Evaluation of Markets

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

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TABLE OF CONTENTS

Executive summary

Currently, electricity market operators use zonal market clearing to clears bids and offers for electricity generation, ignoring the grid constraints within each zone. This brings challenges to the Transmission System Operators (TSOs) and Distribution System Operators (DSOs), who are responsible for the secure operation of their underlying grids.

Flexibility at the distribution level, in the form of heat pumps and heat panels has been demonstrated on Bornholm.

From 2019-01-15 to 2019-03-29 the TSO market was successfully cleared 490 times and the DSO contract market was successfully cleared 10 times. Assuming the bids and offers for flexibility are truly representative (in terms of cost, benefit, flexibility etc.), we have verified that:

- The best combination of bids and offers for flexibility were consistently chosen in both the TSO and DSO markets.
- Aggregators, the DSO and TSO, are able to make a profit through the existence of each of these markets.

By inflating their price of flexibility, there is the opportunity for aggregators to make additional profit in the DSO market (at the expense of the DSO). With current bids into the TSO market, the flexibility from heat pumps could only cover a small proportion of what was required. Thus, further experiments may be required to determine if additional cost savings are possible by implementing different aggregator offering strategy tools, changing how they bid into the TSO market.

In the DSO market, we should consider a market where aggregators bid to limit their absolute consumption, rather than promising to provide demand response of a particular shape. This has the added benefit of allowing them to simultaneously provide services for both the TSO and DSO.

1 Introduction

In the current European electricity markets, the market operators use a zonal model, ignoring grid constraints within each bidding zone that often encompasses an entire country. The zonal market clearing brings challenges to both Transmission System Operators (TSOs) and Distribution System Operators (DSOs), who are responsible for the secure operation of their underlying grids. Ideas based on "flexibility markets" and "flexibility products" as part of ensuring grid security, have recently been proposed, all relying on reservation and activation of flexible resources to meet the TSOs' and DSOs' needs (as well as the needs of other market participants, e.g., balance responsible parties).

In this context, the EcoGrid 2.0 project aims to develop an incentive-based demand response market place for trading flexibility from distributed energy resources, e.g., private households, where system operators and balancing responsible parties can request flexibility to restore the system balance or relieve bottlenecks. The adjustment in consumption by distributed energy resources is delivered by aggregators, which control the devices and participate in that market place. The EcoGrid 2.0 consists of about 1,000 heat pumps and electric radiators on the Danish island of Bornholm (EcoGrid 2.0. n.d.)

The majority of the flexible resources, especially Demand Response (DR) aggregators, is spread at the distribution level, and exploiting the flexibility of these resources may further worsen the DSOs' challenges depending on the utilisation of this flexibility. Several TSO-DSO coordination schemes have been recently proposed, each model having its pros and cons.

We take a different approach, proposing a real-time TSO market for the balancing of supply and demand alongside a fixed-term (e.g., a monthly) contract market for the DSO to purchase demand response during a limited window each day.

The benefits of using the flexibility of the aggregation of thermostatically controlled loads are highlighted in (O'Connell, Madsen, et al. 2014) and (Margellos and Oren 2016). One important observation in the functioning of these loads (and their aggregators in general) is that any load reduction causes a deviation from their steady-state operation, e.g., the set-point temperature of refrigerators. Thus, load reduction needs to follow a load increase to return to this steady state. This phenomenon is referred to as rebound (or kickback) effect (Greening, Greene and Difiglio 2000).

In the market context, this effect is modelled by defining two joint blocks (called response and rebound), one representing the load decrease and another corresponding to the load increase. The rebound block is following the response one with no time gap between the two blocks, and the combination of these two blocks is so-called as an *asymmetric block offer* (O'Connell, Pinson, et al. 2016).

By asymmetric, it means that the rebound and response blocks are not necessarily identical concerning the length of the response/rebound and the load quantity reduced/increased. The TSO and DSO benefit of utilising DR depends on the temperature and consumption patterns, which vary from day-to-day. For some days, the TSO's benefit from DR at the distribution grid level may be greater than the DSO's benefit, and other days it may be less.

Thus, we have defined two distinct DR services in the DSO-level contract market: *Scheduled* and *conditional* services. The former requires the DR units to provide their offer every day; and conditional services, where the DSO must provide an activation signal to dispatch the DR units. One may interpret the conditional demand response as “capacity reservation” for flexibility, which can be activated by DSO.

So far, we have developed the real-time TSO balancing market, the DSO contract market, and aggregator offering strategy tools to coordinate their participation in both of these markets. This report presents the key findings from the operation of these markets in Bornholm.

This report focuses on the market outcomes, with the actual benefit to the grid depending on the accuracy of the verification, the true costs and benefits of the TSO, DSO, and aggregators, and whether or not aggregators actually provide the flexibility services that clear the market. Thus, the financial conclusions we make here have not been compared to what actually occurs in the grid and should not be drawn out of context.

2 Case study description

2.1 Structure of bids and offers for flexibility

At each opening of the TSO market, the TSO places bids for demand response, estimating their requirement. This balancing requirement is stated as an expected regulation needs in KW in 15-minute blocks over the next two hours (see Figure 1).

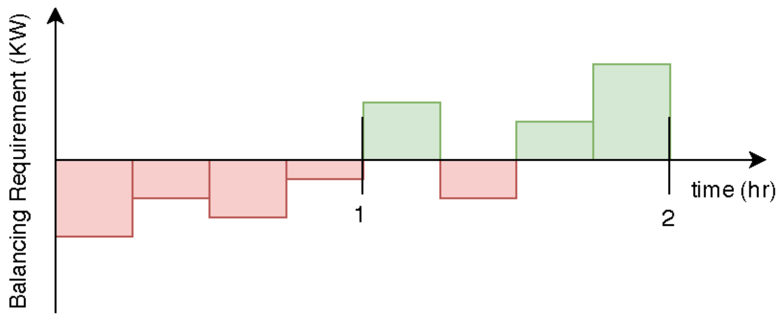

Figure 1: Balancing required by the TSO within a single optimisation horizon

The TSO can purchase additional generation if current levels are insufficient, or else shed generation (e.g. wind) if there is surplus electricity generation (referred to as 'conventional units'). A possibly cheaper alternative is for the TSO to purchase demand response from the aggregators of demand response (Insero and IBM), who aggregate DR in the form of controllable heat-pumps that exist at the DSO level. The Insero units are separated into two groups. The Insero4 units are available to provide flexibility in both the TSO and DSO markets. The Insero5 units are a smaller set of electric heating equipped houses and can only provide flexibility in the TSO market. The offers for demand response from the DR aggregators come in the form of asymmetric block offers, as any load reduction may also come with a load increase (see Figure 2), and must clear the market with this in consideration. See the reports detailing the TSO market clearing (D4.3.2) and the offering strategy tool (D4.3.1) for further information.

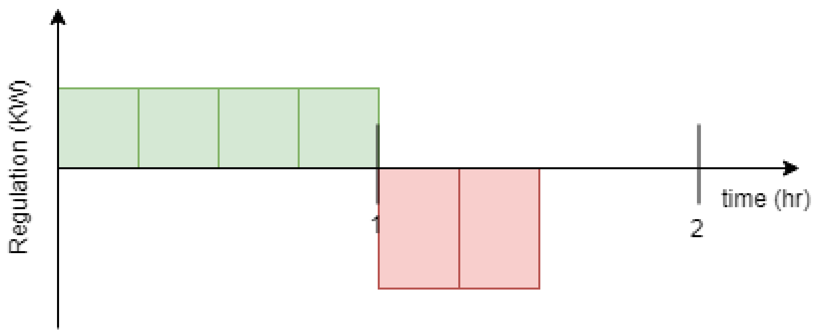

Figure 2: Example of an asymmetric block offer from an aggregator

Comparing the offers for demand response into the TSO market, we see in Table 1 and Table 2 that IBM exclusively offers flexibility which has 1-hour response and rebound, with the offers from the Insero4 and Insero5 aggregators having some variation in response and rebound.

Table 1: Count of offers for demand response at each response length by each aggregator

	Response length			
DER Aggregator		30 minutes	45 minutes	60 minutes
	IBM	0	0	297
	Insero4	144	0	29
	Insero5	125	0	13

Table 2: Count of offers for demand response at each rebound length by each aggregator

	Rebound length			
DER Aggregator		30 minutes	45 minutes	60 minutes
	IBM	0	0	297
	Insero4	0	144	29
	Insero5	0	0	138

3 Trading on the TSO market platform

3.1 Description and verification of the model

Finding: The implemented model correctly utilises the offers for flexibility at minimum cost. There is some redundancy in the case study, giving different solutions with the same cost.

In **Fejl! Henvisningskilde ikke fundet.**, we plot the balancing required by the TSO, which shows that there is a bias towards needing a load decrease rather than a load increase from demand response units. The required demand response (roughly 9MW on average) is typically much larger than can be provided by the available DR units (roughly 25KW on average). Thus the vast majority of the balancing cleared by the market is provided by the conventional units.

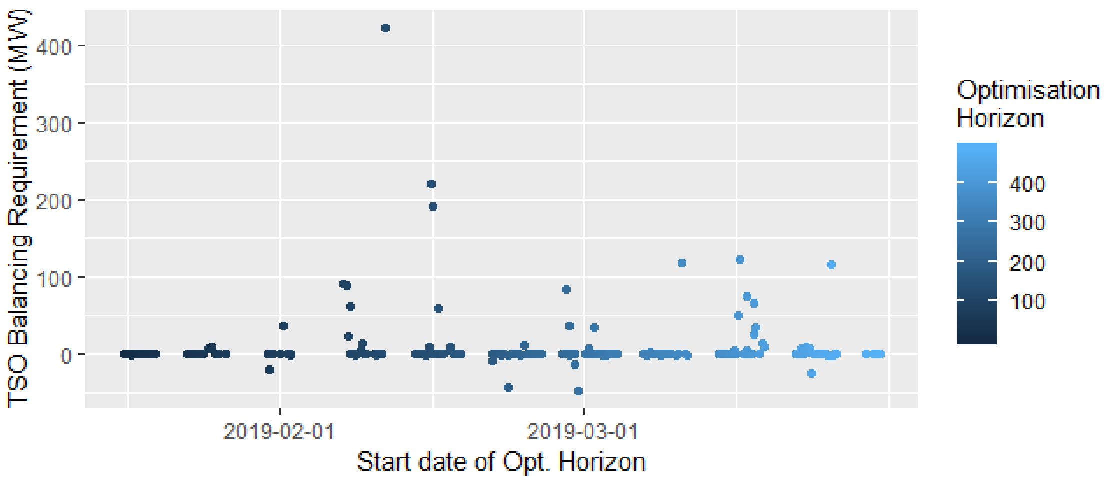

Figure 3: The amount of load reduction (load increase if negative) required by the TSO

To find the optimal combination of DR units at each clearing of the TSO market, the market clearing tool, implemented in C, loops through all of the demand response requirements and selects the combination of aggregated DR and conventional response that minimises the cost of balancing the network. Previously, we have formulated this as an optimisation problem in the mathematical modelling software GAMS. As a sanity check, we compare the results of these two models and show that in the 490 times that the market has cleared, the cost of the solution provided by the two models are identical (see **Fejl! Henvisningskilde ikke fundet.**). This comparison helps to verify that the implemented market selects the optimal offers for DR.

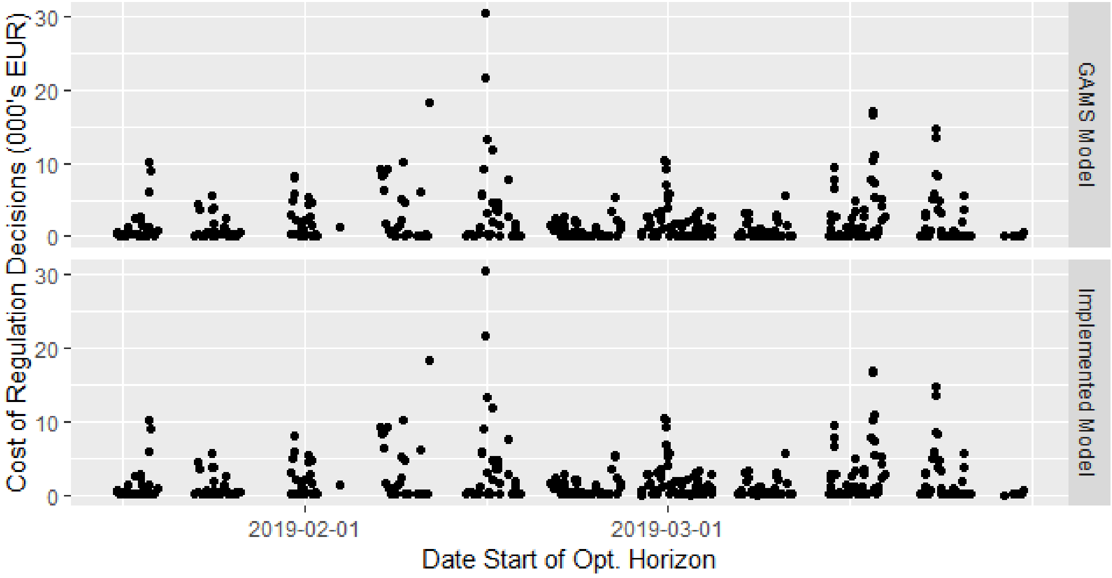

Figure 4: Cost of Demand Response each time the market is cleared

However, as there is some redundancy, we find that there are some instances where the solution obtained may be different, but the objective function (i.e. social welfare) is the same. In **Fejl! Henvisningskilde ikke fundet.**, we see that 10 out of the 490 clearings of the TSO market, we obtained a different solution between the two models. The redundancy of dispatch time is a property of the given data, due to three factors often combining to result in it making no difference (in terms of the overall cost) when a block is dispatched.

- The relatively small size of the aggregated demand response
- The TSO only requiring a load reduction for balancing over the optimisation horizon
- The cost of conventional up-regulation and down-regulation often not changing within an optimisation horizon.

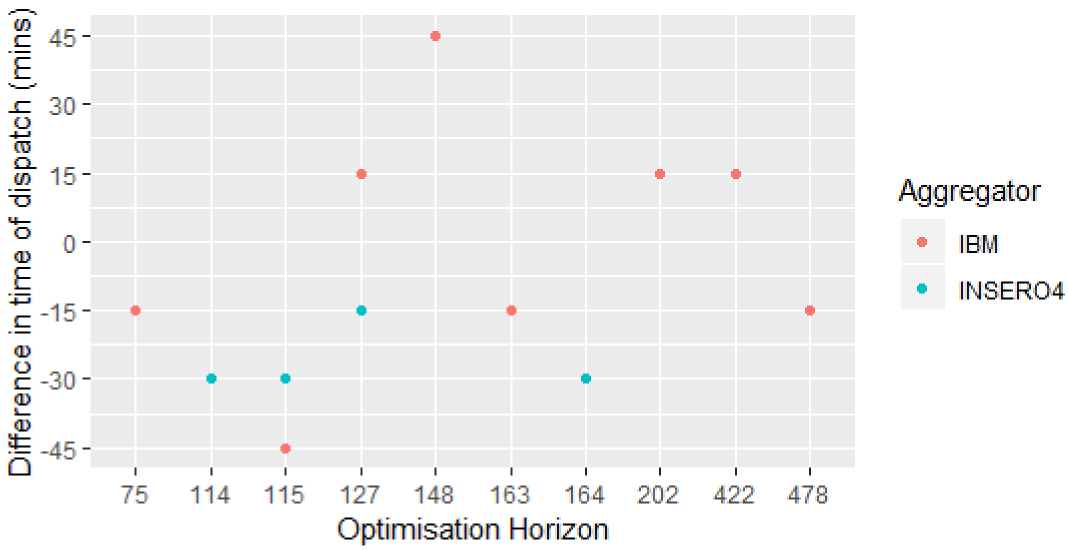

Figure 5: Difference in time of dispatch of block offers.

Overall, the market clearing appears to select the optimal offers for flexibility, and in the future, it would be good to test the market for the case where there are more, and more varied, offers of demand response to further verify that it can clear the market correctly.

3.2 Allocation of benefit in TSO market

Finding: The aggregators and the TSO benefit from the existence of the flexibility market, with the aggregators, especially those offering lower cost flexibility, benefiting the most.

Uniform marginal pricing is used to calculate the price of flexibility at each time-step. Uniform marginal pricing uses the marginal cost of flexibility (i.e. the cost of the unit that would provide the next unit of response) to determine the price of load reduction at each time step. Sometimes, we find this can cause offers for flexibility cleared at a loss for the aggregator. Thus, outside of the market clearing, the TSO must pay the maximum of the bid-cost and the market-clearing price for the demand. We see this ‘uplift payment’, where the TSO pays more than the market-clearing price for demand response, increases the overall payment to aggregators by about €17.5 or 2.5% (Figure 6) and this ‘uplift payment’ is needed for 14 of the 263 payments to the demand response aggregators to ensure profitability (Figure 7).

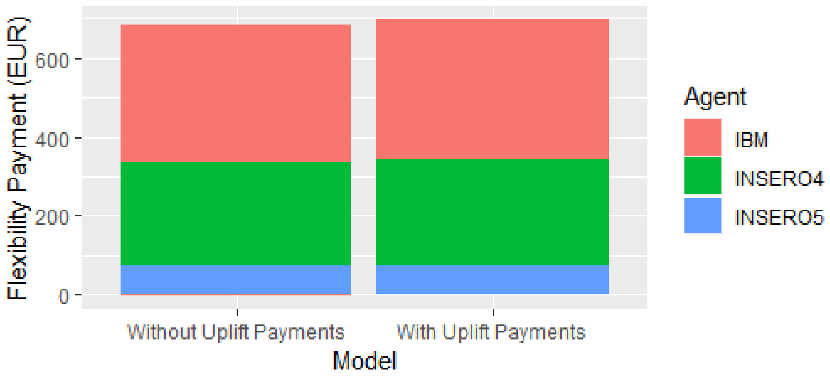

Figure 6: Payment to aggregators for flexibility

Figure 7: Demand response aggregator profit each time the market has cleared (both with and without the proposed 'uplift payment')

Overall, even without uplift payments, we see that the aggregators and the TSO benefit from the existence of the TSO market for demand response. However, at such a small scale, the demand response units have a small impact on the clearing price for balancing at each time step. Thus, we see in Figure 8 that the vast majority of the benefit goes to the aggregators, with more of the benefit going to IBM as their offers for demand response are, on average, less than half of the cost per kWh of the offers from the Insero4 and Insero5 units, while being paid a similar amount.

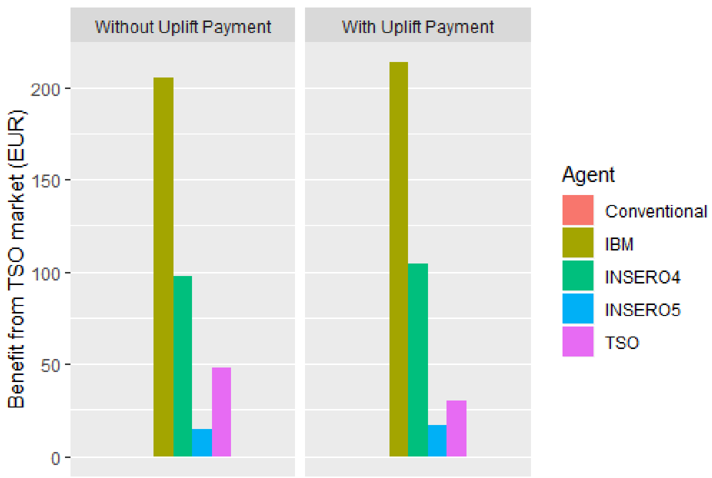

Figure 8: Benefit from the existence of TSO market

3.3 Conclusions

- The implemented model correctly utilises the offers for flexibility at minimum cost. There is some redundancy in the case study, giving different solutions with the same cost.
- The aggregators and the TSO benefit from the existence of the flexibility market, with the aggregators, especially those offering lower cost flexibility, benefiting the most.

4 Trading on the DSO Market Platform

Finding: DSO market clearing chooses optimal offers consistently. Offers into the DSO market and bids for demand response have improved over the experiment.

The DSO market, the formulation and description of which is described in D4.3.2, has been successfully operated a total of 10 times during HS3. Figure 9 shows the bids for demand response from the DSO with each facet showing a different instance of the DSO market being cleared. The highlighted points show the response and rebound of the cleared offers from each aggregator. With the given bids for demand response from the DSO and offers to provide demand response from IBM and Insero, we found that it was optimal to combine their offers for demand response only once. Five of the ten times the market was cleared, only one aggregator was offering flexibility into the DSO market. As the DSO and aggregators begin to coordinate their bids and offers for flexibility better, this combining of multiple offers may begin to occur more often.

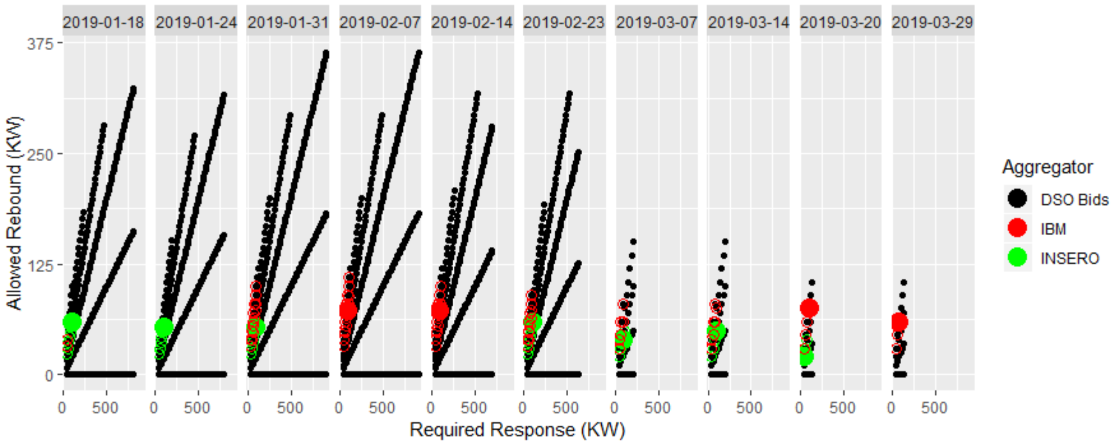

Figure 9: Cleared offers for demand response (hollowed circled indicate other offered that were not accepted)

In Figure 10, we often see that, in terms of the total energy of the response and rebound, there are often offers for flexibility in the TSO market with less overall response compared to offers in the DSO market for both IBM and Insero. As the DSO contracts are fixed term with additional uncertainty in the response that can be provided days or weeks in advance, this suggests that there may be issues in whether they can satisfy these offers when called upon.

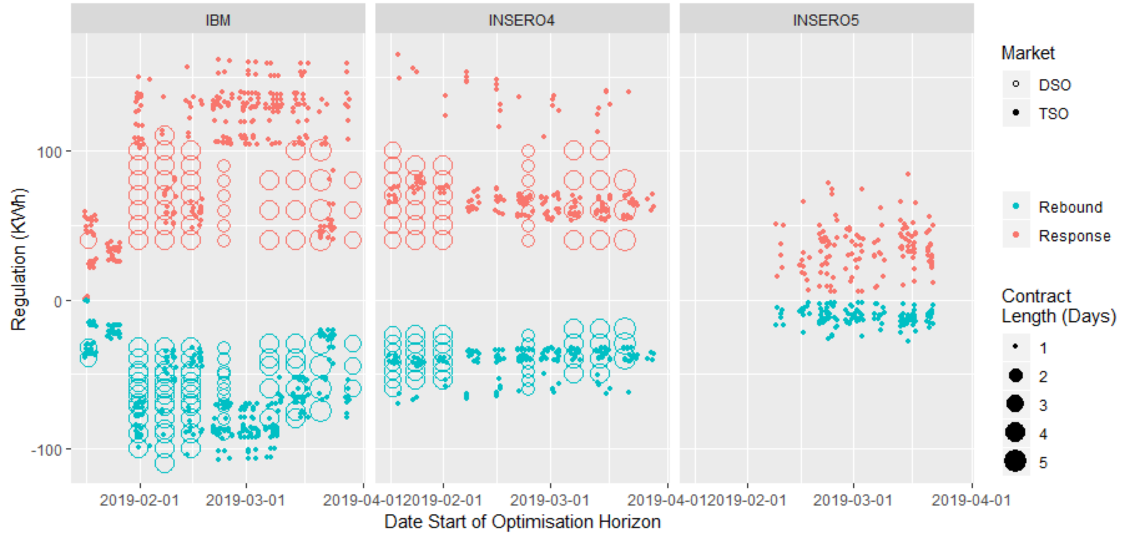

Figure 10: Energy of response and rebound of the aggregators offers into the TSO and DSO markets

In Figure 11: DSO Profit from each purchased DSO service, we plot the DSO's profit (based on their expected benefit from the demand response and each time the contract market was cleared. The extreme fluctuations in this profit seen here are driven by changes in the DSO tender price throughout the ten contracts.

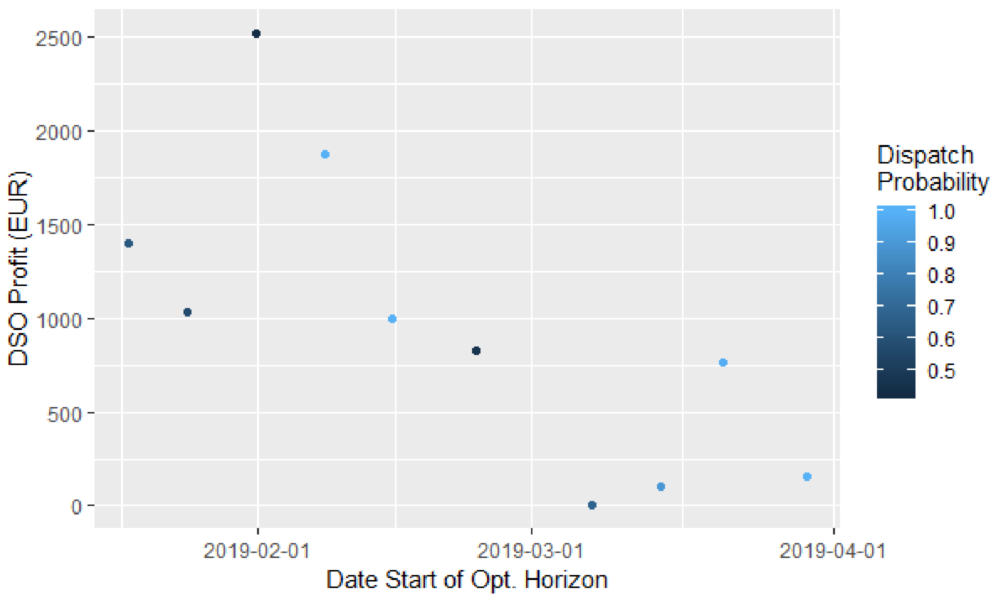

Figure 11: DSO Profit from each purchased DSO service

4.1 Conclusions

- DSO market clearing chooses optimal offers consistently.
- Offers into the DSO market and bids for demand response have improved over the experiment.

- There are potential concerns in whether or not the aggregators can consistently satisfy their contracts for flexibility (i.e. not being able to provide the promised load reduction) over the entire length of the contract.

5 Social Welfare in the Regulating Power Market

5.1 Cost savings due to TSO Market

Findings: Aggregated demand response satisfies a very small proportion of the overall balancing needs for the TSO. Improvements may be seen with additional distributed energy resources or improvements in the aggregator bidding strategy.

In the current implementation of the market in Bornholm, an insignificant proportion of the flexibility (roughly 0.06% of both the total load reduction and load increase) and a smaller proportion of the cost (roughly 0.04%) is provided by the DR aggregators at a single distribution level node (see Figure 12 and Figure 13). This is because a market of national size has been simulated, and the flexibility that a small number of houses on Bornholm can offer is dwarfed by the market participants and flexibility requirements as a whole.

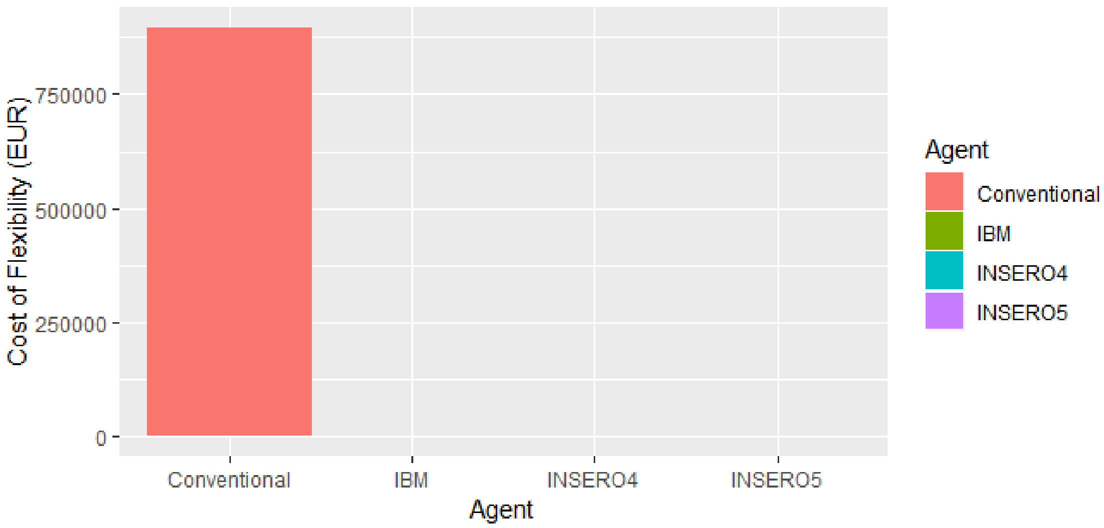

Figure 12: Cost of each type of flexibility over the entire experiment

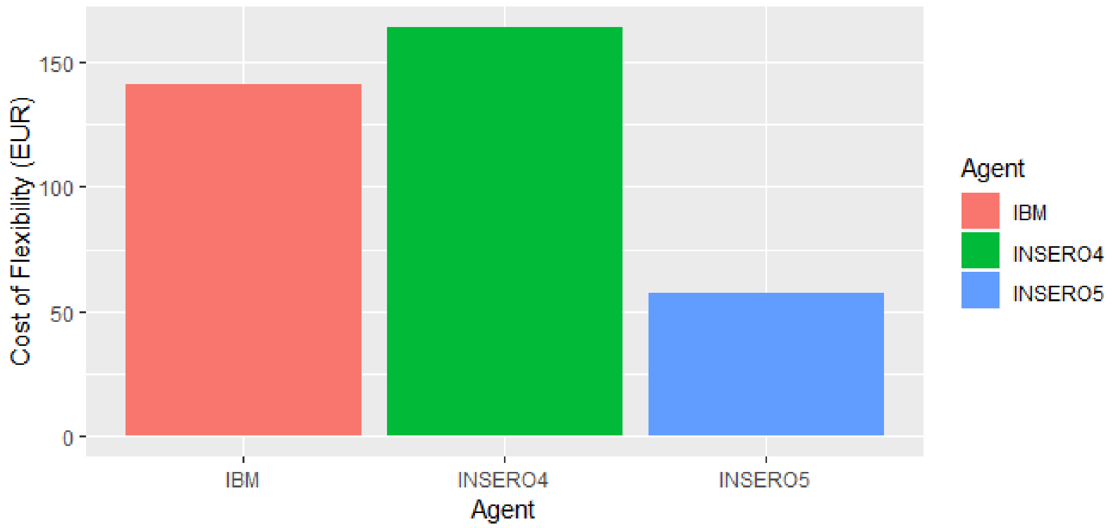

Figure 13: Cost of flexibility over the entire experiment (only Demand Response units)

To calculate the cost savings from demand response, we first calculate a baseline cost that assumes all flexibility is satisfied by the conventional or slack units (in our case study none of the flexibility needs were satisfied by the slack units), subtracting this from the cost from our implemented market that includes demand response included as part of the flexibility. Over the 490 times the market has cleared (corresponding to 980 Hours or nearly 41 full days), we see in Figure 14 there is roughly €365 in total savings, assuming agents have bid their true costs and benefits from providing and utilising flexibility. Thus, in every two-hour window when the market is opened, we see cost savings of €0.74 on average, where the reduction in the use of conventional response more than compensates the increase in costs in demand response. We also see in Figure 15 that there is a large variance in the potential benefit of demand response. However, it has never lead to flexibility response being more expensive than the baseline – a crucial result in confirming that the EcoGrid market delivers value despite any demonstration-related flaws in the market setup.

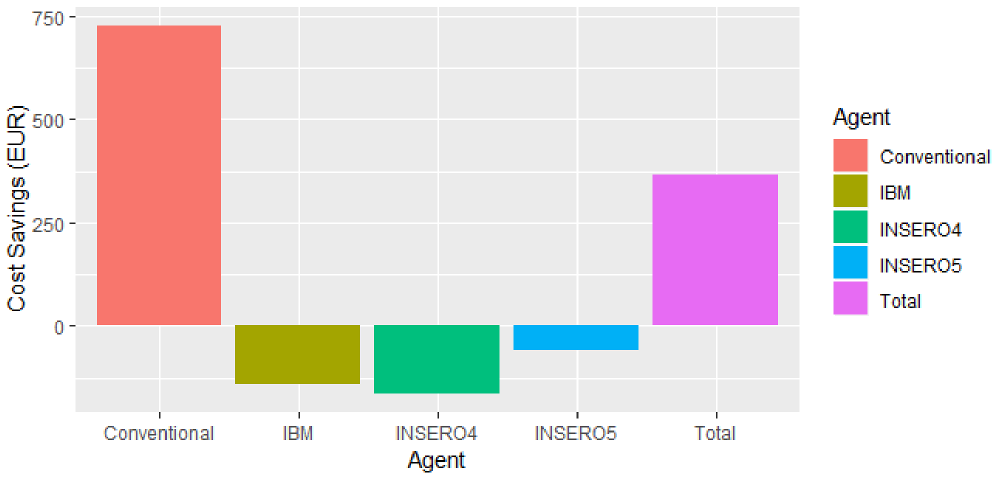

Figure 14: Cost savings, compared to baseline, from each type of response over 41 days

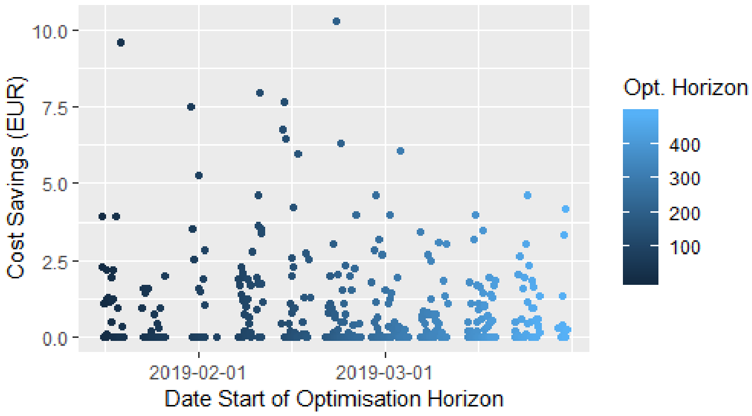

Figure 15: Total cost savings in each two-hour window the market has cleared

As markets for demand response continue to be developed, flexibility will be available across many distribution nodes (compared to just a single one in our experiment), and additional flexibility will be available within each distribution grid (as additional sources of flexibility become available). Thus, we can see how the cost savings might change as we scale up the available flexibility. In Figure 16, we plot the balancing cost as we assume additional flexibility is available. With the given prices and offers for flexibility, we see that at best we can hope for €20 000 in cost savings over the 980 hours utilising the demand response. There may be additional savings if DR aggregators can offer more diverse offers for flexibility and types of demand response (e.g., demand response with more diverse shapes), i.e. it is entirely possible that this result is inaccurate since aggregator strategies with advance and capabilities will increase as their portfolio size increases.

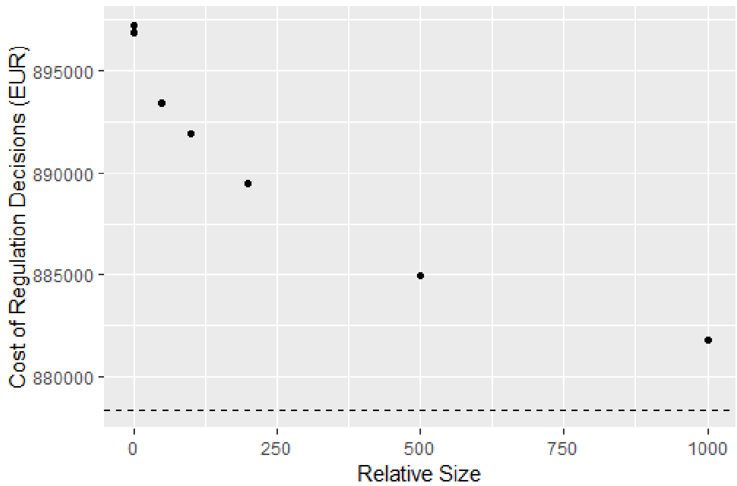

Figure 16: Cost of TSO balancing as we multiply flexibility by different amounts (dotted line assumes infinite capacity) over 41 days

5.2 Cost savings due to DSO Market

Finding: With the DSO market only operated ten times, it is difficult to infer the true benefit obtained the DSO through the market clearing.

In Figure 17, we plot the cost savings each time the contract market was cleared. These cost savings are calculated by first starting with the stated expected benefit, as stated by the DSO and subtracting the stated cost of satisfying this contract by the aggregator that cleared the market. The extreme fluctuations in this profit seen here are driven by changes in the DSO tender price throughout the ten contracts. Thus, it would be beneficial to operate this DSO market for longer, in hopes that this calculated profit will end up fluctuating less and reflect the true benefit to the DSO.

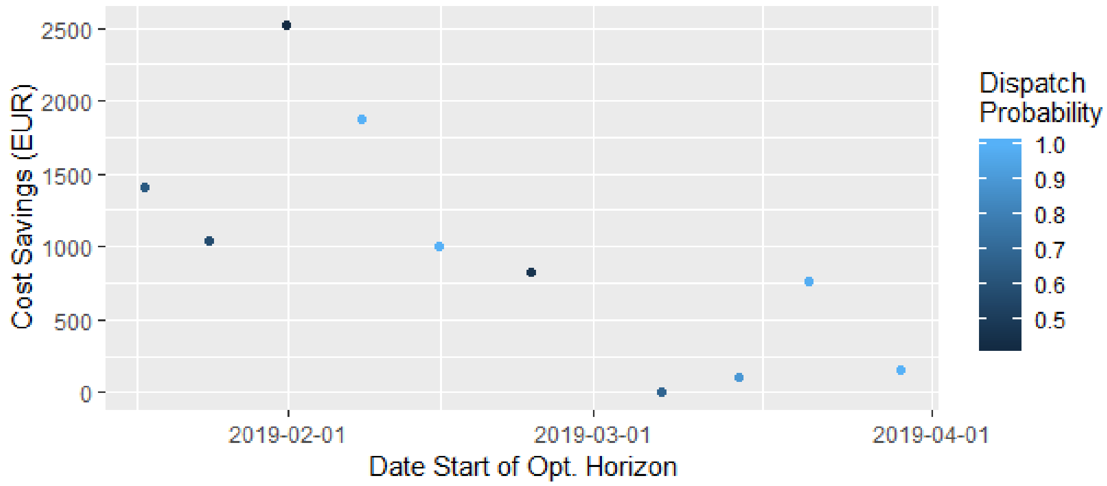

Figure 17: DSO Profit from each purchased DSO service

5.3 Conclusions

- Conventional flexibility still makes up a vast majority of the utilised flexibility in the TSO Market.
    - Improvements may be seen with additional distributed energy resources, improvements in the aggregator bidding strategy, or a market redesign.
- There is an average saving of €0.74 in each 2-hour window, which will likely grow as the market prices increase significantly towards 2035 (Capion, Stryg and Poulsen 2018).
- There may be additional savings if we convert the DSO contract market into a capacity market, where aggregators are paid for limiting their consumption, allowing them to participate in the TSO and DSO markets simultaneously.
- Additional experiments with the DSO market may be required to infer the true benefit obtained the DSO, thus the long-term social welfare gains from the DSO market.

6 Aggregator participation in markets

Finding: Overall aggregators make a profit participating in the TSO and DSO markets. Aggregators should be able to make an additional profit in the DSO market with an improved bidding strategy.

In Figure 18, we see that, in terms of the total energy of the response and rebound, the offers for flexibility in the TSO and DSO markets are often very similar for both IBM and Insero, with significant overlap. As the DSO contracts are fixed term and fairly large uncertainty in the response that can be provided days or weeks in advance, there may be issues in whether they can satisfy these offers when called upon.

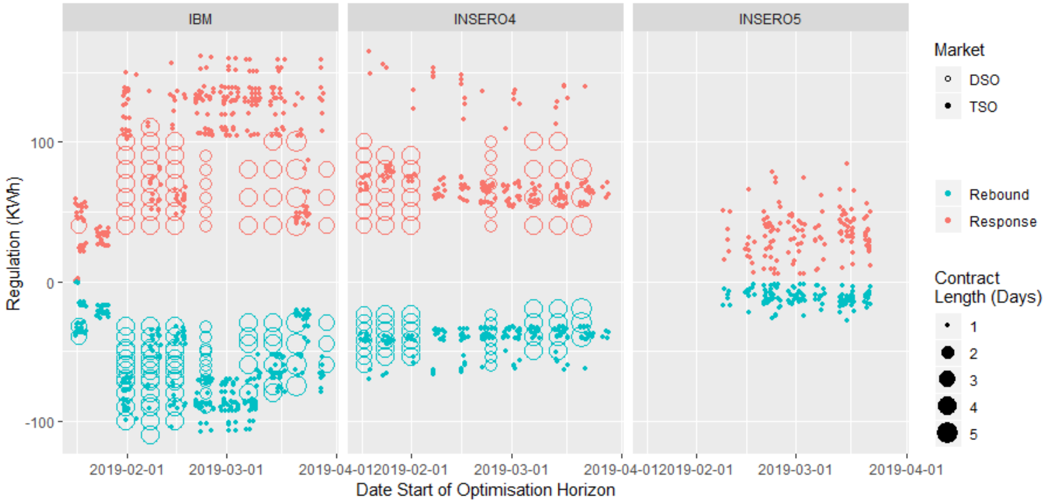

Figure 18: Energy of response and rebound of the aggregators offers into the TSO and DSO markets

In Figure 19, we plot the DSO's profit (based on their expected benefit from the demand response and each time the contract market was cleared. The extreme fluctuations in this profit seen here are driven by changes in the DSO tender price throughout the ten contracts. So far, assuming aggregators bid reflecting the true cost of providing their demand response, have broken even every time the market has cleared. This is because prices are based on the most expensive unit that is cleared by the market, and every time the market has cleared there have either only been one unit clearing the market, resulting in the cost of their unit equalling the price they are paid. The one time multiple units cleared the market (the contract that cleared on 2019-03-20) both units cost exactly the same per KWh. Thus neither aggregator made a profit (beyond any profit built into the price of their bid).

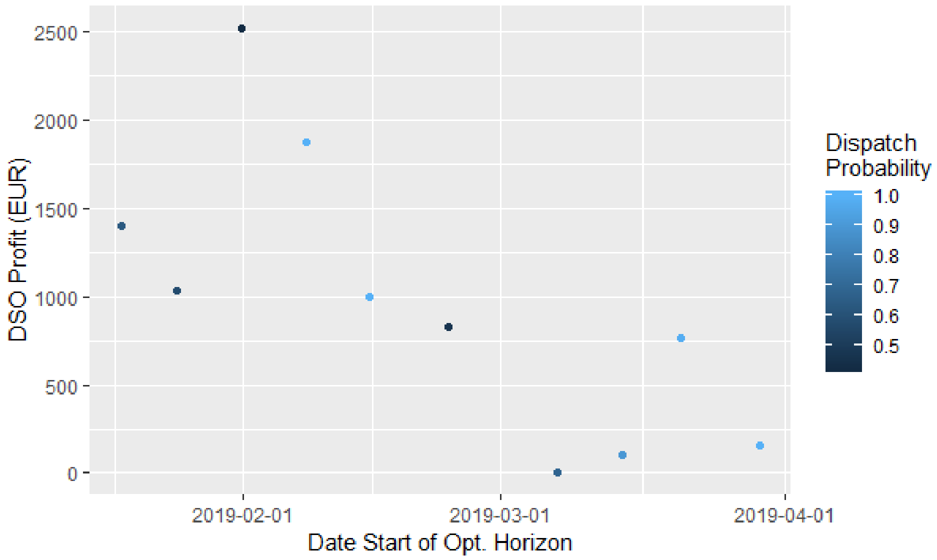

Figure 19: DSO Profit from each purchased DSO service

6.1 Coordination of aggregators' participation in TSO and DSO markets

In Figure 20, we plot the revenue each aggregator earns each time the TSO and DSO market clears. As the DSO market is a fixed term contract lasting up to five days, we normalise this revenue to the length of the contract. In Figure 19, we saw that the DSO often, based on their offers, seem to have made a large profit on many of their bids for demand response, which seems to have been unexploited thus far, where aggregators could have bid a higher price (based on the revenue earned over time from the DSO market). We see similar levels of revenue for the aggregators on both the TSO and DSO markets, suggesting they can estimate their opportunity cost fairly well. There appears to be room for improvement as aggregators should be able to increase their profit from the DSO market with improved estimates for the DSO tender price.

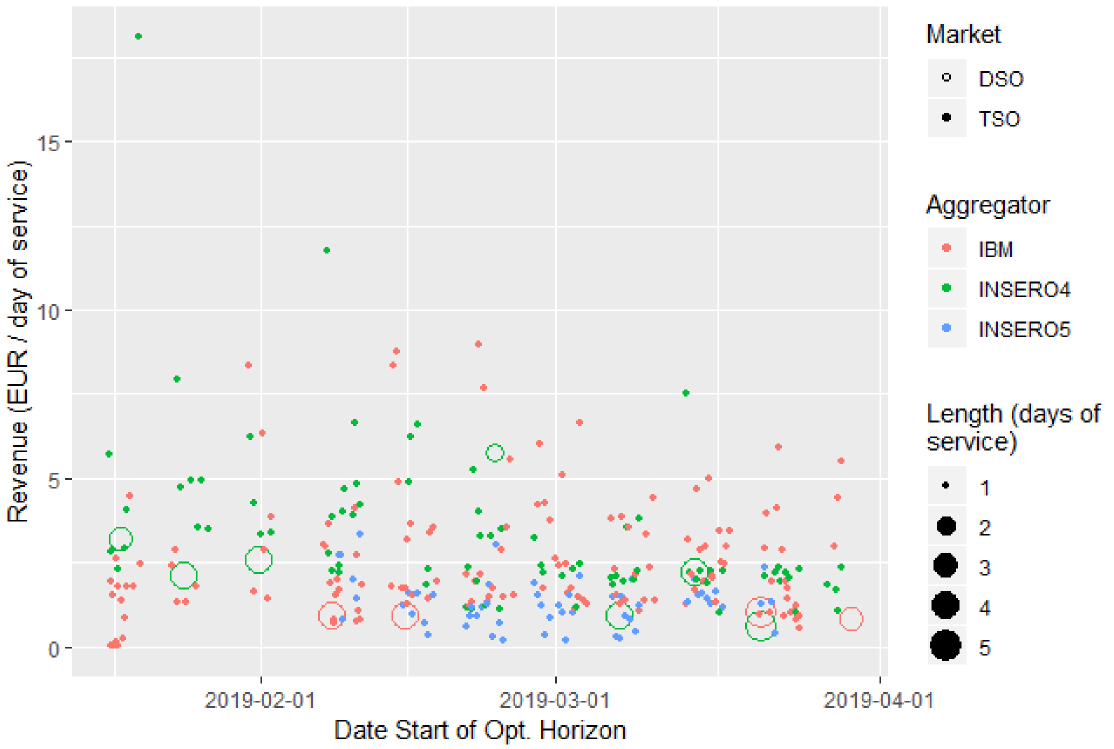

Figure 20: Aggregators' normalised profit in the TSO and DSO markets

6.2 Conclusions

- Overall aggregators make a profit participating in both the TSO and DSO markets.
- Offers into the DSO market have improved over the experiment.
- Aggregators should be able to make additional profit in the DSO market with an improved bidding strategy.

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