted to demonstrate a market platform where small-scale flexible consumption can be requested and traded as services to balance responsible parties, as well as the transmission and distribution grids. The market design is based on the Danish "Supplier-centric Model"[2] (Engrosmodellen) and designed in a way so that integration with the existing markets is possible.

Today, balance responsible parties pool production units and large consumers to sell services to the electricity market. In this way, aggregation is taking place today, but in EcoGrid 2.0 we wanted to test the aggregator concept for a large population of small units, such as heat pumps and electric vehicles. The aggregators make agreements with consumers for managing the flexible consumption from households and pool the consumption in quantities large enough to be sold on the market. We also wanted to find out what could motivate the consumers to let aggregators manage their consumption in order to help the power system.

Low transaction costs are required to make a business case for sourcing flexibility from numerous small units. It is easier to find a business case for a large load such as MW-scale heat pumps serving thousands of households in district heating systems or industrial cold stores. A goal in EcoGrid 2.0 was to test whether existing smart meters could be used as the only data source to monitor and manage flexibility in private households. The existing measurements also need to be accurate enough to validate delivery of services in the market, because the cost of sub-metering would be prohibitive for small consumers.

When an aggregator manages and pools flexible consumption it requires specialised expertise, large amounts of data and new tools. The aggregator must estimate the quantity of flexibility each household can deliver at any given time. In EcoGrid 2.0 three aggregators developed aggregator tools to forecast flexibility and demonstrated that it is possible to manage and pool flexibility.

---

[2] In the Supplier-centric model, system operators do not have direct contact with consumers. Instead, retailers provide customer service, and trade on energy markets on consumers behalf.

EcoGrid 2.0 is a large project with many partners, executed over 3 years. The biggest risks we have experienced are:

- The equipment installed in the private households: the equipment was installed as part of a previous project (EcoGrid EU) and both the devices themselves and the communications systems they relied on were unstable.

- The private households' willingness to let aggregators manage their heat pumps and electric heating panels without receiving compensation: We focused on the participants' comfort, and sometimes had to limit our demonstrations, so that the participants noticed them as little as possible. The objective was that the participants should not notice the demonstrations at all, and we therefore chose not to probe the limits of consumer comfort. We owe the participants on Bornholm a big thanks for their understanding and participation in the project – without them we would not have achieved such unique results.

- The seasons: we could only make the demonstrations during periods of cold weather. Delays in our project therefore had significant impact in the demonstrations, which is why we had to set hard deadlines for deliverables.

- The length of the project: EcoGrid 2.0 was a long-running project from conception to completion. We have experienced a high turnover among project participants. The knowledge and skills of participants were highly sought after in the job-market and tenure was often shorter than 5 years. Even though project participants were quickly replaced, it took time for the new participants to familiarise themselves with such a large project.

5 Results and Findings

5.1 Green transition and EcoGrid 2.0

Denmark and the rest of the world are facing a necessary green transition. With the Paris Agreement, the majority of the world's greenhouse gas emitters committed themselves to limiting the global temperature increase to less than two degrees.

In Denmark, the political target in 2018 was to have one million electric and hybrid vehicles in 2030 and to be climate neutral with a fossil-free power system by 2050 at the latest (figure 1). The targets were replaced in June 2019 by the new Danish government with a political target to reduce greenhouse gasses by 70 % in 2030 (compared to the 1990 level) and stop sale of new diesel and gasoline cars in 2030. Electrification and the green transition pose a challenge to the power system with new consumption and production patterns.

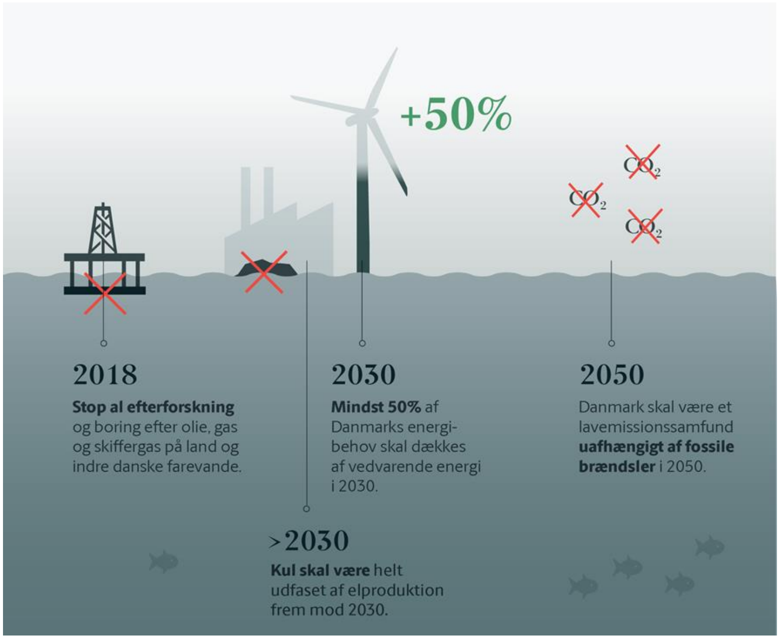


Figure 1. Danish climate policy targets in April 2018.
Source: https://www.regeringen.dk/nyheder/danmark-som-foregangsland-paa-energi-og-klima/

Increased consumption from heat pumps and electric vehicles, as well as fluctuating production from renewable energy sources such as wind turbines and solar cells, requires changes to both the structure and operation of the power system. Previously, the power stations adjusted their electricity production to match the electricity consumption. With the green transition, we will need flexibility in electricity consumption, so that it is adapted to the production from wind and solar energy, without overloading the electrical grid. This means changes in consumption patterns, such as moving heating consumption away from the evening peak (cooking) and charging of electric vehicles at night. The green transition will also require changes in the operation of both the transmission grid and the distribution grid. Increased electricity consumption

for heating and transport and more decentralised production will challenge power grid capacity and the way the grids are operated. Grid reinforcement is one option, but can the challenges be solved in other ways at lower cost?
In EcoGrid 2.0, we have developed a solution for the green electricity market of tomorrow with flexible electricity consumption. We have managed flexible consumption in private households and municipal buildings and provided services to the power system, so that we can help the power system to:

- integrate more green energy and reduce CO_2 emissions
- reduce costs through better utilisation of power system capacity, by keeping consumption below the load limits in the transmission and distribution grids, and thereby reducing the need for investments in the power system.
- maintain a balance between production and consumption

Over three heating seasons, we have tested our market live on Bornholm and in Horsens. 800 consumers on Bornholm have made their heat pumps and electric heating panels available to the project. The municipality of Horsens has allowed us to manage the consumption in selected municipal buildings (schools, kindergartens and nursing homes). Three aggregators have managed the electrical heating systems and have competed on the market to provide flexibility services.

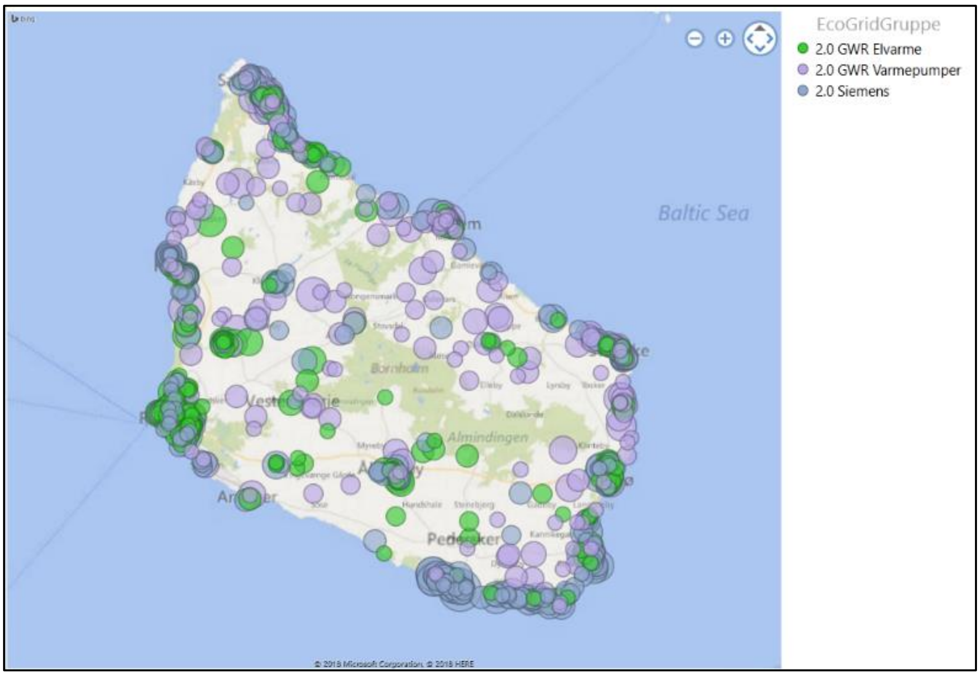


Figure 2. Overview of available flexibility in EcoGrid 2.0 at Bornholm.

EcoGrid 2.0 has built on previous research and development projects. We have reused the heat pump control equipment which was installed in the EcoGrid EU project. In the specification of the market for local flexibility, we have used the results from, among others, the iPower and IDEAL projects. The EcoGrid 2.0 market platform is an extension of the FLECH platform which was initially developed in iPower, showing the benefit of continuous and long-term investment in research and development projects dealing with smart grids and smart power systems.

EcoGrid 2.0 is unique because we have not only specified a market and the necessary tools for identifying and utilising flexibility from 800 private households (75 % houses, 25 % summer houses). We have performed live demonstrations of it with real consumers for three years – from involvement of private consumers, management of flexible consumption, design and implementation of a market on which flexibility is traded, to necessary tools for the power system, as well as for aggregators, who identify flexible consumption, pool it in quantities which can be sold on the market and manage it in accordance with market demand.

We have developed a market for flexible consumption based on the Supplier-centric Model (Engrosmodellen) and shown, by means of the demonstrations from Horsens, that it was easy to include a new aggregator in the developed market. We have matured the implementations of both the market and tools, such that we are ready to move beyond demonstrations and towards commercial operation. Our market and tools utilise existing technologies, that are commercially available today, making it possible to start up the market tomorrow.

The following sections describe what we have developed, implemented and demonstrated, as well as the results we have achieved. During EcoGrid 2.0, we have prepared a series of reports describing our work in more technical details. These reports have all been published on the website www.ecogrid.dk.

5.2 Market for flexibility

The actors in the EcoGrid 2.0 market for flexibility are:

Buyers of flexibility:

- TSO – Transmission System Operators
- BRP – Balance Responsible Parties
- DSO – Distribution System Operators

Sellers of flexibility:

- Aggregators – the bridge between the private households and the power system; this new actor pools flexible power consumption from hundreds of private households and sells it on the electricity market.

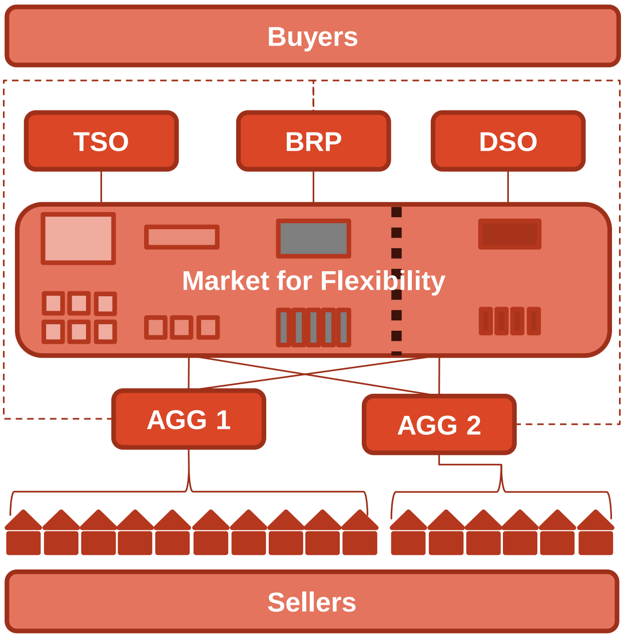


Figure 3. Overview of market actors and their roles in the market.

In EcoGrid 2.0, we have developed and implemented all the tools and algorithms necessary to enable us to request, manage and trade flexibility, including:

1) management of heating in private households. We have developed an interoperability layer, which means that aggregators can control heat pumps and electric heating panels independently of the communication form and the model of equipment installed in the households. This function could easily be extended to electric vehicles.
2) development of forecasting tools for flexibility, as well as grouping of flexibility in larger pools, and offering flexibility on the market based on an optimal bidding strategy.
3) transformation of a need for flexibility from DSO, TSO and BRP into services that they can request on the market.
4) market platform for trading, with clearing algorithms that find the optimal combination of incoming bids.
5) activation of flexibility.
6) baseline tools which verify that activations of flexibility have performed as contracted.

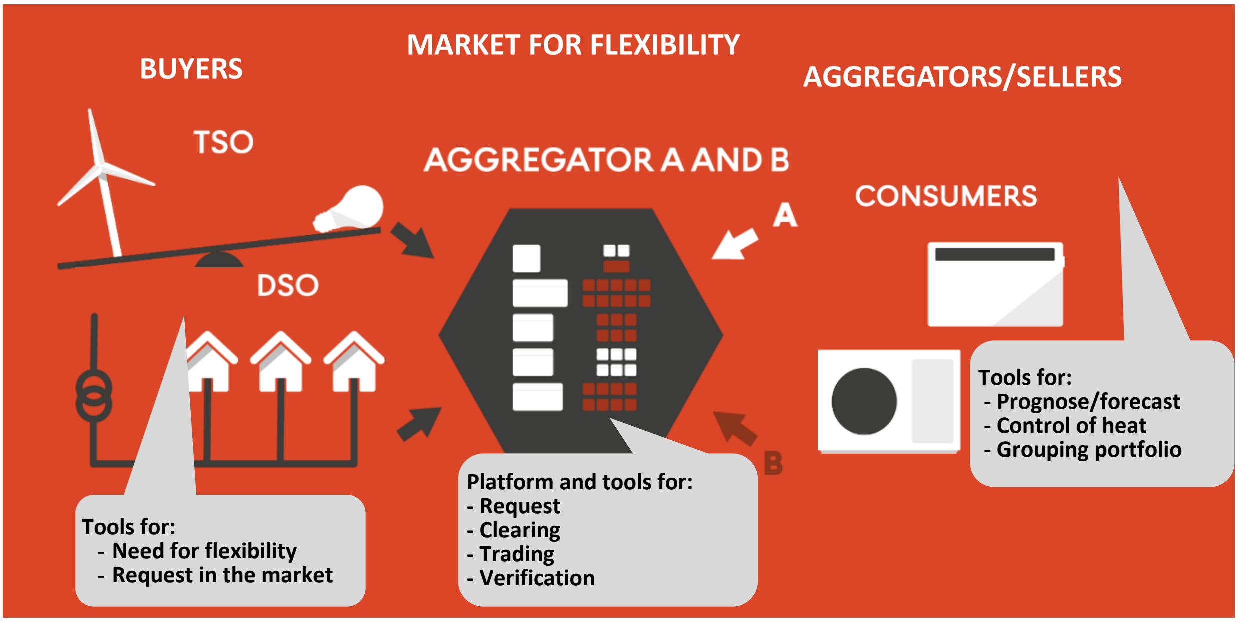


Figure 4. Illustrations of actors in the EcoGrid 2.0 market.

5.2.1 Market structure

The market structure in EcoGrid 2.0 is built, for demonstration purposes, to operate in parallel to existing markets. It operates in a separate trading platform because existing markets do not allow demand response units like those used in the EcoGrid 2.0 project to participate due to requirements on minimum bid sizes, validation and verification. Operating a parallel trading platform for flexibility outside of existing markets additionally has the benefit of allowing the EcoGrid 2.0 project to develop new services based on flexibility from private household that can bring value to the power system in the future e.g. local services for DSOs.

Our goal in EcoGrid 2.0 was to commercialise flexibility, making the developed market platform more than just a research tool, but a viable way forward for existing markets. As flexibility from private household reaches significant levels and its value becomes apparent, the existing markets will likely adapt to allow the services developed in EcoGrid 2.0 to be traded, effectively merging the EcoGrid 2.0 flexibility market with the existing markets.

5.2.2 Services to the market

The basic commodity traded on the EcoGrid 2.0 market is active power, traded in timeslots of fixed length. To be traded in the market, it needs to be formulated as services that are tailored to the needs of the buyers (TSO, BRP and DSO).
These services can be grouped into two categories:

- **Scheduled services**
  Services that are activated at the contracted point in time and delivered over the contracted duration of time (e.g. 100 kW load reduction activated at 18:00 and delivered for a duration of 1 hour).

- **Conditional services**
  Services that are contracted for a period of time but are activated at the request of the buyer (e.g. reserve the ability to activate 100 kW load reduction for a duration of 1 hour in the period from 18:00 to 24:00 in the winter season).

For more details see:
EcoGrid 2.0 Market Specification, December 2016:
https://www.dropbox.com/s/lhe35zdexatcuda/Market%20Specification%20EcoGrid%202.0.pdf?dl=0

EcoGrid 2.0 demonstration cases, January 2017:
https://www.dropbox.com/s/0gz2ux2mykuitqc/Demonstrationer%20i%20EcoGrid%202.0%C2%B4s%20marked%20for%20fleksibelt%20elforbrug%20DK.pdf?dl=0

5.2.3 Market implementation

We have built a flexibility market platform that provides common services to the participating parties such as communication, authentication, clearing, notification and settlement. The market platform can host multiple types of flexibility services and multiple concurrent service requests.

We have demonstrated successful trading of TSO and DSO services on a market platform.
371 TSO services and 54 DSO services were demonstrated. Of those, the aggregators bids were accepted and executed for 209 TSO and 36 DSO services.

All registered aggregators are informed by the EcoGrid 2.0 market platform, when a new service request is published. The aggregators bid according to their bidding strategy, specifying the volume of flexibility they offer and the volume of any corresponding rebound, as well as the price of the offered service. The accepted offers are selected using the dedicated clearing algorithms developed in EcoGrid 2.0 for the DSO (distribution congestion management) and TSO (system balancing and transmission congestion management) services.

The market clearing algorithm for the TSO service for system balancing requires additional data on energy availability and prices from conventional generating units; this data is imported from the EcoGrid 2.0 data warehouse. The clearing algorithm also determines the payments for the contracted services. For the system balancing service, the payments are based on the marginal maximum price per time step derived from the prices of offers.

For the DSO services, the payments calculation is based on maximum accepted bid (marginal pricing) derived from the offers submitted by the aggregators.

For the contracted aggregator services, the market platform is also responsible for relaying the activation information. If a service is specified as conditional and the buyer decides to activate this service, the buyer sends an activation notification to the EcoGrid 2.0 market platform, which is then forwarded by the market platform to the aggregators providing this service. For scheduled services the market platform automatically sends activation notification messages shortly before the scheduled starting time.

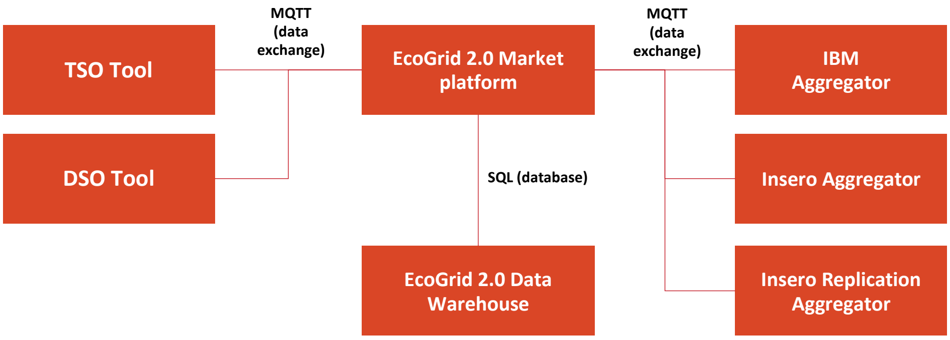


Figure 5. Illustration of market platform.

For more reports see:
Market design specification:
Link: 23.august 2019:Market design Specification (3.2.1.)

Tool to prepare market requests, January 2018
Link:
https://www.dropbox.com/s/rry9wmnt5h0kwte/D4.2.1%20Tool_for_market_requests%201.0.pdf?dl=0

Description of implemented toolset for TSO:
Link: 23.august 2019: Description of implemented toolset for TSO (5.2)

Evaluation of ICT hosting environments:
Link: 23.august 2019: Evaluation of ICT Hosting Enviroments (3.3.1.)

Description of DSO tools:
Link: 23.august 2019: Description of DSO tools 1.0 (5.1)

DSO Marked Formulation:
15.november 2018: DSO Marked Formulation

DSO Tool for quantification of flexibility benefit, service request and activation
Link: 15.november 2018: DSO Tool for quantification of flexibility benefit, service request and activation

Tool for market interaction and service delivery
Link: 15. november 2018:Tool for market interaction and service delivery

Offering Strategy Tool:
Link: 14. juni 2018: Offering Strategy Tool

Use Cases for EcoGrid Flexibility Ecosystem
Link: 15.november 2018: Use Cases for EcoGrid Flexibility Ecosystem

5.2.4 Temporal resolution of smart meters

Metering availability, communication delays, and temporal resolution all impact the quality of control and verification, and ultimately the feasibility of trading flexibility in a marketplace such as the one EcoGrid 2.0 proposes. Since smart meters are expected to reach 100% penetration and communication delays were previously investigated in EcoGrid EU, an objective of the EcoGrid 2.0 project was to investigate the impact of different smart meter temporal resolutions. EcoGrid 2.0 participants were equipped with 5-minute metering, which is a higher resolution than most Danish electricity consumers have today or will have in the near future (1-hour transitioning to 15-minute, BEK nr 75 af 25/01/2019: Bekendtgørelse om fjernaflæste elmålere og måling af elektricitet i slutforbruget).

The complexity of the aggregator's job when trying to be compliant with the chosen verification is simplified when moving to 15-minute and hourly resolutions.
Lower metering resolution hides large peaks and dips in consumption and production, but 15-minute metering is considered acceptable for the DSO.

EcoGrid partners assumed that the error would be larger for 5-minute intervals than 15-minute and hourly intervals – the longer the interval, the lower the resolution, and the larger the error – as uncertainty in demand gets larger as shorter time spans are observed. E.g. a kettle boils for two minutes, creating a very large (and very difficult to predict) power spike of 2 kW, which would create a noisy signal at the 5-minute resolution, but creates very little noise at the hourly resolution as the 2 kW is averaged over 60 minutes instead of 5.

If true, this would mean that it is easier for aggregators to deliver what they promised to the market with lower-resolution metering, such as hourly metering. This is because fluctuations that happen within the measured time interval – e.g. within a one-hour block – gets averaged out. Fluctuations can happen due to the uncertain nature of human behaviour, uncertainty in the weather forecast (which correlates directly to the amount of demand response available) and complexity of an aggregators strategy for controlling heat pumps.

To test this assumption, we developed demand response verification models to check if the aggregator did what it said it would do – we have used several industry-standard error metrics such as the mean absolute error (MAE) and mean average percentage error (MAPE). We also applied a more advanced performance metric[3], that looks at a

[3] https://orbit.dtu.dk/en/publications/demand-response-for-a-secure-power-system-operation(09791bc6-d182-4f2d-ae3e-34e31a176eab).html

single activation (for example an hour) and checks if the aggregator kept demand response (and any rebound) within an allowable prediction interval for the whole hour (and subsequent rebound time).
When using the MAE metric, we observed that the error is almost identical for 5-minute, 15-minute and hourly metering for the majority of demand response activations, likely due to the fact that the population of a few dozen houses is enough to smooth out one or two kettles being turned on for 2 minutes.

For a small minority of tests, the MAE can be up to 25% higher for 5-minute metering compared with hourly. Demand response tests with a high MAE may have coincided with aggregator experimentation, as it therefore cannot be excluded that, in a national rollout of demand response, the MAE would be identical for all metering resolutions, as it was for most of the 80 HS2 tests we analysed.

For the more advanced performance metric, that analyses if the aggregator can keep demand response within an approved prediction interval (which describes the uncertainty of demand without demand response), going from 5- to 15-minute resolution increases the apparent performance of the aggregator by 2.4 %, while going from 5-minute to hourly resolution increases the apparent performance of the aggregator by 10.5 %. The apparent performance describes how well the aggregator keeps demand response within the prediction interval.

Ultimately, this means two things:

1. Contrary to the MAE metric, the performance metric suggests that 15-minute and hourly metering hides variation in the aggregator response, mean that demand response quality looks worse from a system perspective the higher the metering resolution used.
2. It is in the aggregator's interest to have hourly metering, as it is easier for the aggregator to deliver what it promised.

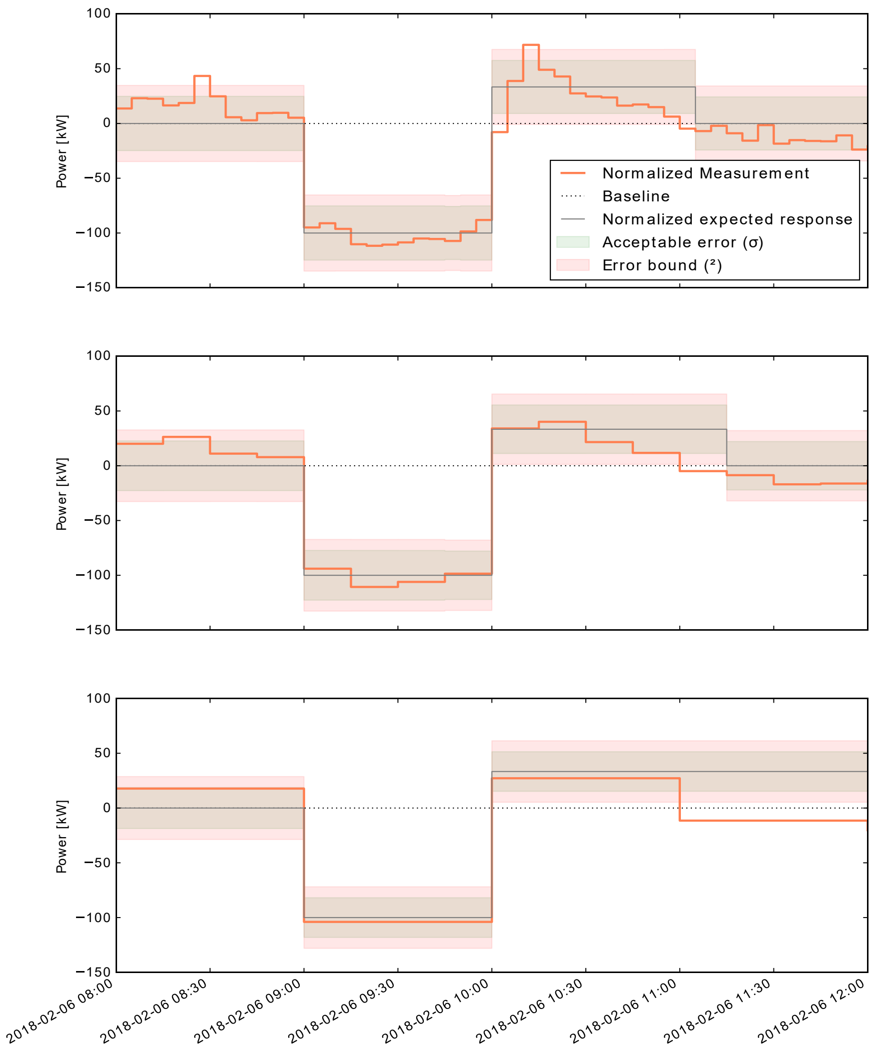


Figure 6. A comparison of 5-minute, 15-minute and 1-hour resolutions for a demand response test with IBM houses showing improved performance (seen from the aggregator's perspective) with hourly metering.

The impact on the TSO and DSO of different metering strategies is also impacted by metering resolution, as a lower resolution can hide large peaks and dips in consumption and production power. For example, 15-minute metering hides short-lasting peaks, which are on average 22.8 % larger when 5-minute metering is available. Moving to hourly metering hides an additional 8.1 % of the largest short-lasting peak. What this means is that the TSO or DSO may have to live with demand response that over- or under-delivers by 22.8 % during a 5- minute period when only 15-minute metering is installed. In practice, however, power system components can usually cope with a 30-minute overload without failure[4] making 15-minute metering acceptable for the DSO. 15-minute metering also has the benefit of being broadly compatible with European tertiary control with a reaction time of 15 minutes[5], which would therefore represent a significant asset to the TSO.

[4] (Nersessian & Kaiser, 1996)
[5] (Kyriakides & Polycarpou, 2014)

For more details see:
Verification of services within EcoGrid 2.0
Link: https://www.dropbox.com/s/8v67mf2reny9l67/Verification%20of%20services%20within%20EcoGrid%202.0%20V2.pdf?dl=0

5.2.5 Baseline verification of flexibility sold on the market

In the EcoGrid 2.0 project we need a tool to verify if a flexible service traded in the market has been delivered or not. For that we define a baseline as a prediction of demand and generation, assuming no external control. A baseline is a useful tool for multiple actors in the future power system.

Historically, a balance responsible party makes load forecasts for a large portfolio in the day-ahead market, and deviations from these equate to the energy traded in the balancing market. However, as new market constructions arise, with separate transmission and distribution clearings and different BRP responsibilities being proposed, a single load forecast does not have the detail required to verify intraday activations from smaller consumer aggregations.

To verify if a flexible service has been delivered, we have developed baselines to predict consumption if flexibility is not activated. The baselines are based upon historical data from the electricity meters and external variables that influence electricity consumption. Machine learning techniques are used to generate high quality forecasts for baselines, with average prediction errors of roughly 5 % for the high and medium voltage grid.

Besides being used as baselines for verification of delivered services in the market, the developed forecasts can be used by TSOs and DSOs to estimate consumption and optimise grid operation, identifying future bottlenecks and improving the utilisation of power grid capacity.

A central use case for baselines is when demand response is activated for congestion management on low and medium voltage feeders. DSOs can use baselines to ensure aggregators aren’t gaming the market by causing the congestion in the first place. With modern cloud infrastructure, such baselines can be automatically built for thousands of feeders daily at a low annual cost.

In the EcoGrid 2.0 project, we have developed the infrastructure necessary to efficiently build baselines using decentralized databases combined with machine learning models. We have made two years’ worth of EcoGrid 2.0 baselines available on the website, where daily changes to aggregator portfolio, combined with updated metering data, lead to updated baselines forecasted five days into the future. Energy disaggregation is also updated daily, to provide new forecasts of PV generation and electricity demand due to heating. Such a tool allows all market participants to benefit from increased transparency, lower costs, and a better understanding of their customers.

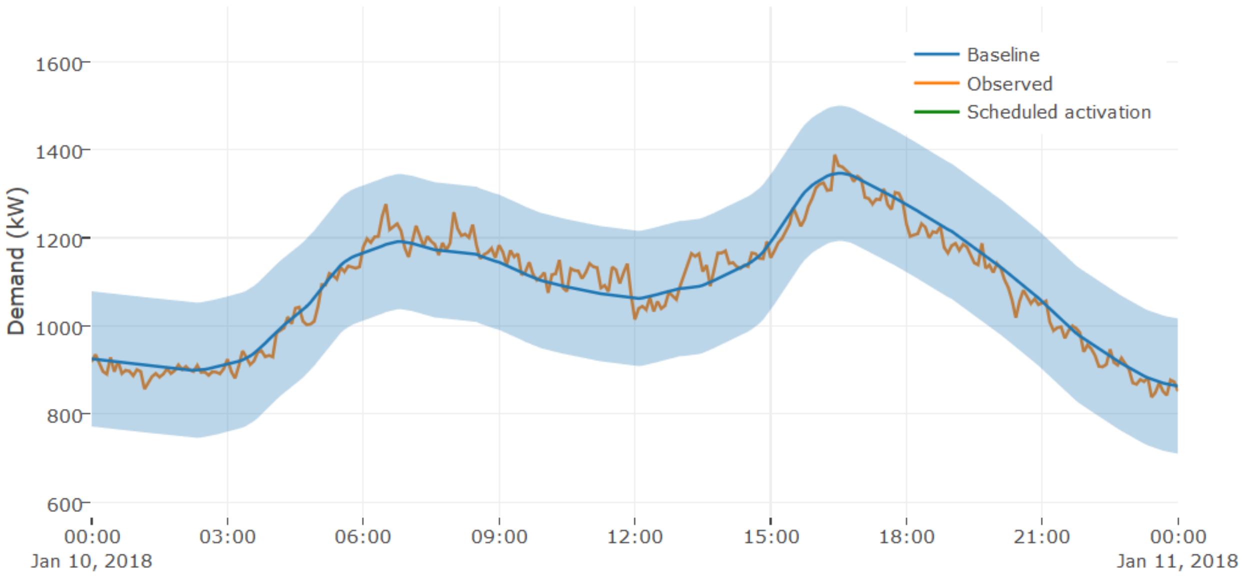


Figure 7. An example baseline for the EcoGrid 2.0 portfolio from January 10th 2018. The light blue area represents the baseline's uncertainty.

5.2.5.1 How baselines are constructed

The baseline is built based upon hundreds of variables that influence electricity consumption. A simple model is shown below, where variables are multiplied by a weight and summed to give a result in kWh/15 min.

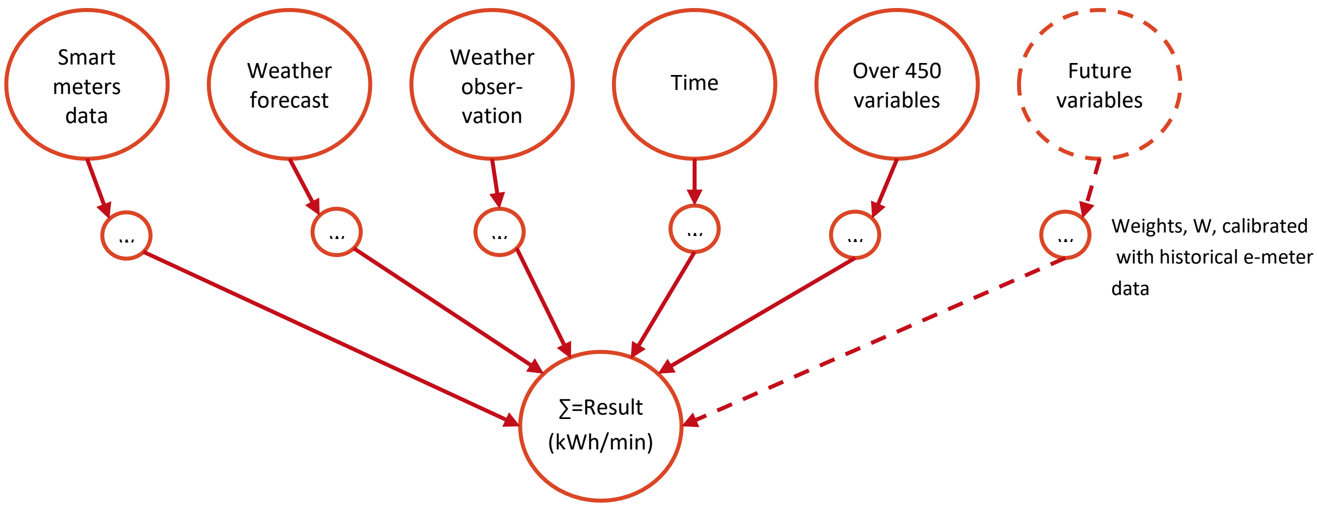


Figure 8. Illustration of the multiplied variables in the baseline model.

For very low levels of aggregation – e.g. on low voltage feeders with 20 houses – errors of 20-30% may be observed for the baseline forecast, making verification for immediate service delivery difficult. This compares to under 5% (average) for baseline forecasts at high voltage levels. When the forecasting error is large, baselines can only be used to verify service delivery when multiple demand response activations are observed. Verification is then performed on the mean response, which must lie within the confidence interval that is relative to the aggregation size (there is a bigger confidence interval for smaller aggregations).

5.2.5.2 How can system participants rely on a black box function?

If a baseline is based on a multilinear regression, where the TSO, DSO and aggregator have full access to data and the model used, then the baseline function is a white box model with full transparency. This is a desirable outcome for all parties involved, as it would lower costs for all market participants by reducing redundancy.

If the baseline is created with proprietary data and deep learning models that are a black box, then a baseline-responsible party could be identified. A baseline-responsible party could be similar to the forecasting responsibilities of the TSO today; BRPs have a tendency to buy slightly more load than expected in the day-ahead market due to price-asymmetry in the intraday and real-time markets, which means the TSO must make its own load forecast that is not just the sum of BRP trades.

5.2.5.3 Challenges and limitations of baseline-based DSO services

Throughout the project relative DSO services, based on baselines, were traded, activated and evaluated. It was shown how these can be offered and delivered with satisfactory accuracy and help decrease a feeder's consumption over some period. However, there are potential drawbacks and limitations with baseline-based services.

Baseline-based services can lead to conservative bidding from the aggregators' side. Flexibility services can be activated for various reasons e.g. anticipated network congestions or voltage violations or network reconfiguration. Since the aggregator must always be able to reduce consumption when called upon, it would tend to offer the amount of flexibility it is able to provide under all circumstances - to be on the safe side. In the case of thermal loads this means that it would bid according to the warmest forecasted day of the provision period. However, it is less likely that it will be activated on such a warm day. If aggregators bid conservatively, the offered load reduction will be smaller than what could be achieved on cold days, when flexibility is needed the most. Second, EcoGrid 2.0 has developed a baseline method which estimates the "natural" power consumption without external aggregator control. While this approach works well for heating systems, it can be challenging to define what the "natural" behaviour of other flexibility sources is, e.g. battery systems or electrical vehicles. The behaviour of batteries and electrical vehicles is defined through the owners' objectives, for example energy cost or CO_2 minimization. Finally, baseline services are unable to efficiently prevent network challenges which arise from aggregator actions on the wholesale markets. For instance, an aggregator could significantly increase its power consumption to deliver a down regulation service on the balancing market. Thereby, the aggregator causes a congestion problem on a primary substation. Without real-time network observability, as is the case now below substations, it is not possible to mitigate such congestions by relying solely on baseline-based relative flexibility services.

To avoid the potential drawbacks and limitations detailed above for DSO services, the use of absolute services, such as the power limitation service described in EcoGrid Deliverable 2.2, should be considered. Absolute services have different characteristics than the relative services demonstrated in EcoGrid 2.0 and can avoid the potential drawbacks and limitations listed above. However, absolute services have their own drawbacks and limitations, and therefore further research into absolute services is necessary.

5.3 The Aggregators

The aggregator is the bridge between the private households and the power system; this new actor pools flexible power consumption from hundreds of private households and sells it on the electricity markets. The goal of an aggregator is to maximize the value of the flexibility provided by the demand response units, while respecting the individual participants' requirements, specifically user comfort.

We have demonstrated that aggregators can manage flexibility from private households and deliver services to the power system.

We have shown it is possible to control a portfolio of heating systems and estimated the amount of energy consumption flexibility with digitalization and machine learning.

In Ecogrid 2.0 we had three aggregators – two aggregate the private households on Bornholm (IBM and INSERO) and one aggregator controlling municipality buildings in Horsens (INSERO).

The aggregators need tools to handle data from the private household regarding power consumption and generation and combine the data with temperature and weather forecast data to build and refine a model of power consumption for each individual household. The electricity consumption models for the demonstration in heating season 3 were built based on about 32 GB of measurement data collected starting from October 2016.

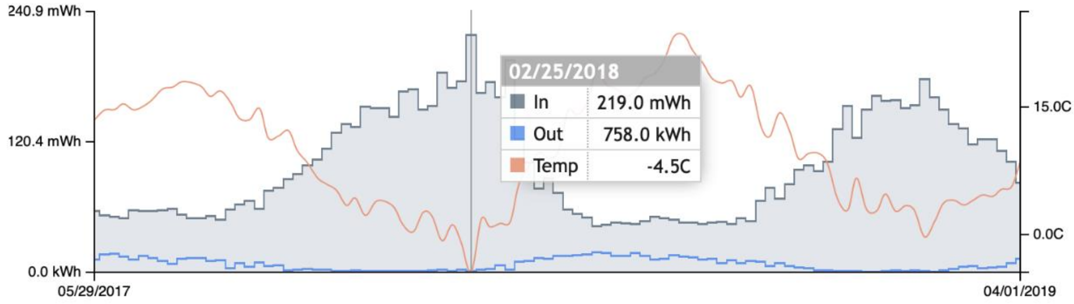


Figure 9. Electricity consumption and generation of a group of EcoGrid 2.0 households and outdoor temperature from IBM.

The aggregators autonomously learned the behaviour from the private households and estimated the amount of energy consumption flexibility the individual household could contribute at any point of time depending on the past household consumption patterns and outside temperature. A number of statistical and machine learning methods were used in this data driven process. The models were validated and tuned based on samples of historical data reserved for validation purposes.

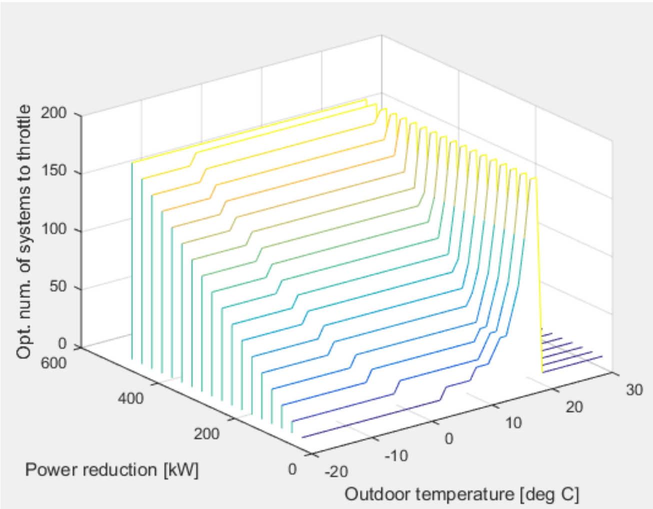


Figure 10. IBMs aggregator tool. Estimation of the amount of flexible energy consumption from a group of consumers.

For more details see:

Tool for characterizing the aggregated flexibility of residential thermostatically controlled loads

Link:https://www.dropbox.com/s/ly37i0918san3is/D4.4.1%20-%20Tool%20for%20characterizing%20the%20aggregated%20flexibility%20of%20residenti.._Final%20report%201.0.pdf?dl=0

Description of implemented toolset for aggregator

Link: 23.august 2019: Description of implemented toolset for aggregator (5.3)

Aggregator tool and demand response

Link: 23.august 2019: Aggregator tool and demand response (4.5.1)

Tool for optimal dispatch of portfolio of DERs
Link: 23.august 2019: Tool for optimal dispatch of portfolio of DERs (4.4.2.)

5.3.1 Aggregator operation tool

The foundation of the project were the 800 private households on Bornholm. During the EcoGrid EU project, each private household had a Home Energy Management System (HEMS) retrofitted into their existing electric heating systems, either heat pumps or electric heating panels.

To assist monitoring and planning of maintenance, an "operation tool" was developed. Such a tool will also be required for future aggregators for their operational tasks. Among other features, the tool allowed to monitor the status of equipment in homes, to plan service visits by technicians and to communicate with consumers.

The aggregators need an operation tool to monitor the status of the equipment in the private households.

On a software architectural level, the aggregators operation tool is a combination of a classic customer relationship management system and a set of specialized systems and functionalities related to the Home Energy Management Systems infrastructure. As such, the operation tool will most likely be an integration between several systems, where some are commercial off-the-shelf products, and others are developed for the purpose or come with the specific Home Energy Management System. The architectural setup of the operation tool is depicted in the figure below.

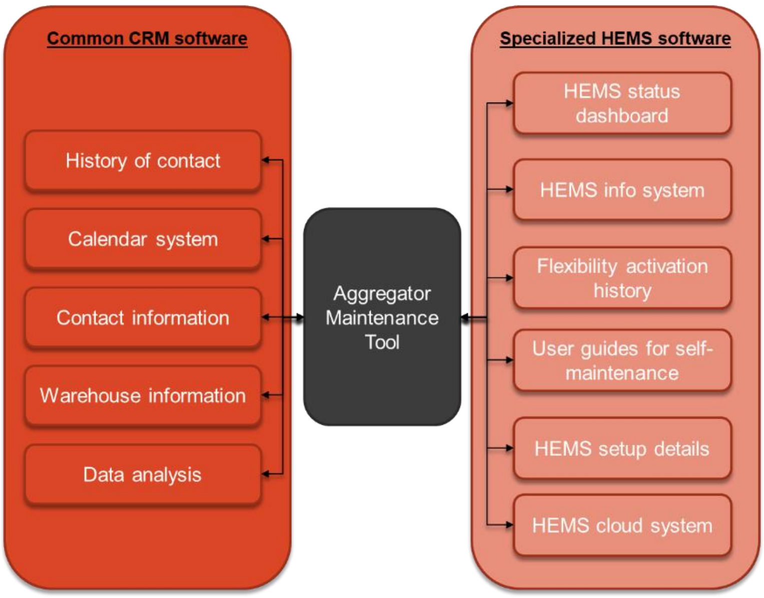


Figure 11. An architectural depiction of the applied and integrated functionalities and information systems in the aggregator maintenance tool.

For more details see:
The Bornholm Flexibility Platform
Link: 23.august 2019: The Bornholm Flexibility Platform (7.1)

5.3.2 Flexibility interoperability platform

The EcoGrid 2.0 project utilised two different home energy management systems, GreenWave Reality and Siemens SYNCO Living, neither of which offered a standard interface for external control. In order to enable aggregators to control these through the interoperability protocol, a Flexibility Interoperability Platform was developed. The flexibility interoperability platform was hosted on the EcoGrid 2.0 blade center. Interoperability ensures that the different home energy management systems can be controlled by aggregators in a uniform way, and is important for two reasons:

1. Interoperability lowers the barrier-to-entry for aggregators and maximizes the potential size of the aggregators portfolio.
2. Interoperability allows consumers to choose their aggregator freely, independent of their type of home energy management system.

We have successfully implemented a Flexibility Interoperability Platform that makes it possible for the aggregators to control heat in a uniform way, independent of what equipment the households have installed. At the same time, the platform allows consumers to freely choose aggregators.

During the course of EcoGrid 2.0, the requirements for an interoperability protocol have been explored by way of use cases supporting various control scenarios. The use cases consider a vast range of current and future home energy management systems capabilities, as well as an expansion to a broader range of demand response units that can provide flexibility to the grid. It also covers handover of demand response units among aggregators, allowing consumers to choose their aggregator freely.

A subset of the interoperability protocol was specified in detail. The specified subset enabled aggregators to control whether the heating system was turned on or not. While the specification only covered a subset of the protocol, the specification was made with an eye towards the full scope of the protocol, and it was based on existing, open standards to ease adoption by demand response/home energy management systems manufactures and aggregators.

The flexibility interoperability platform components are illustrated in the figure below. Each household is represented in the flexibility interoperability platform by a virtual demand response unit. Communication between the aggregator control systems and the virtual demand response unit is done using the interoperability protocol and is facilitated by the aggregators' message broker. The virtual demand response unit translates messages from the aggregators into device-type specific actions, which forwarded to the cloud systems of the manufacturers of the home energy management systems.

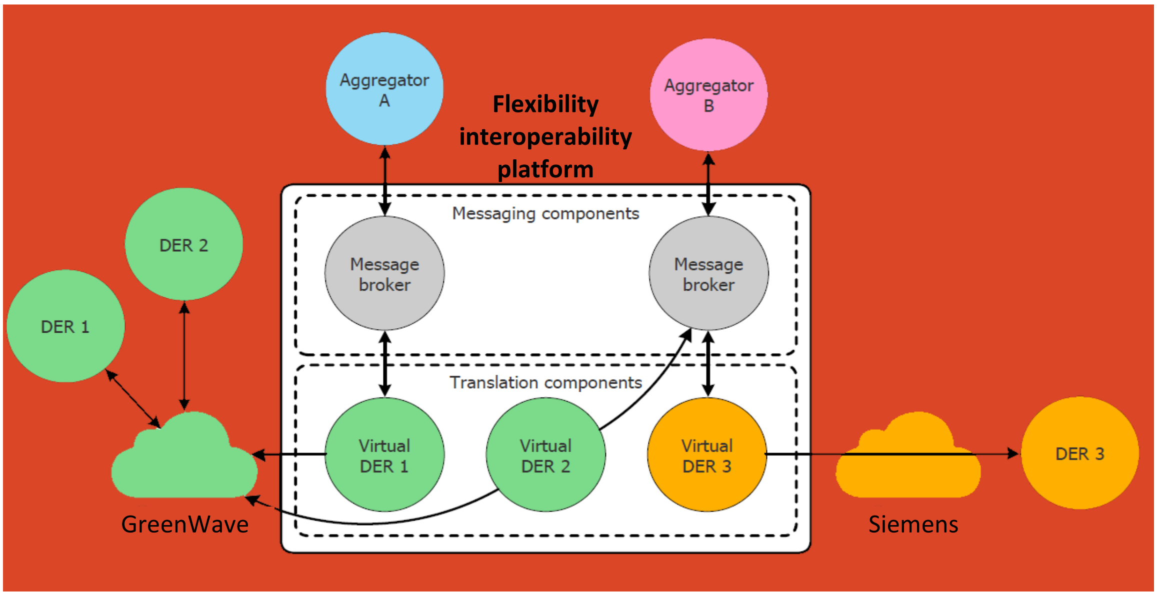


Figure 12. Components of the flexibility interoperability platform.

5.3.2.1 Findings and recommendations

Existing open standards are available which satisfy the communication and data modelling requirements of the EcoGrid 2.0 interoperability protocol. OPC UA is an example of one such standard, and the implementation used in EcoGrid 2.0 was fully based on OPC UA principles.

In order to allow consumers to choose their aggregator freely, we recommend setting up a formal alliance of aggregators. Such an alliance would be tasked with maintaining the interoperability specification, and members would have responsibilities towards the alliance to ensure consumers can choose their aggregator freely.

EcoGrid 2.0 demonstrated that it is possible to utilise a cloud platform to translate between the interoperability protocol and proprietary protocols while still providing acceptable control characteristics and error rates. However, this requires a thorough understanding of the home energy management systems. This requires extensive testing and may require enlisting expert knowledge of the manufacturers. In a commercial setting, aggregators may choose to run their own platform, or a third party could operate such a platform as a paid service on behalf of multiple aggregators. The flexibility interoperability platform is an example of such a platform and can be used as a basis for providing such a service. But we recommend that manufacturers implement the protocol on-device instead. Avoiding a centralized cloud system can provide better security and scalability, and on-device implementations can integrate better with local intelligence.

For more details see:
Description of implemented toolset for HEMS
Link: [23.august 2019:LRSC HEMS Result (7.2)]

Tool for flexibility interface
Link: [17.september 2019: Tool for flexibility interface]

5.4 Developed tools and digitalisation

In EcoGrid 2.0 we have developed new tools for TSOs, DSOs and aggregators, so they can request, buy, sell, activate and control flexibility. For system- and balance responsible parties, there are tools in the existing markets to buy upward and downward regulation today. But for congestion management in transmission and distribution companies buying upward and downward regulation is a new way to go and there are no tools on the market. In EcoGrid 2.0 we have developed and tested tools to for congestion management, and these tools are ready for commercialisation.

To develop the tools in EcoGrid 2.0, we have used several different data sources (measurements from smart meters, weather forecasts, load from the grid, electricity prices, CO_2-emmision etc.). We have utilised the benefits of digitalization and machine learning to make algorithms, forecasts of consumption and baselines for verification. EcoGrid 2.0 has shown that digitalization gives new opportunities and solutions to facilitate the green transition and increase the utilisation of power grid capacity.

The following tools have been developed:

Transmission:

- Service request - request for flexibility in the market
- Market clearing mechanism for asymmetric block bids (i.e. bids that include a desired response, and a rebound)

Distribution:

- Load modelling- Identification of bottlenecks and the need for flexibility - Coherent tools based on load forecasts and the economic value of potential services (consumption scenarios, component lifetime and comparison of grid reinforcement versus buying of flexibility)
- Service request- request for flexibility in the market
- Activation of flexibility
- DSO service verification
- Market clearing mechanism for distribution services

Aggregators:

- Predict flexibility - models for prediction of flexibility in household based on historical consumption, temperature and weather forecasts while respecting the private households' comfort limits
- Portfolio control - combine flexibility from many private households, including control of rebound
- Maximize value of the flexibility (profit) from DSO and TSO market while respecting the households' comfort limits
- Bidding and activation tool - offering bids into the market and activation of the flexibility.
- Operation tool

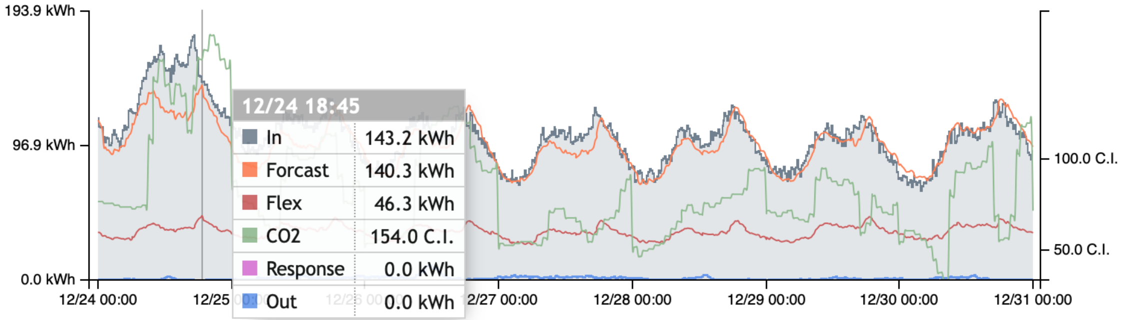


Figure 13. Aggregator tool to control portfolio of flexibility, IBM.

Market:

- Market platform - common services to the participating parties such as communication, authentication, clearing, notification, settlement and other necessary services to provide market platform for trading of energy services. Hosting multiple types of flexibility services and multiple concurrent service requests from different buyers.
- Baseline for verification - Transparent baselines based on multilinear regression, where the TSO, DSO and aggregator have full access to data.
- Flexibility interoperability platform - makes it possible for the aggregators to control the heating systems in a uniform way, independent of the equipment in the household. At the same time, the platform allows consumers to freely choose aggregators. Until we have standards for communication with and management of flexible consumption in households, we need a tool that can communicate with different equipment and communication standards.

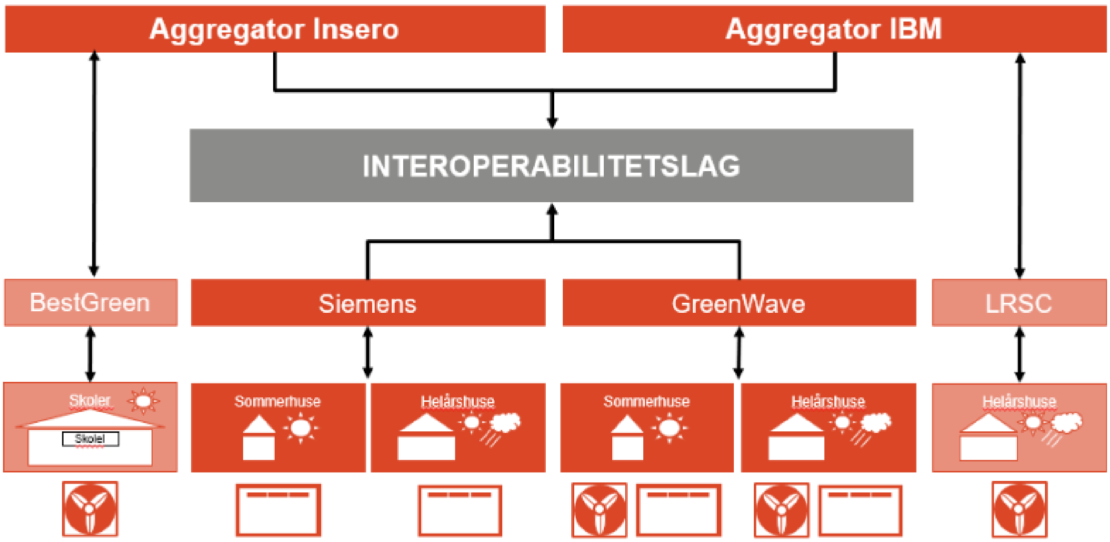


Figure 14. Illustration of interoperability layer.

In the report “Use Cases for EcoGrid Flexibility Ecosystem”, November 2018, you can read about the connection between the different actors and the tools.
Link: https://www.dropbox.com/s/d8s4re5c6905azg/D4.0%20incl%20use%20cases.pdf?dl=0

For more details see:
Tool for flexibility interface
Link: 23.august 2019: Flexibility Interoperability Platform (8.2b)

Evaluation of flexibility Interoperability Platform:
Link: 23.august 2019: Evaluation of Flexibility Interoperability Platform (5.4)

5.5 Demonstration results

All the demonstrations made in EcoGrid 2.0 can be viewed on:
http://www.electricitybaseline.com

In EcoGrid 2.0 we have demonstrated:

- **that we can manage flexibility from private households and deliver services to the market:**
  - **conditional services to the DSO with a high accuracy, even when the service is activated on short notice.**
  - **scheduled load reductions to the DSO with a high accuracy.**
  - **balancing services with thermal loads to the TSO, thus reduce balancing service costs.**
  - **control the rebound effect. This means that flexibility can be used in the power system without creating new peaks and bottlenecks.**
- **a verification method for TSO and DSO services.**
- **how and how much flexibility that can be offered by private electric heating.**
- **that DSOs can model and forecast network load allowing them to**

Below you can read about the demonstrations in EcoGrid 2.0, where two aggregators delivered flexible services to the market.

5.5.1 Aggregator tool: control and forecast of flexibility

The aggregators created models of energy consumption for each individual household based on historical household electricity consumption patterns and outside temperature. The models were used to estimate the amount of flexibility an individual household can contribute at a specific point of time depending on the weather forecast. To deliver a service to the market, the aggregators combined the flexibility forecasts from the households in their portfolios. The households were divided between the two aggregators and the aggregators developed separate tools to manage their portfolio of households.

5.5.1.1 Aggregator IBM:

In the EcoGrid 2.0 demonstration setup, the private households managed by an aggregator are very diverse in terms of size, insulation, electric power generation capabilities, heating system characteristics, requirements regarding indoor temperature, etc. These all strongly impact the amount of flexibility a heating system of an individual private household can contribute. There are large households with high indoor temperature requirements which provide high flexibility; many resident households belong to this category. There are households with negligible flexibility, since they only use only a very small amount of electricity for heating and thus only small savings can be achieved by switching-off their electric heating system. This is the case for many of the summer houses.

The figure below illustrates the theoretic and empirical total load reduction that can be achieved by a population of 209 resident households equipped with heat-pump heating systems for different outdoor air temperatures at a certain point in time. This set of households can deliver 348 kW at -5 °C, 267 kW at 0 °C, and 190 kW at 5 °C. This means that at a particular point of time an average household of this set delivers a load reduction of 1.66 kW at -5 °C, 1.27 kW at 0 °C, and 0.91 kW at 5 °C.

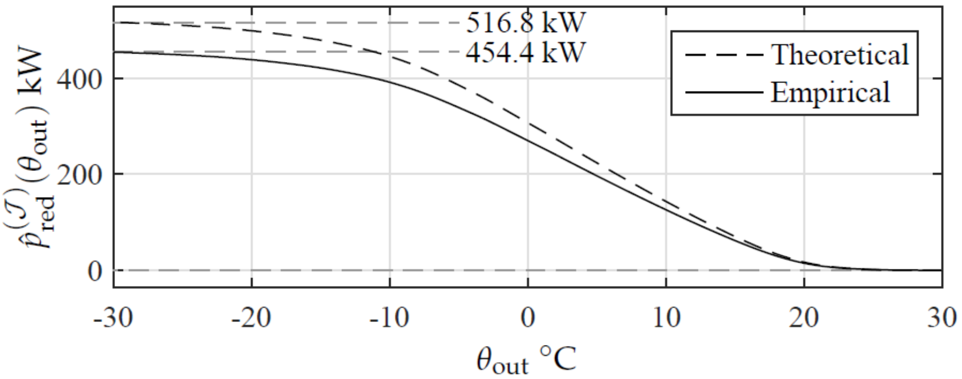


Figure 15. Expected load reduction from 209 heat-pump households at different outdoor temperatures.

The electricity consumption of a household heating system, and thus the amount of flexibility depends on the day of week and the time of day. The figure below shows the aggregator generated forecast and measurement data for 132 resident households with electric heating panels for the week from 24.12.2018:

- The filled grey area shows the overall measured electric power consumption of these households in kWh with 15-minute resolution.
- The blue line shows the measured output power generated by the households.
- The orange line shows the forecasted power consumption for these households computed by the aggregator model at the time of planning based on historical data and weather forecasts.
- The red line shows the model based estimated flexibility of these households.

One can clearly see that the time of day has a strong influence on the flexibility available from the households.

The temperature at 19:00 on 24.12.2018 was around 0°C, at this temperature this set of 132 households can deliver a load reduction of 22.3 kWh/15 minutes, which is equal to 89.2 kW of load reduction. An average household with electric heating panels in this group can deliver around 0.87 kW at -5 °C, 0.68 kW at 0 °C, 0.50 kW at 5 °C at this point of time.

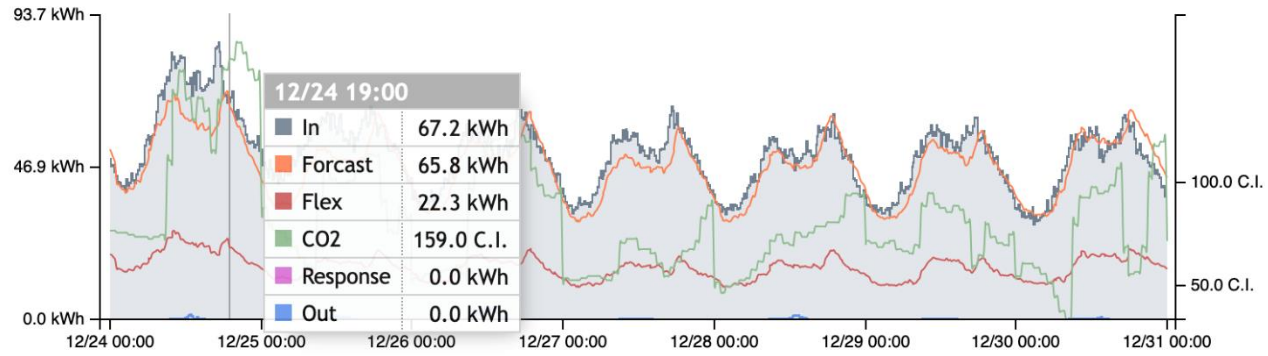


Figure 16. Expected load reduction from 132 electric heating households.

The results show that accurate flexibility estimations are performed by the aggregator for a larger set of households; the average load reduction can be predicted accurately with a median error of 6.7 %.

5.5.1.2 Aggregater INSERO:

Through a series of tests, we created a model that estimates the flexibility for different outside temperature and times of the day. When the outside temperature is -5 °C**,** flexibility is 1.1 +/- 0.1 kW per household. At 0 °C flexibility is reduced to 0.8 +/- 0.1 kW per household.
Since summer houses are mostly kept at a low inside temperature, usable flexibility in those houses is much smaller. Flexibility available in houses with electric heating panels is slightly smaller than in private households with heat pumps (by 0.2 kW).

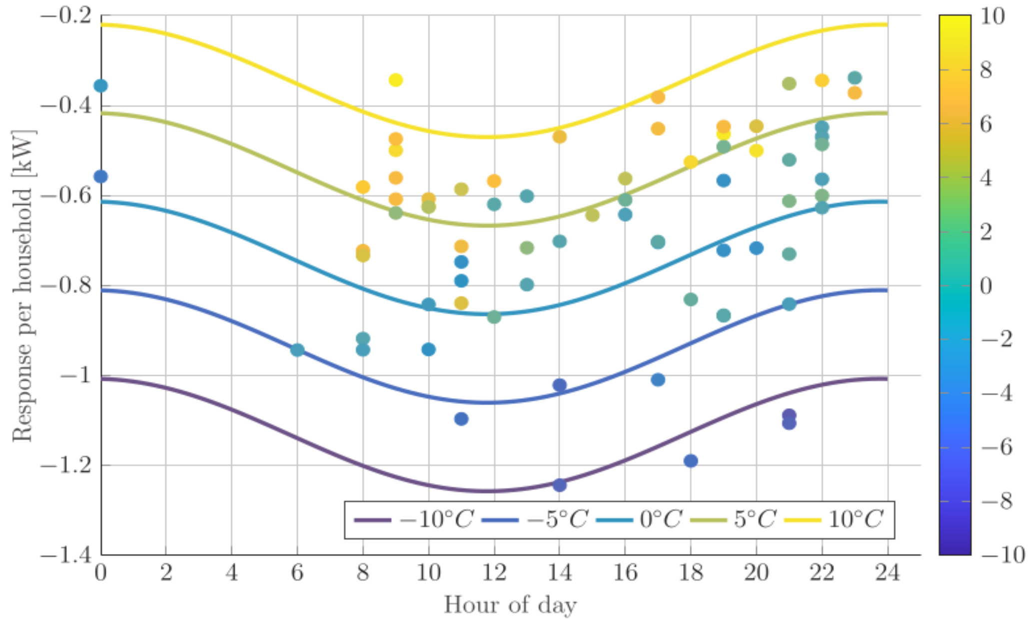


Figure 17. Load reduction potential of private households with electric heating panels.

The graph above shows the load reduction potential of private households with electric heating panels depending on the hour of the day and the outside temperature. Each dot represents a test, which was conducted in the project. The lines show the resulting flexibility model (for temperatures 10 °C, 5 °C, 0 °C, -5 °C and -10 °C). Flexibility is highest during cold days at noon.

Control and forecast of flexibility: We have predicted and controlled the flexibility from private households and delivered services to the market.

5.5.2 Control of rebound

INSERO Aggregator tool:
When heating in a private household is switched off, the house cools down. To heat the house back up again, the house needs to be heated more afterwards (but it does not mean that if a house were 22 °C before the switched off it has to heat to e.g. 25 °C, the setting is still 22 °C, but the heat pump will run for a longer time). This effect leads to an increased energy consumption, after flexibility has been activated. The resulting increase is called rebound.

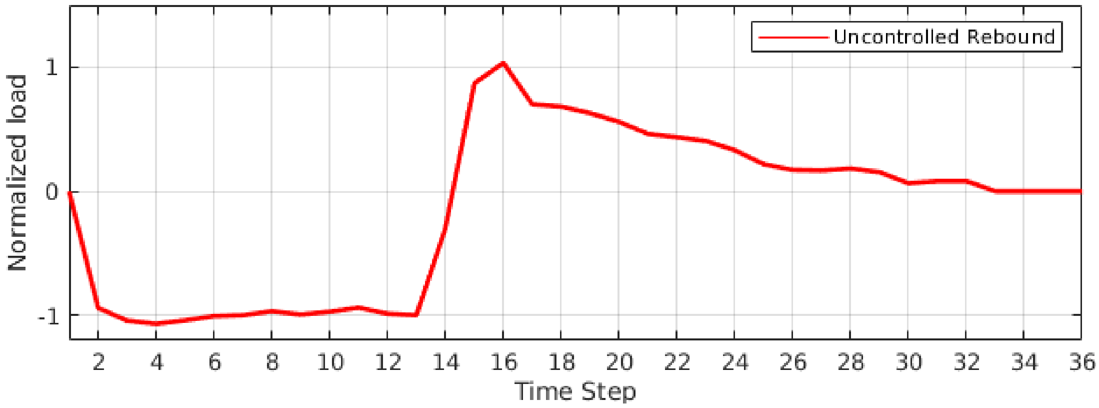


Figure 18. Uncontrolled rebound effect from heat pumps.

The graph above shows the rebound behaviour of heat pumps. The peak of the rebound is not quite as high as the rebound of electric heating panels and it does not drop back as fast as electric heating panels.

We have shown that this rebound can be avoided through smart control. This is done by stretching out the period during which the heating in the households is switched on again in an optimal way.

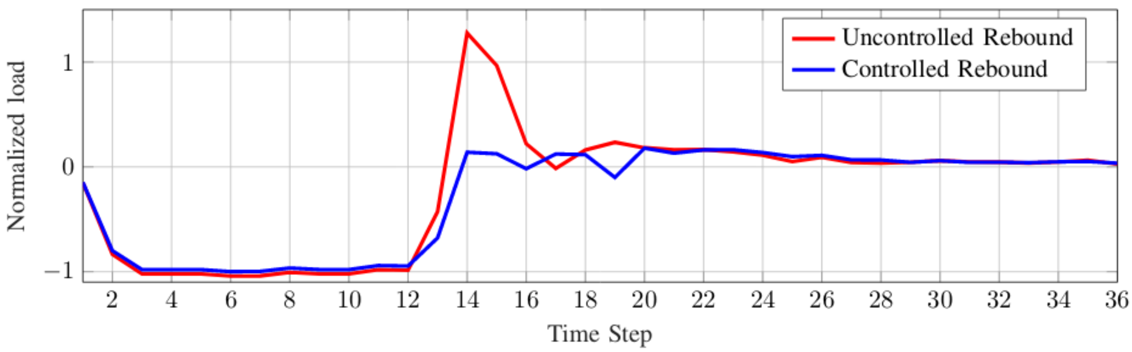


Figure 19. Controlled and uncontrolled rebound effect from electric heating panels.

The graph above shows the shape of the rebound of electric heating panels, when it is uncontrolled (red) and when it is controlled (blue). When uncontrolled its peak exceeds the size of the initial load reduction. When controlled, the rebound effect can be mitigated.

Control of rebound: We have controlled the rebound effect. This means that we can use flexibility in the power system without creating new peaks and bottlenecks.

5.5.3 Trading on the market platform

5.5.3.1 Aggregator IBM:

The aggregator's offering strategy defines when the available flexibility of a household is used in the offers for the market requests. Furthermore, the offering strategy defines how to prioritise the market request and determines the pricing of the offered services. In heating season 3 the aggregator strategy tool coordinated TSO and DSO market requests, as well as manual tests.
Every hour the aggregator received a new TSO market request with a balancing period of two hours beginning in the following hour. Overall it responded with a bid to 371 of these market requests using the estimated flexibility of available resident households; the response duration of the aggregator offers into the TSO market was always one hour with natural rebound duration of one hour as well. 209 of the issued bids were accepted by the market platform and the associated flexibility activations were successfully performed by the aggregator in the time period specified in the contract received from the market platform. The flexibility volumes of scheduled CO_2 or electricity prices product activations were also included and used to additionally accommodate TSO market requests; this combination was helpful for the aggregator to offer higher volumes in its bids for TSO markets.

During the demonstrations in heating season 3, the aggregator received 54 DSO market open requests from the market platform. The DSO requests were generally received at the beginning of the week and requested services from a specified set of households in a region, with activations in the coming working days of the week, which requires longer term resource planning from the aggregator. The aggregator responded with offers to 36 of these requests using the available flexibility of summer houses and residential households specified in the DSO market open notification message. 18 issued DSO service bids were accepted and scheduled for unconditional activations (50%) and conditional activations (50%) in the specified periods.

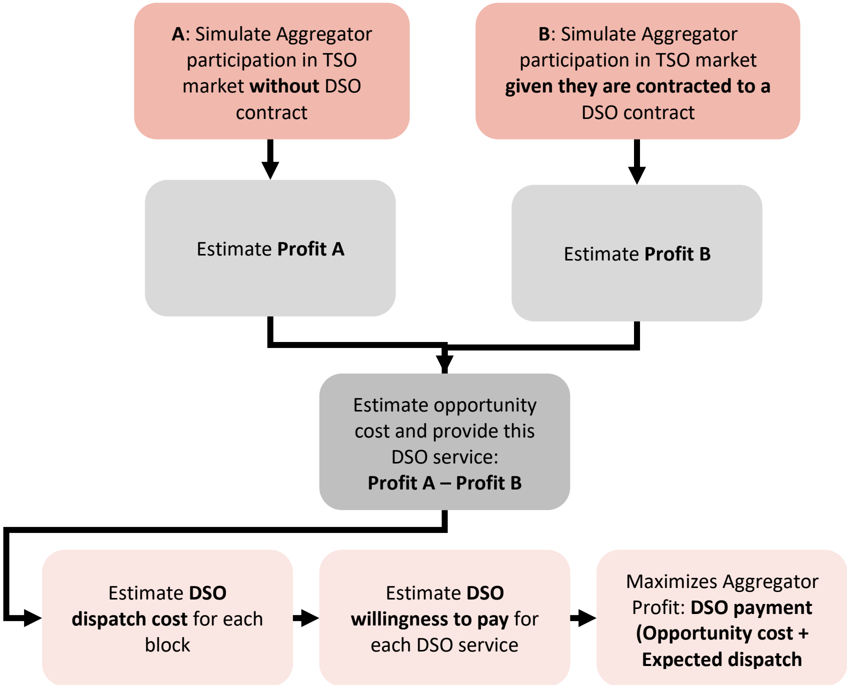


Figure 20. Flow chart of aggregators offering strategy.

In EcoGrid 2.0 the aggregators have the option to bid into two markets, which were found to be best suited for flexibility from private heating. They can bid on the balancing market or offer local DSO services through the DSO market. The graph above illustrates the decision-making process.

Trading on the market platform: We demonstrated that the aggregators can trade the available flexibility of their managed households on the market platform and strategically make bids for the services and markets where their profit is highest.

5.5.4 Scheduled load reduction

The aggregators manage the repository of scheduled load reduction requests; a registration of such a request is initiated as a result of an accepted TSO market offer, an accepted scheduled DSO market service, a CO_2 or electricity price product activation, or a manual test plan. The aggregator executes the scheduled load reduction request at the specified point in time by switching off the heating systems of the specified set of households; after the activation period the heating systems are switched on again. Overall 247 scheduled load reduction requests were successfully executed by the aggregators during the demonstration period of heating season 3.

5.5.4.1 Aggregator IBM:

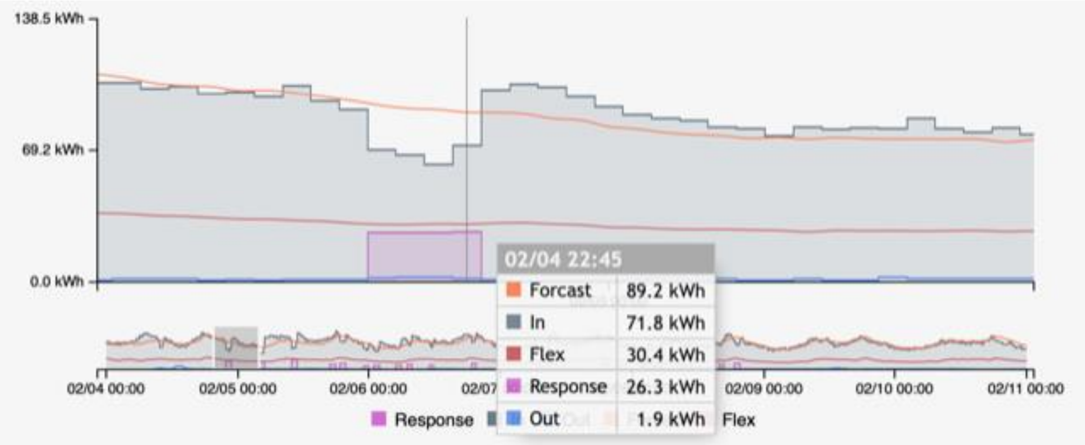


Figure 21. Load reduction execution on a set of 200 households.

The figure above shows the execution of a load reduction. The grey filled area shows the electricity consumption of 200 residential households with the basic product on 04.02.2019. One can see that without the flexibility activation shown by the pink filled area, the actual electricity consumption would be close to the aggregator forecasted consumption shown by the orange line in the graph. This graph illustrates an observation that the response volumes of one-hour activations of a set of households with diverse mix of different heating systems are often compensated by not as high but longer rebound periods.

5.5.4.2 Aggregator INSERO:

We have delivered scheduled load reductions at specific grid nodes within the distribution grid.

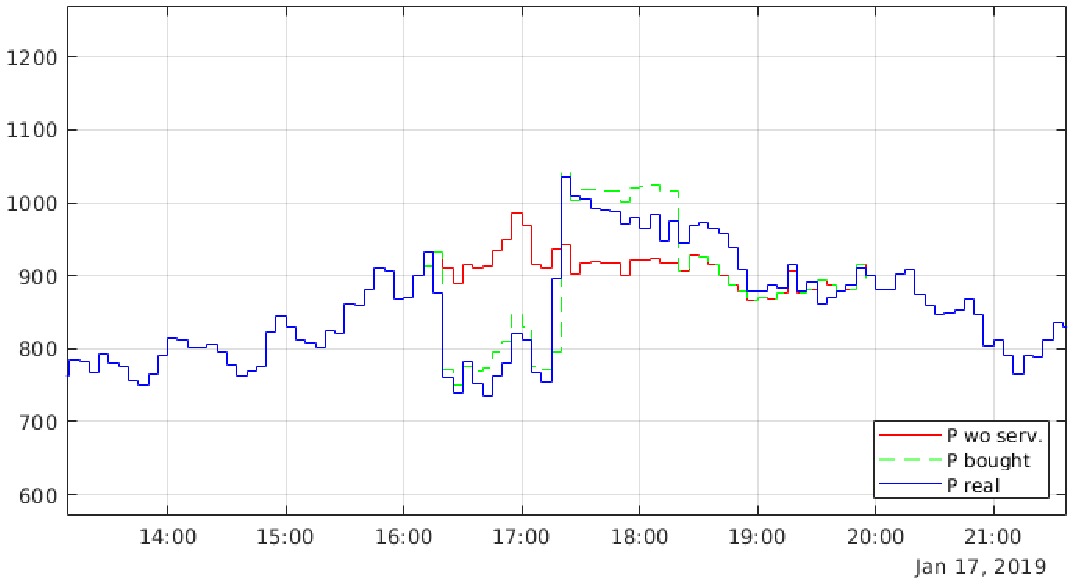


Figure 22. Power flow through a transformer station during the time of a DSO service activation.

The plot above shows the power flow through a transformer station during the time of a DSO service activation. The red curve shows the predicted load without the service. Between 16.15 and 17.15 the load was reduced through a DSO service (blue).

Scheduled load reduction: We have delivered scheduled load reductions to the DSO and TSO with a high accuracy.

5.5.5 Conditional load reduction and increase services

5.5.5.1 Aggregator INSERO:

Distribution operators must be able to acquire DSO services with a long lead time (e.g. 1-12 months ahead of time). Since load conditions cannot be forecasted so far in advance, it is not known if a bought service will be needed. Therefore, EcoGrid 2.0 has proposed conditional services which can be bought well in advance but are activated only hours before use. This grants DSOs the level of security they need, while also making sure that no unnecessary activations take place. We have designed a market mechanism which allows to trade both scheduled and conditional services together. Since conditional services are not always activated, aggregators can offer such services at a lower cost. Further, we found that conditional services were as reliable as scheduled services.

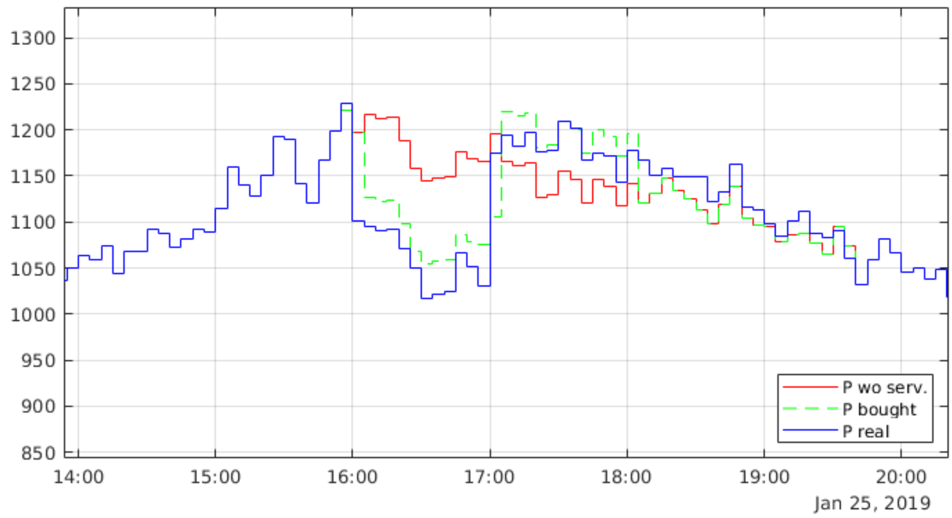


Figure 23. Example of a conditional service activation.

We found that the conditional activation of services does not affect the service reliability and accuracy.

Aggregator IBM:
In January 2018 we turned off 450 heat pumps for an hour and reduced the consumption by 1/3 (300 kW). That corresponds to 124 MW at a national level.

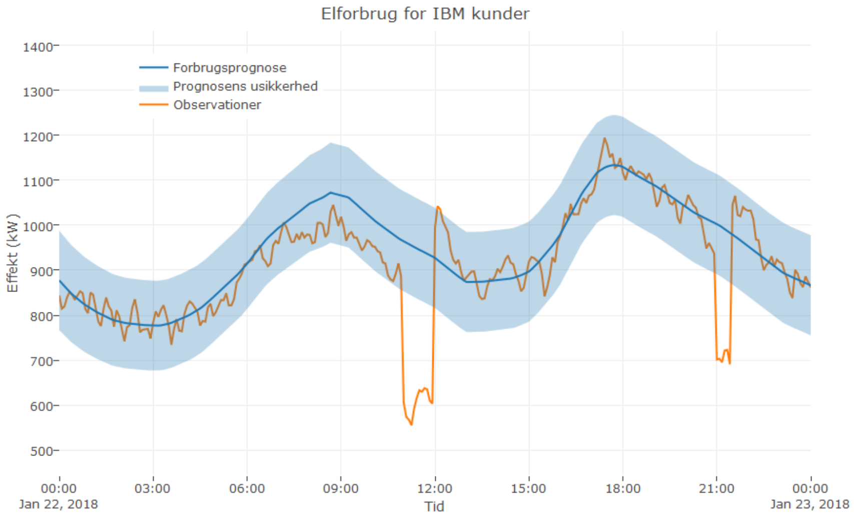


Figure 24. Example of conditional load reduction.

5.5.5.2 Aggregator INSERO:
In November 2017 we turned on 350 electric heating panels and increased the consumption by 559 kW - 2,3 times higher than before the activation. That corresponds to 560 MW at a national level.

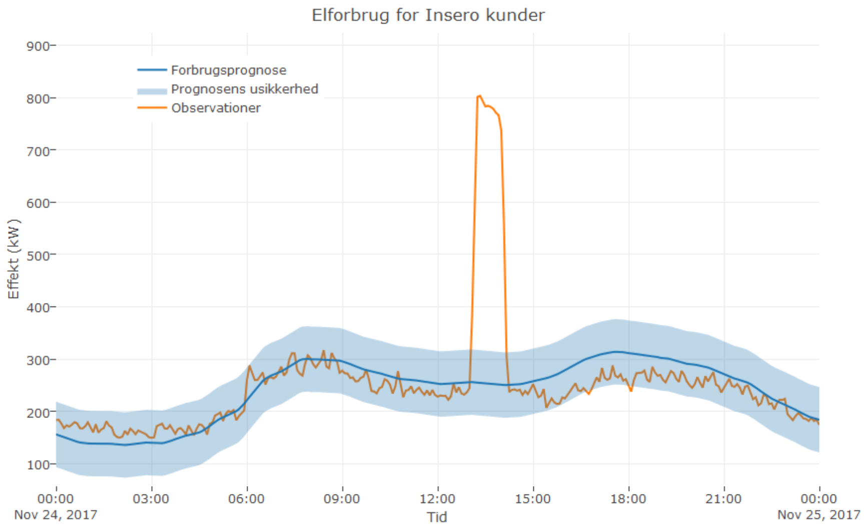


Figure 25. Example of load increase.

Conditional load reduction and increase services: We have delivered conditional services to the DSO with a high accuracy, even when the service is activated shortly before the delivery period.

5.5.6 Balance service

Aggregator INSERO

Balance services are used to manage unexpected load and generation changes in the power system. In the past, such services have been delivered by large carbon-intensive power plants. In the future, demand-side flexibility can contribute to the system level by offering such services.

In EcoGrid 2.0, 393 balancing services have been delivered to the TSO market. This would have reduced the TSOs operating cost. Since the TSO is financed through the general electricity tariff, this reduces costs for all network users.

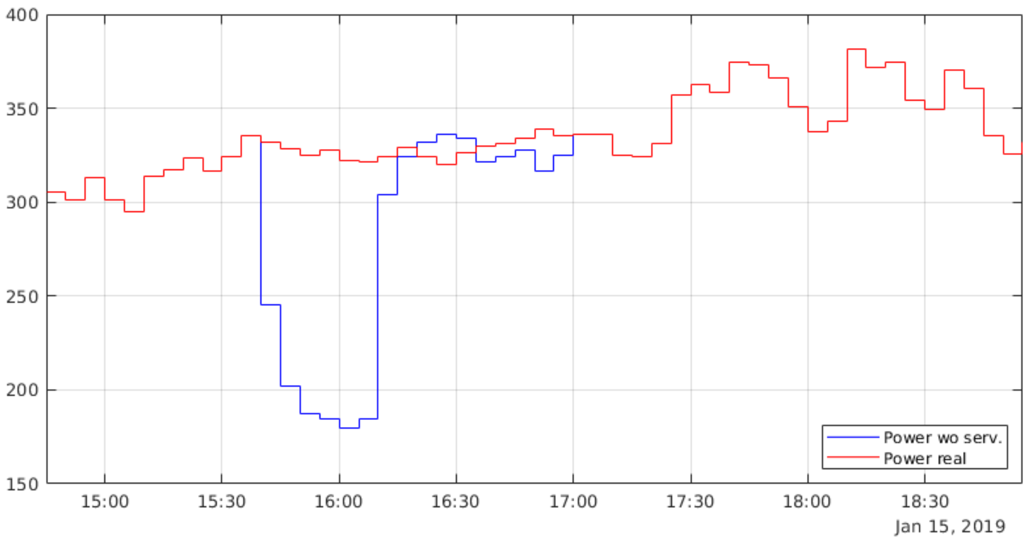


Figure 26. Load reduction.

Using demand response in the balancing markets has the potential for reducing system costs while at the same time displacing fossil fuels.

Balance service: Household flexibility can deliver balancing services to the TSO. EcoGrid 2.0 has shown how and how much flexibility can be offered by private
electric heating. Balancing services from aggregators reduce balancing service costs

5.5.7 DSO load modelling

The figure below shows the power flow through a distribution transformer on the 15.02.19 (red line). The red dashed line represents the transformer rating, which should not be exceeded. The load uncertainty interval three months ahead is represented through the two black dashed lines. The load could potentially lay anywhere in the area between the two black dashed lines. This uncertainty originates mainly from the uncertainty around the ambient temperature during a typical February day, which varies between plus ten and minus ten degrees Celsius. On cold days private households must heat more. This increases the power flowing through the distribution grid. As the graph shows, in the worst case, the transformer station could be overloaded and damaged. Therefore, the DSO requests a load reduction service. One day before the delivery period a much better temperature forecast is available, and the uncertainty is much smaller (blue). A transformer overloading can now be ruled out and the DSO can decide whether a service activation is beneficial or not.

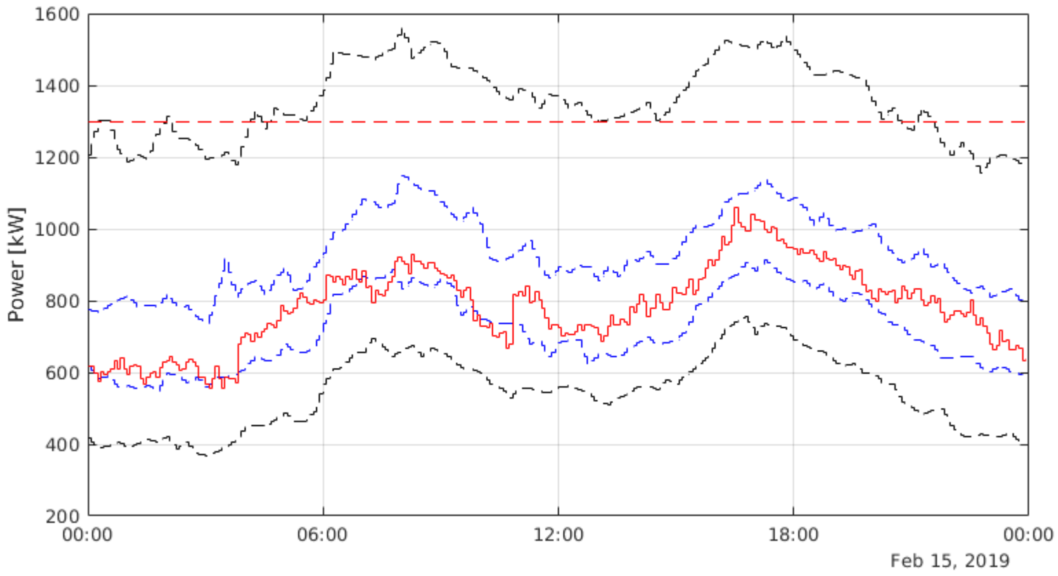


Figure 27. Forecasted network load.

DSO load modelling: DSOs can model and forecast network load allowing them to request meaningful DSO services.

5.5.8 Flexibility services for medium voltage grids

In the future, DSOs will face additional loads in their grid as well as flexible units, which deliver services to the TSO. To avoid network congestion, DSO services can be used. EcoGrid 2.0 has established a market platform, which allows DSOs to buy such services. Hence, DSOs must be able to analyse the benefit of each individual DSO service request. The DSO tool for service requests uses historical consumption profiles to forecast the load in the distribution network. Then the cost of network operation with and without DSO services is calculated. The result defines the benefit for the DSO for each possible service request.

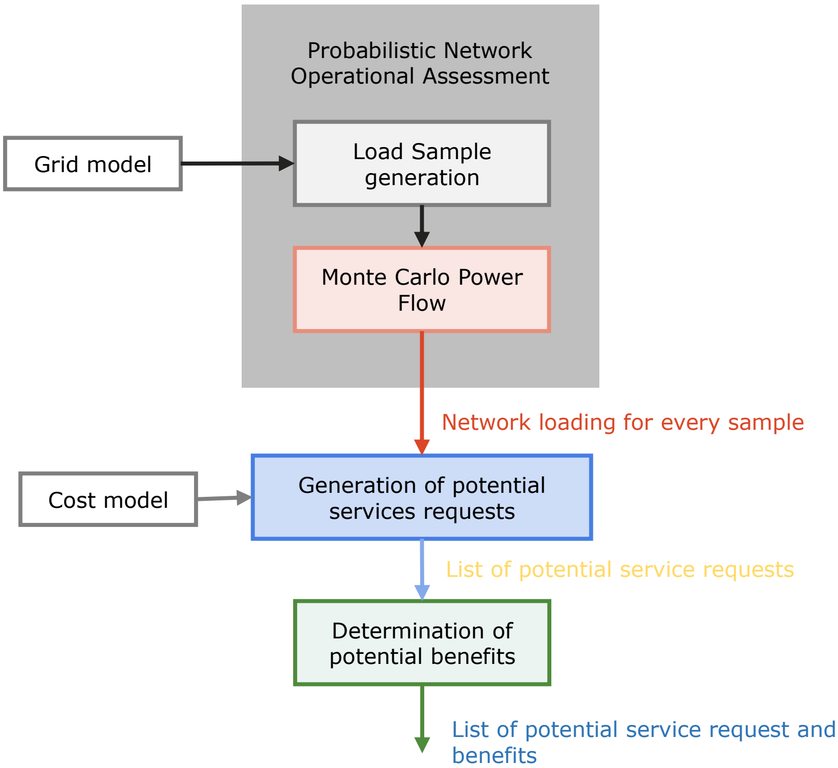


Figure 28. Illustration of DSO tool.

The graph below illustrates the accuracy with which DSO services were delivered in EcoGrid 2.0. Each dot represents a DSO service which was requested and delivered to the DSO. The requested amount is represented through the x-axis and the delivered amount is represented on the y-axis.

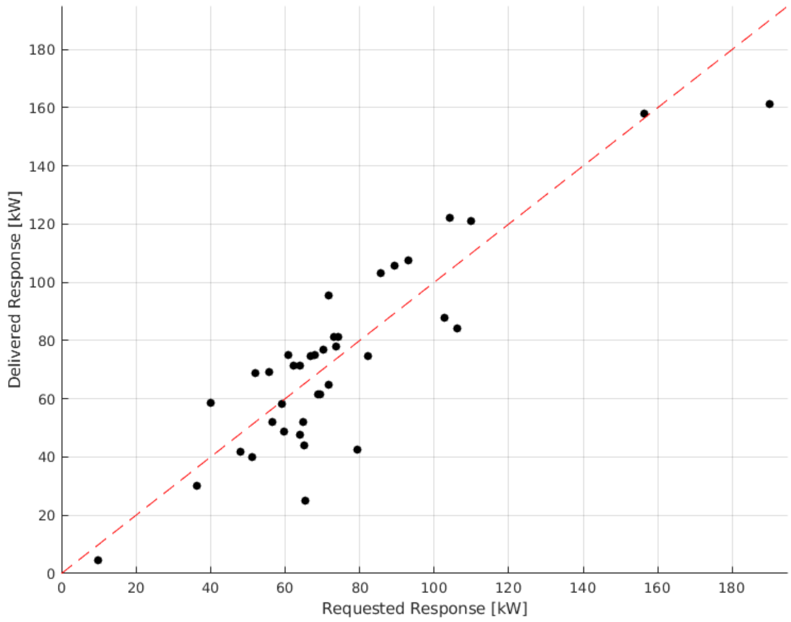


Figure 29. Delivered versus requested DSO flexibility services.

Flexibility services for medium voltage grids: The DSO can benefit from DSO services.

5.5.9 Trading on the market platform

During heating season 3, the marketplace received one TSO market open request every hour and published the associated notification messages to all subscribed aggregators, which could thus rely on getting an hourly opportunity to bid into a new TSO market. In the market open request, the TSO specifies the balancing need for a time period and the maximum price the TSO is prepared to accept. The balancing time period in the TSO requests was set to two hours for all markets, the start of the balancing period was in the next hour following the request, and the market trading period was set to 15 minutes.

For 371 opened TSO markets offers from registered aggregators were received:

- for 299 of these markets one offer from an aggregator was received
- for 62 markets two offers from two aggregators were received
- for 10 markets three offers from three aggregators were received.

Overall, 209 aggregator bids for the TSO markets from the three participating aggregators were accepted and the activation of the contracted services was performed. For the small number of aggregators and short balancing time period, the execution of the TSO market clearings always resulted in optimal solutions and took only some milliseconds; the implemented TSO clearing methods demonstrated the potential to scale and to support larger installations.

During the demonstration in the last heating season, 36 DSO market open requests were processed by the market platform. The DSO requests were generally issued by the DSO tool at the beginning of the week and requested services from a specified set of private households in a region with activations in the coming working days of this week. The specified private households were managed by the two aggregators in the project, IBM and Insero, giving the two aggregators the opportunity to bid for the service delivery for the same DSO markets. The DSO market clearing algorithm determines which of the offered services will be accepted. The clearing algorithm allows to combine the bids of different aggregators to provide a service utilising the combined aggregated flexibility of private households in a region managed by different aggregators.

The execution of DSO market clearing always resulted in an optimal solution. With two aggregators submitting bids to the market, the execution time of the DSO market clearings was not measurable at the milli-seconds resolution; the implemented DSO clearing methods demonstrated the potential to scale and to support larger installations. The contracted DSO services were specified as *unconditional* (25%) as well as *conditional* (75%). To initiate the required activations of conditional services, the activation notification messages were sent by the DSO tool and propagated by the market platform to the aggregators. The service activations were then performed by the aggregators.

The figure below shows one day of market activations for IBM. The top plot shows how regulating market pricing deviates from the spot price several times in one day. The bottom plot shows how this impacts consumption, where the aggregator only bids – or is activated – for some of the regulating market events. For other events, conventional generation alone is activated.

The bottom plot also shows a DSO activation at 17:45 after three regulating market activations earlier in the day, highlighting that the aggregator can utilise its portfolio's flexibility several times in one day and for different purposes.

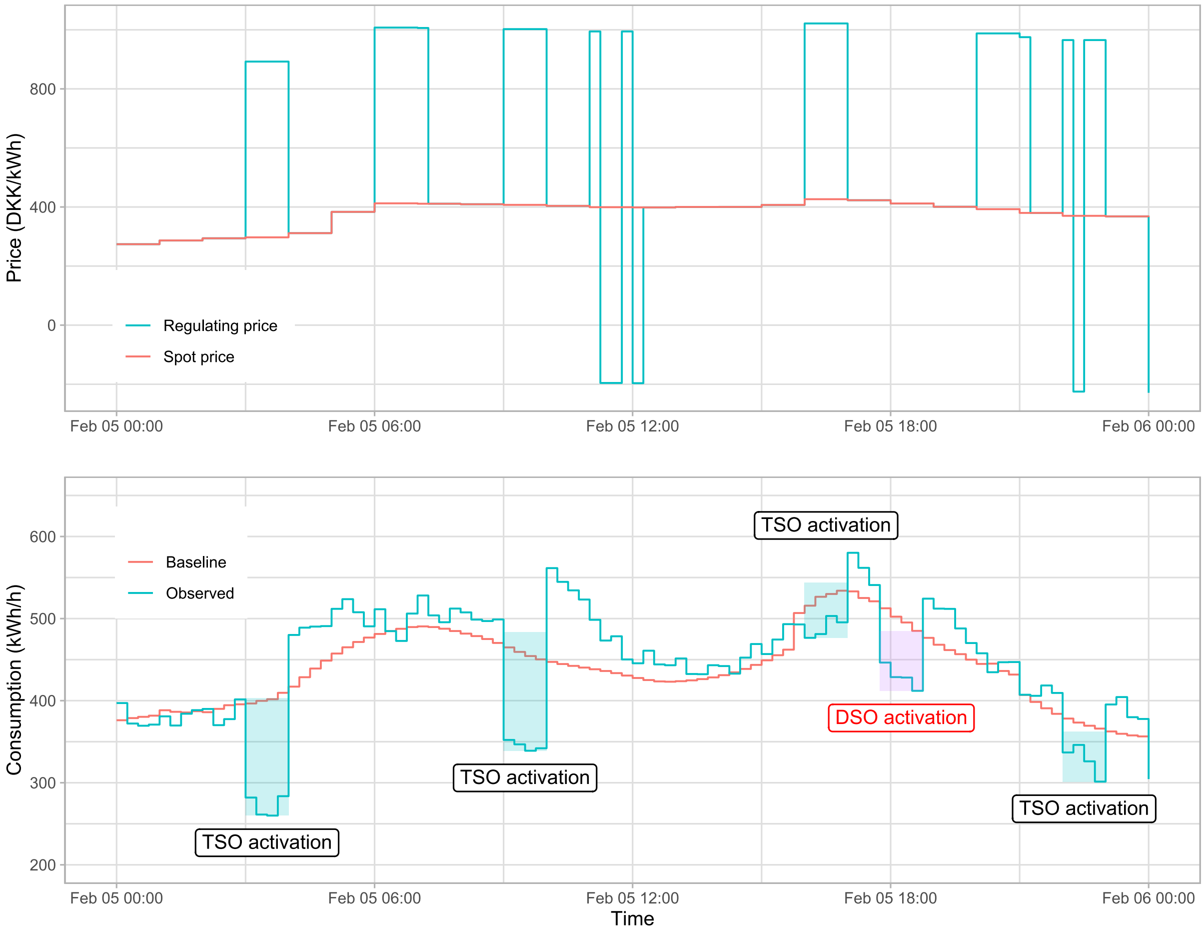


Figure 30. Example of market activations for the IBM aggregator portfolio.

5.5.10 Verification of delivered service

The verification process of both the DSO and TSO services has been defined for services that are based on a baseline.

Figure 31 illustrates how flexibility services are verified in the EcoGrid 2.0 setup. The blue line shows the predefined baseline. Relative to this baseline, a flexibility service is defined by an ideal response that is represented by the blue dashed line. The grey area shows the uncertainty interval of the baseline with a width equal to σ. The acceptable range of the service delivery is defined as an interval of the same width around the ideal response. An additional tolerance interval with a width ε is defined. In this interval the service delivery is partially accepted. Figure 32 applies this process to a real test, which was carried out on the 16.02.18.

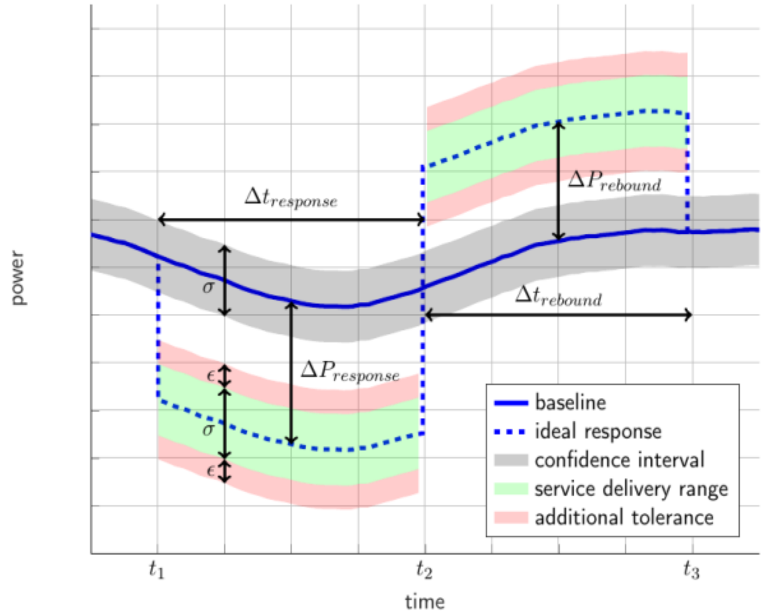


Figure 31. Illustration of the verification process of flexibility services.

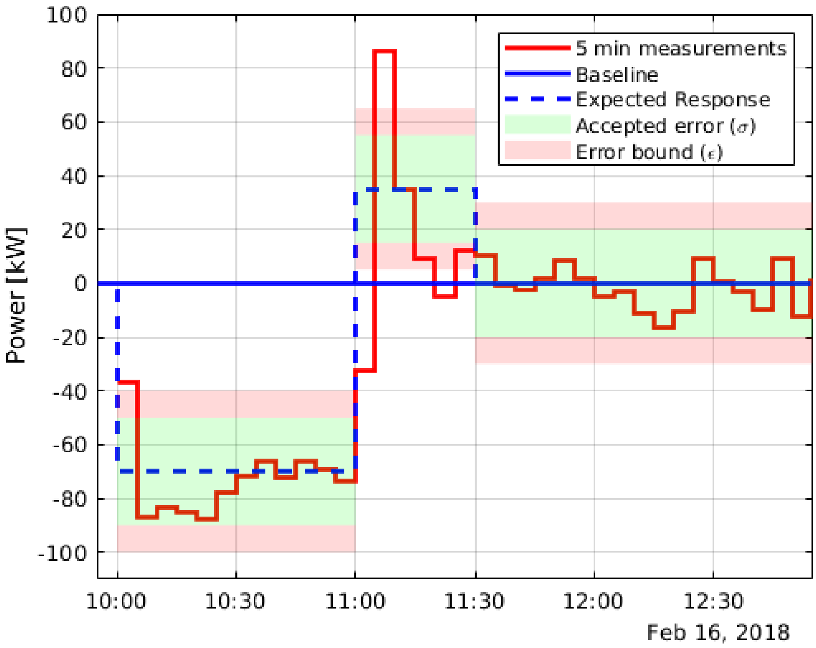


Figure 32. Verification of a specific service delivered on the 16th of February 2018 during heating season 2. This specific service was delivered without rebound control, as rebound control was first implemented in heating season 3.

5.5.11 Flexibility interoperability platform

Tests of the flexibility interoperability platform were run in order to describe the latency and error rates that aggregators would observe during control of the full portfolio. The tests imitated a scenario in which both aggregators would perform a full activation simultaneously, by switching off heating of their entire portfolio. The tests showed that aggregators could expect a maximum latency of approx. 70 seconds for successful activations and approx. 80% percent of the portfolio would activate successfully.

Table 1 shows the number of aggregator activations performed, while table 2 shows the number of interactions between the flexibility interoperability platform and HEMS's in order to perform those activations.

Aggregator activations	Siemens	GreenWave	Total
Total	19,682	82,776	102,458
Errors	308 (1.6%)	9,613 (11.6%)	9,921 (9.7%)

Table 1. Total number of aggregator activations from January 15th to April 5th and the number of errors in the same period.

HEMS interactions	Siemens	GreenWave	Total
Total	195,500	97,055	292,555
Errors	71,783 (36.7%)	23,872 (24.6%)	95,655 (32.7%)

Table 2. Total number of interactions between flexibility interoperability platform and HEMS's from January 15th to April 5th and the number of errors in the same period.

For more details see:
DSO Market Formulation
Link: https://www.dropbox.com/s/cx5b29qvdkyg7bt/4.3.2%20DSO%20Market%20Formulation_withAuthor.pdf?dl=0

DSO Tool for quantification of flexibility benefit, service request and activation
Link:https://www.dropbox.com/s/fsx3svlat1g7mpu/4.1.1%20DSO%20tool%20for%20quantification%20of%20flexibility%20benefit%2C%20service%20request%20and%20activation.pdf?dl=0

Tool for market interaction and service delivery
Link:https://www.dropbox.com/s/cl5rvwvlava852i/D4.2.2%20-%20Tool%20for%20market%20interaction%20and%20service%20delivery.pdf?dl=0

Offering strategy tool
Link:https://www.dropbox.com/login?cont=https%3A%2F%2Fwww.dropbox.com%2Fhome%2FEcoGrid.dk%2FRapporter%3Fpreview%3DD4.3.1%2BEcoGrid%2B2.0.pdf

Evaluation of market
Link: 23.august 2019: Evaluation of Markets (8.6)

Evaluation of Services and Tools
Link: 23.august 2019: Evaluation of Services and Tools (8.2a)

DSO service evaluation
Link: 23.august 2019:DSO service evaluation (4.1.2.)

Tool for characterizing the aggregated flexibility of residential thermostatically controlled loads
Link:08. januar 2018: Tool for characterizing the aggregated flexibility of residential thermostatically controlled loads

Evaluation of Communication Standards
Link: 23.august 2019: Evaluation of Communication Standards (3.1.3.)

5.6 Behaviour of private consumers on Bornholm

Overall, it was successfully demonstrated that consumers can be made to deliver flexibility to the power system. Furthermore, it was demonstrated that flexibility can be delivered without compromising consumers' comfort – often they did not even notice that they were delivering flexibility.

In EcoGrid 2.0, we also wanted to examine what aggregators would have to offer private consumers to convince them to let aggregators make their consumption flexible. We created a website and asked the private consumers to choose between three different products:

- Environment –manages heating based on CO_2 emissions (and services to TSO or DSO).
- Economy –manages heating based on electricity price (and services to TSO or DSO).
- Basic – manages heating only when delivering services to TSO or DSO.

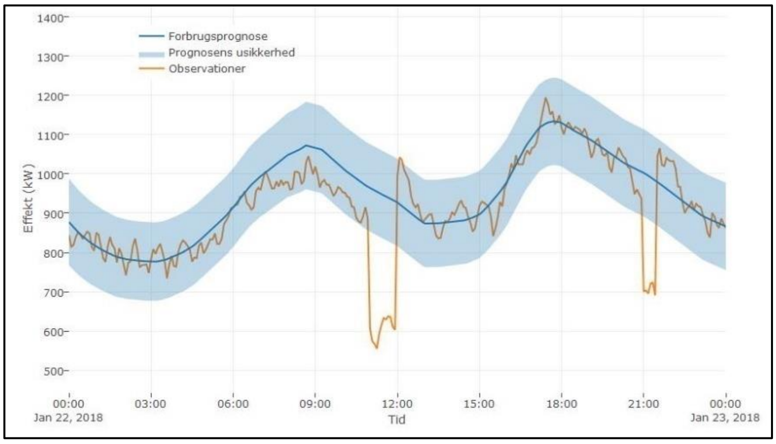
Consumers are generally interested in their own consumption, comfort and economy, and not in the needs of the power system.
It is complicated to communicate the aggregator role to the consumers. In many situations, it will therefore often be advantageous to only use aggregator as an internal technical term.
Trust and confidence in those who manage the consumption plays a key role for the consumers.
Remove technical complexities and use simple user interfaces.
Flexibility must be introduced in a simple way and build on existing habits.

When dealing with consumers, we encountered several challenges:

- The demand for flexibility comes from the power system and not from private consumers. In other words, we tried to offer products to a new market which consumers do not understand nor demand.
- In principle, private households had already agreed to let their consumption be managed: As a condition for participating in the demonstration project, they had accepted that we could manage their consumption. We only subsequently asked them to choose how we were to manage their consumption. This order means that we cannot conclude what incentives consumers should be offered to convince them to offer flexibility in a commercial context. The consumers had already accepted that we managed their consumption and they did not request any products.
- We could not offer the households money a lower electricity price or servicing of their heat pump etc., since EcoGrid 2.0 is a research and demonstration project. The only thing we could offer was products with fictitious estimates for reductions

of CO_2 emissions or potential cost reduction if they were paying variable electricity prices. Households were interested in data from the electricity meters, but such data had already been made available to them in the EcoGrid EU project, which meant that this could not be offered as a new service.

The conclusion was that the motivation for the private households' choice of products was rather to support the demonstration than out of interest. Those who did not choose a product were automatically assigned the basic product. Via email requests, we succeeded in motivating some of the households to switch from the basic product to the economy product or the environment product. But our conclusion is that participants' primary motivation for choosing products was that their local utility company, Bornholm Energi og Forsyning, urged them to do so. We have no clear results (due to the setup) indicating that they wanted to participate in the project, choose products and let other parties manage their consumption if a foreign enterprise had contacted them. We have to conclude that their participation in the project and their willingness to let us manage their consumption were primarily due to their confidence in their local utility company and their support for a project aimed at developing solutions for a green transition.



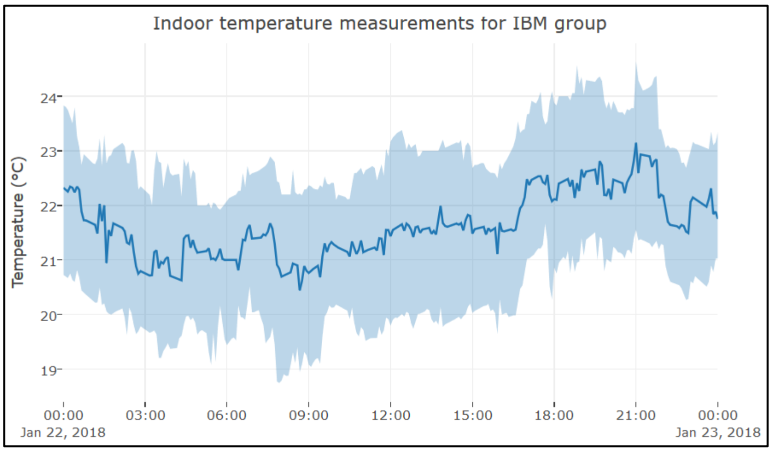


Figure 33. The first diagram shows two demonstrations of load reduction, the diagram below shows the indoor temperature at the private households the same day.

Our experience from the EcoGrid 2.0 project is:

- Private households are willing to let others manage their heating consumption, but confidence in those who manage the consumption plays a key role. Relinquishing control of heating is partly relationship driven. In EcoGrid 2.0, this party was the local utility company, but we expect that other communities or companies in which people have confidence or with which they have a relationship can have the same effect. The Bornholm islanders joined the project because they felt they were doing something good for Bornholm and the green transition. Flexibility trading is a new market which is unfamiliar to consumers. Many households would like to be green and economical when heating their homes. If we are to succeed in utilising flexible consumption, this must, to begin with, be done through existing relations. It will be an advantage to exploit existing channels for the introduction of electricity products where consumers relinquish control to provide flexibility.

- The aggregator role is complicated to communicate to consumers. It will therefore often be advantageous to only use this as an internal technical term.

- Technical products are difficult for consumers to relate to. Consumers are generally interested in their own consumption, comfort and finances, and not in the needs of the power system. Products for which 'repayment' is made with flexibility should be integrated in existing electricity products, services and platforms. All private households are more interested in heating comfort than in flexibility products. A product must contain something that they demand.

- Comfort is not only a temperature range: there is a complex relationship between the experience of temperature, comfort and technology that enables consumption management. If, for example. consumers are used to running their heat pump continuously, they start to worry if it stops periodically even though temperature does not drop below the comfort limit of the household.

- The technicians who installed and serviced the equipment for management of flexibility were of central importance in getting the consumers to accept the idea of flexible consumption. Through visits, the technicians were able to reassure the consumers and could often make them accept wider temperature comfort limits than they had before their dialogue with the technicians. The technicians' function as salespersons should not be disregarded when starting up a new market. They play a crucial role in landing and holding on to consumers and guiding them in their choices and settings.

- Many of the electricity consumers on Bornholm had a good overview of their electricity and heating consumption and the costs thereof. If the aggregators can offer products which could expand the possibilities in which consumers are interested (consumption, comfort and economical solutions), this could be valuable to some consumers. For example, professional help with settings and optimisation of the heat pump may be relevant to some consumers' understanding of their own consumption, comfort and household finances.

- The right communication is important to help drive consumer behaviour.

For more details see:
Costumers willingness and Ability to Offer Flexibility
Link: 23.august 2019:Costumers willingness and Ability to Offer Flexibility(8.4)

Costumers Comfort When Delivering Flexibility to Aggregators
Link: 23.august 2019: Costumers Comfort When Delivering Flexibility to Aggregators (8.2d)

Costumers willingness and Ability to Offer Flexibility
Link: 23.august 2019: Costumers willingness and Ability to Offer Flexibility (8.2c)

Products to households
Link: 23.august 2019: Products to households (6.1.5)

Forbrugernes perspektiver på fleksibelt elforbrug
Link: 05. marts 2017: Forbrugernes perspektiver på fleksibelt elforbrug

Behavioural Design in EcoGrid 2.0
Link: https://www.dropbox.com/s/smkx9i8a9brat16/EcoGrid2.0_Status_Report_KRUKOW_sep2017.pdf?dl=0

5.7 Replication in Horsens

The motivation for the parallel demonstration in Horsens, was to prove that the same principles of flexible energy consumption can be applied to a significantly different setup. Where the demonstrations on Bornholm focus on providing the flexibility from many small sources in the form of private households and summer houses, the Horsens demonstrations aim to provide the same service from a few larger sources (11-15 sites), in the form of schools, kindergartens, eldercare facilities, sport facilities and office buildings. The goal is to prove that the demonstration setup in Horsens can act as a third aggregator that trades on the TSO market.

The secondary purpose of the demonstrations in Horsens is to show that the tools developed for flexibility in residential houses can be transferred to a completely different IT and hardware setup.

Results from the demonstrations in Horsens

- **The aggregator delivered 100 kW of flexibility for 30 minutes and 80 kW for 60 minutes from no more than 15 locations.**
- **The rebound effect is much lower than anticipated, and with no significant increase in gas usage in the heating systems.**
- **Users of the buildings have not experienced any loss of comfort; in fact, the demonstrations have not been noticed at all.**
- **The aggregator setup is built using a mix of existing and new components, with parts being re-used from the Bornholm setup. The re-use of existing infrastructure results in a much lower initial cost.**
- **We have proven that it is possible to add additional aggregators to the existing market.**
- **We have demonstrated a commercial value from trading flexibility in markets.**

The aggregator setup used for the demonstrations in Horsens is a combination of tools. Some are developed as part of the demonstrations on Bornholm, such as the TSO market integration. Some tools and most of the infrastructure is developed as part of the daily operations of the heat pumps and some tools are developed specifically for this application. See the figure below.

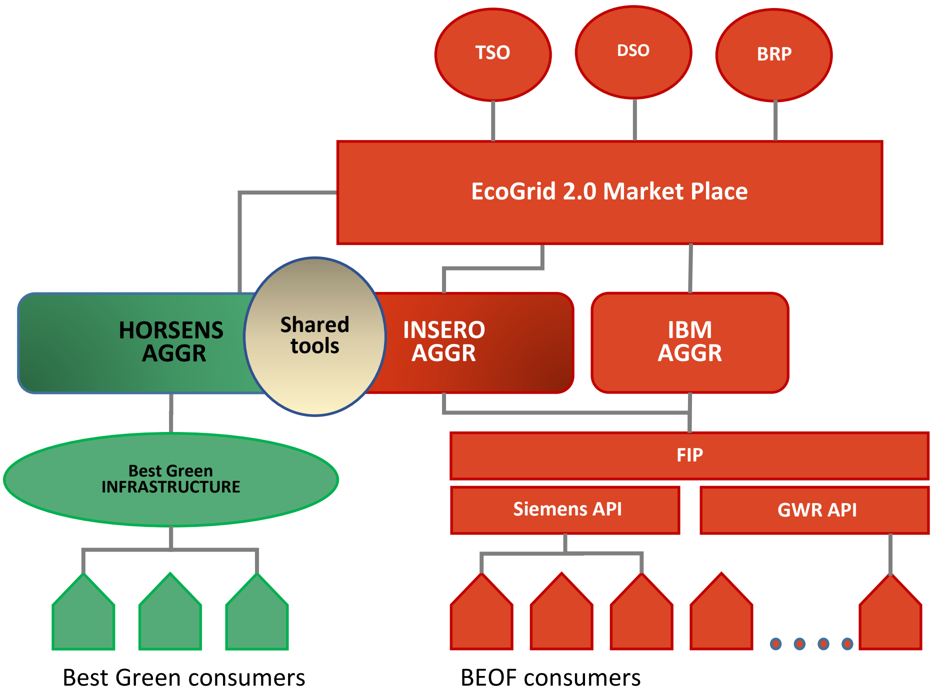


Figure 34. Full EcoGrid 2.0 aggregator setup.

The software developed specifically for the purpose includes tools for baseline and flexibility estimation and portfolio control. Baselines are calculated based on historical data on electricity usage, weather and indoor temperatures supplied by IC-meters from all buildings. The baseline estimation tool determines the baseline using machine learning. From the baseline, weather forecasts and time of day, available flexibility is calculated. The algorithms for baseline and flexibility are regularly updated to optimise their performance.

When we tested each location separately, we got decreases in the consumption of 10-20kW at outside temperatures between -2 ºC and 4 ºC. The tests caused no problems for the succeeding normal operation of the heat pumps. After finalising the tests, no users of the buildings reported reduced temperature comfort. The tests went smoothly seen from the perspective of Horsens Municipality and the relation to the municipality is very positive.

When we combined the municipalities buildings, we achieved flexibility ranges from 30 kW to 100 kW for 30 min. and 60 min. activations. The average flexibility for market activations was around 40 kW, with an expected value of 55 kW. The main difference between delivered and expected value is caused by uncertainty in the baseline and flexibility estimates. The average rebound was around 25 kW. The graph below shows a typical 30 min. activation. Here it is also seen that the actual electricity consumption fluctuates as heat pumps are started and stopped. Due to the small number of heat pumps, the relative uncertainty is quite high compared to the setup with many houses on Bornholm.

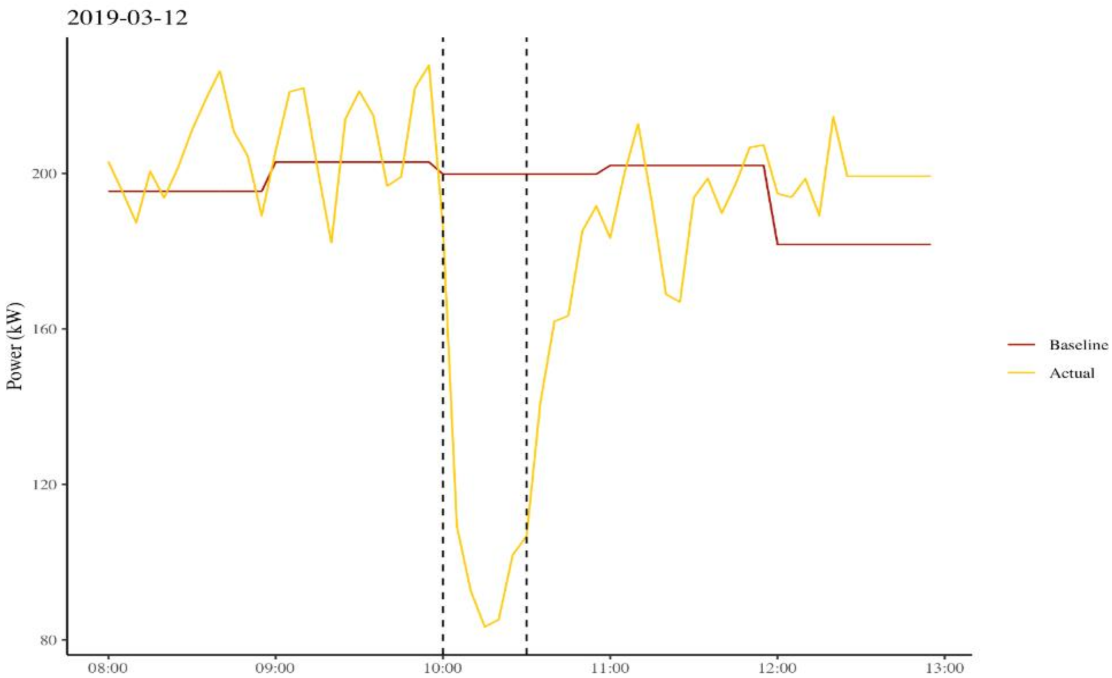


Figure 35. Power consumption during a 30 min. activation, compared to baseline.

In general, a good amount of flexibility was achieved. The rebound is significantly lower than expected but lasts longer. This can be partly explained by the significant thermal inertia in the large buildings. Even though most of the buildings are fitted with a gas furnace, that will start if the indoor temperature drops too much, there has been no significant increase in gas usage during or after activations. Most of the demonstrations were performed without indoor temperature data. Despite performing activations without indoor temperature data, no complaints have been received from the consumers. Subsequent interviews showed that no one had experienced any loss of comfort, in fact several janitors in buildings were un-aware that the demonstrations had been performed. The combined results show that it is possible to apply the same principles from supplying flexibility from household houses to a completely different environment and still provide a valuable flexibility service.

Using buildings owned and run by the municipality introduces another party with a strong obligation to ensure a high level of indoor comfort for the users of all the buildings. Just as with the homeowners on Bornholm, being a research and demonstration project, we had no way of compensating the municipality for letting us control the heating installations. Instead, we relied on the goodwill of the municipality. That is not to say, that the municipality does not gain from participating in the project. Most Danish municipalities have a declared goal to actively work towards a greener Denmark. Horsens especially so, as they are a "Klima Kommune". Being a part of EcoGrid 2.0 is a concrete action towards their green intentions. Many municipalities, including Horsens, have a goal to be technological first movers within digitalisation. This helps the municipality stand out and attract new tech companies. The EcoGrid 2.0 case can help Horsens in this promotion.

For more details see:
Evaluation of demonstrations in Horsens
Link: 23.august 2019: Demonstrations in Horsens (8.3)

6 Conclusion

In Ecogrid 2.0 we succeeded in activating flexibility from private households on a large scale and utilising this flexibility in the power system. This is a solution for the green electricity market of tomorrow. The flexibility can be used to

- integrate more green energy and reduce CO_2 emissions.
- reduce costs for consumers through better utilisation of power grid capacity, by keeping consumption below the load limits in the transmission and distribution grids, and thereby reducing the need for investments in the power grid.
- maintain a balance between production and consumption

The project has succeeded in researching and demonstrating promising new technologies, now commercial companies should take the initiative and continue the journey towards widespread flexible consumption.

Conclusions in Ecogrid 2.0:

- Consumers can provide flexibility without compromising their heating comfort.
- We can manage the flexibility from private households on a large scale and utilise this flexibility in the power system.
- Flexibility can be traded on a market based on the Supplier-centric Model (Engrosmodellen).
- We can take advantage of data and digitalisation to move consumption, integrate more renewable production and improve utilisation of the capacity of the power system.
- Standardisation is necessary in a commercial flexibility market.

The project's findings are:

- An aggregator is needed to recruit and control the flexible consumption.
- Digitalisation and machine learning give new opportunities to monitor and utilise the capacity of the power grid.
- Green transition and flexibility on the electricity market from private households can be achieved if consumers become involved. Private households are willing to let others manage their heating to provide flexibility, but confidence in those managing the consumption plays a key role. Relinquishing control over the heating in your house is partly relationship driven.
- It is difficult for consumers to relate to the role of aggregators and trading of flexibility. Consumers are generally interested in their own consumption, comfort and finances, and not in the needs of the power system. In order to convince consumers to sell their flexibility, they must be offered something that has value for them, for example professional help with configuration and optimisation of their heat pump.

7 Annex

The Reports for EcoGrid 2.0 can be find on: www.ecogrid.dk

EVALUATION OF DEMONSTRATION:

Evaluation of market
Link: 23.august 2019: Evaluation of Markets (8.6)

Evaluation of Services and Tools
Link: 23.august 2019: Evaluation of Services and Tools (8.2a)

DSO service evaluation
Link: 23.august 2019:DSO service evaluation (4.1.2.)

Tool for characterizing the aggregated flexibility of residential thermostatically controlled loads
Link:08. januar 2018: Tool for characterizing the aggregated flexibility of residential thermostatically controlled loads

Evaluation of Communication Standards
Link: 23.august 2019: Evaluation of Communication Standards (3.1.3.)

Evaluation of flexibility Interoperability Platform:
Link: 23.august 2019: Evaluation of Flexibility Interoperability Platform (5.4)

Evaluation of ICT hosting environments:
Link: 23.august 2019: Evaluation of ICT Hosting Enviroments (3.3.1.)

Evaluation of demonstrations in Horsens
Link: 23.august 2019: Demonstrations in Horsens (8.3)

Verification of services within EcoGrid 2.0
Link:
https://www.dropbox.com/s/8v67mf2reny9l67/Verification%20of%20services%20within%20EcoGrid%202.0%20V2.pdf?dl=0

MARKET SPECIFICATION

Market design specification:
Link: 23.august 2019:Market design Specification (3.2.1.)

DSO Marked Formulation:
15.november 2018: DSO Marked Formulation

Tool for market interaction and service delivery
Link: 15. november 2018:Tool for market interaction and service delivery

Tool to prepare market requests:
Link: 08. januar 2018: Tool to prepare market requests

Tool for flexibility interface

Link: 23.august 2019: Flexibility Interoperability Platform (8.2b)

Use Cases for EcoGrid Flexibility Ecosystem

Link: 15.november 2018: Use Cases for EcoGrid Flexibility Ecosystem

Tool for market interaction and service delivery

Link:https://www.dropbox.com/s/cl5rvwvlava852i/D4.2.2%20-%20Tool%20for%20market%20interaction%20and%20service%20delivery.pdf?dl=0

Offering Strategy Tool:

Link: 14. juni 2018: Offering Strategy Tool

DSO Tool for quantification of flexibility benefit, service request and activation

Link: 15.november 2018: DSO Tool for quantification of flexibility benefit, service request and activation

TOOLS FOR DSO, TSO AND AGGREGATORS

Description of implemented toolset for HEMS

Link: 23.august 2019:LRSC HEMS Result (7.2)

Description of implemented toolset for HEMS

Link: 23.august 2019:LRSC HEMS Result (7.2)

Tool for flexibility interface

Link: 17.september 2019: Tool for flexibility interface

Tool for characterizing the aggregated flexibility of residential thermostatically controlled loads

Link:https://www.dropbox.com/s/ly37i0918san3is/D4.4.1%20-%20Tool%20for%20characterizing%20the%20aggregated%20flexibility%20of%20residenti.. Final%20report%201.0.pdf?dl=0

Description of implemented toolset for aggregator

Link: 23.august 2019: Description of implemented toolset for aggregator (5.3)

Aggregator tool and demand response,

Link: 23.august 2019: Aggregator tool and demand response (4.5.1)

DSO Tool for quantification of flexibility benefit, service request and activation

Link:https://www.dropbox.com/s/fsx3svlat1g7mpu/4.1.1%20DSO%20tool%20for%20quantification%20of%20flexibility%20benefit%2C%20service%20request%20and%20activation.pdf?dl=0

Description of DSO tools:

Link: 23.august 2019: Description of DSO tools 1.0 (5.1)

Description of implemented toolset for TSO:

Link: 23.august 2019: Description of implemented toolset for TSO (5.2)

Tool for optimal dispatch of portfolio of DERs

Link: 23.august 2019: Tool for optimal dispatch of portfolio of DERs (4.4.2.)

CONSUMERS AND PRODUCTS

Costumers willingness and Ability to Offer Flexibility

Link: 23.august 2019: Costumers willigness and Ability to Offer Flexibility (8.2c)

Costumers Comfort When Delivering Flexibility to Aggregators

Link: 23.august 2019: Costumers Comfort When Delivering Flexibility to Aggregators (8.2d)

Products to households

Link: 23.august 2019: Porducts to households (6.1.5)

Forbrugernes perspektiver på fleksibelt elforbrug

Link: 05. marts 2017: Forbrugernes perspektiver på fleksibelt elforbrug

Behavioural Design in EcoGrid 2.0

Link:
https://www.dropbox.com/s/smkx9i8a9brat16/EcoGrid2.0_Status_Report_KRUKOW_sep2017.pdf?dl=0

Read more at www.ecogrid.dk