

Delivery no.: 6.3.6

The possibility of performing FNR with the BESS



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Preface

EnergyLab Nordhavn – New Urban Energy Infrastructures is an exciting project, which will continue until the year of 2019. The project will use Copenhagen's Nordhavn as a full-scale smart city energy lab, which main purpose is to do research and to develop and demonstrate future energy solutions of renewable energy.

The goal is to identify the most cost-effective smart energy system, which can contribute to the major climate challenges the world are facing.

Budget: The project has a total budget of DKK 143 m (€ 19 m), of this DKK84 m (€ 11 m) funded in two rounds by the Danish Energy Technology Development and Demonstration Programme (EUDP).

Forord

EnergyLab Nordhavn er et spændende projekt der løber til og med 2019. Projektet vil foregå i Københavns Nordhavn, og vil fungere som et fuldskala storbylaboratorium, der skal undersøge, udvikle og demonstrerer løsninger for fremtidens energisystem.

Målet er at finde fremtidens mest omkostningseffektive energisystem, der desuden kan bidrage til en løsning på de store klimaudfordringer verden står overfor nu og i fremtiden.

Budget: Projektets totale budget er DKK 143 mio. (EUR 19 mio.), hvoraf DKK 84 mio. (EUR 11 mio.) er blevet finansieret af Energiteknologisk Udviklings- og Demonstrationsprogram, EUDP.

Disclaimer

This delivery consists of excerpts from a Master thesis performed at DTU by Camilla Lund called "Techno-economic analysis of operational strategies for a battery energy storage system installed in Nordhavn".

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List of Abbreviations

FNR	Frequency-controlled Normal Reserve
FDR	Frequency-controlled Disturbance Reserve
PFR	Primary Frequency Reserve
NOIS	Nordic Operational Information System

Executive Summary

This delivery is an excerpt from the Master thesis “Techno-economic analysis of operational strategies for a battery energy storage system installed in Nordhavn” by Camilla Lund performed at DTU and in collaboration with Radius.

The frequency regulation service called Frequency-controlled Normal Reserve (FNR) is investigated and simulated for the BESS in Nordhavn. The current regulations required that a FNR unit responds to both over and under frequencies linearly, where it is fully activated at $50\text{Hz} \pm 100\text{mHz}$.

Strategies for the current FNR regulations are simulated. It was found the FNR service is not well suited for BESS participation and therefore two changes to the regulations are investigated: 1) Introducing a $\pm 20\text{ mHz}$ deadband and 2) allowing the BESS to take 15 minute breaks when it is fully charged or discharged. These changes both improve the BESSs ability to participate in FNR.

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1. Introduction

The following text consists of excerpts from a master thesis performed at DTU by Camilla Lund called "Techno-economic analysis of operational strategies for a battery energy storage system installed in Nordhavn".

This chapter introduces ancillary services in Denmark and in detail discusses the regulations of those most relevant for the BESS. To ensure balance between consumption and generation in real-time, Energinet.dk uses ancillary services. "Ancillary services" is a broad term referring to many different services, which maintain system stability. Energinet.dk defines its necessary ancillary services as [1]:

- Frequency-controlled reserves
- Secondary reserves
- Manual reserves and regulating power
- Properties required to maintain power system stability

Frequency-controlled reserves refer to Primary Frequency Reserves (PFR) in DK1 and Frequency-controlled Disturbance Reserves (FDR) and Frequency-controlled Normal Reserves (FNR) in DK2. They aim to automatically stabilise the frequency to around 50 Hz and focus on small, short-lived frequency deviations.

Secondary reserves are also called Load Frequency Control. This type of bi-directional reserve is only used in DK1 and aims to restore the frequency to 50 Hz. Production units change their set points to handle the change in the power balance.

Manual reserves and regulating power ensure that there is enough regulating power bids to handle the outage of a dimensioning unit, also commonly known as the N-1 criterion. These reserves alter their production set points to bring the frequency back to its nominal value. In DK1, these reserves are purchased daily, while in DK2, they are purchased for five-year contracts. They are also split into fast and slow, where fast reserves must be able to supply in 15 minutes and slow reserves react within 2 hours.

Properties required to maintain power system stability refer to the other services which maintain system stability. This includes black start, voltage control, inertia and short circuit power.

The frequency reserves are contracted on a reserve market. The Nordic TSOs use a common platform for planning their frequency reserves, called NOIS (Nordic Operational Information System), which was introduced in 2002 [2]. The regulating power bids received

by each TSO are submitted to NOIS, so the TSOs can better plan efficient and secure operation.

The frequency-controlled reserves, FNR, FDR and PFR are most applicable for a BESS, where FNR is the topic of this report. The presented information is a summary of the information in [1], [3] and [4].

2. Frequency-controlled normal operation reserve (FNR)

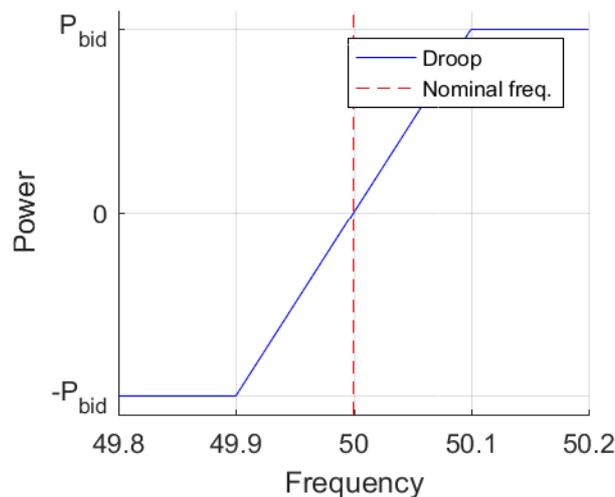


Figure 1: The droop for FNR

FNR is bidirectional frequency control and is therefore activated for both under- and over-frequencies. It is automatic and can be provided by both production and consumption units. FNRs are provided symmetrically meaning upward and downward regulation reserves are sold/purchased together. The total required amount of frequency-controlled normal operation reserves in RG Nordic is 600 MW, which is split proportionally between the member TSOs. Energinet.dk acquires these reserves in collaboration with Svenska Kraftnät, and their individual shares are negotiated annually. In 2012, Energinet.dk's share was 23 MW and Kraftnät's share was 230 MW [5].

The FNR units are active for frequency deviations in the interval 50 Hz \pm 100 mHz, and there is no deadband, meaning they are almost always active. The power is supplied linearly from 0 to full power at \pm 100 mHz as depicted in Figure 1. When considering a battery, upward regulation means discharging into the grid, while downward regulation means charging. The reserve must be fully activated within 150 seconds and must be able to supply power continuously. The reserves can be a combination of units including consumption, that combined can fulfil the contract.

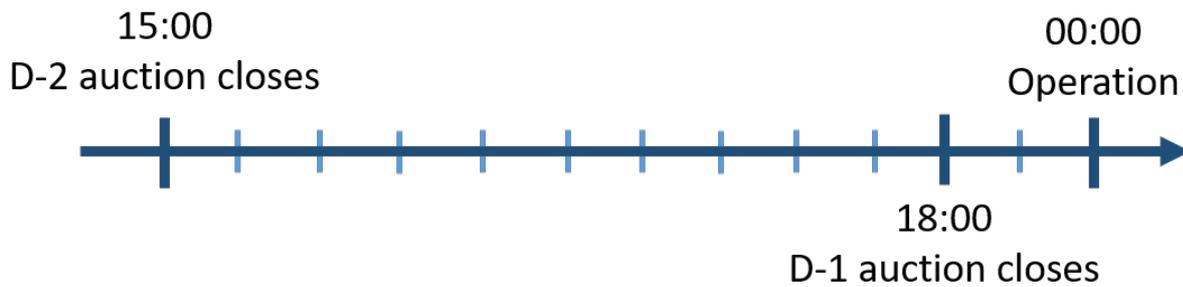


Figure 2: The timing for FNR bids.

The reserves are acquired on daily auctions, where a portion of the reserve is purchased two days before operation (D-2) and the remaining is contracted one day before operation (D-1). The bids have an hourly resolution. The (D-2) bids must be submitted at 15:00 two days before operation. The (D-1) bids are received until 18:00 on the day before operation. Figure 2 shows this timing. All bids accepted on their respective days are binding.

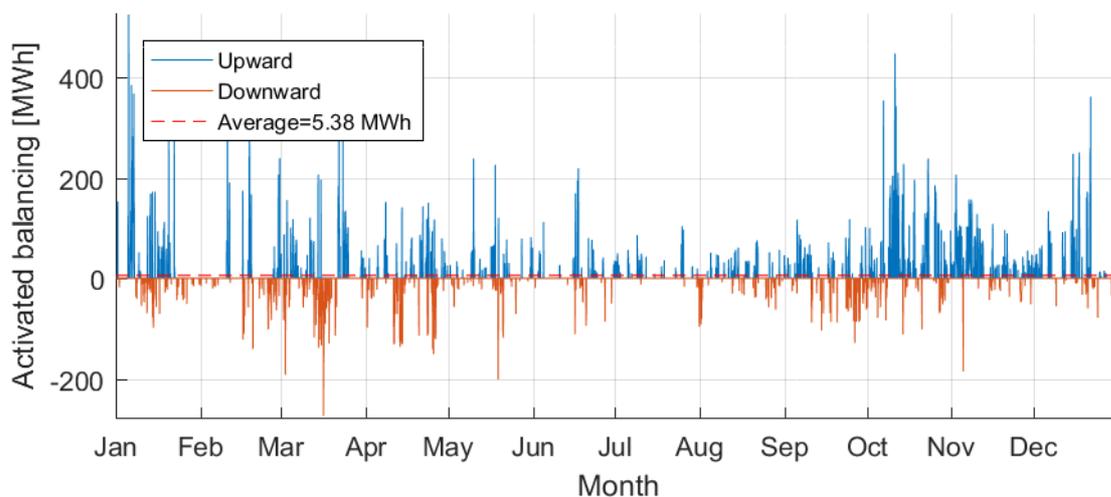


Figure 3: The balancing prices in 2016.

All bids must be at least 0.3 MW and are accepted in their entirety. The reserves are chosen starting from the lowest priced first. The players receive an availability payment as pay-as-bid. The actual energy supplied is compensated using the balancing prices for upward and downward regulation. Figure 3 shows the upward and downward regulating prices for 2016. The actual activation of the reserves is controlled individually and there is no centralised command signal. The actual delivery of services is checked in tests performed by Energinet.dk. In case of inability to supply, the player does not receive the availability payment and must cover any additional costs incurred if Energinet.dk must obtain additional reserves. Energinet.dk will simply contract the next supplier in the merit order curve, meaning these extra costs are equal to or higher than the last accepted supplier. It is reasonable to assume that the penalty is 10 to 100% above the bid [6].

3. FNR and the BESS

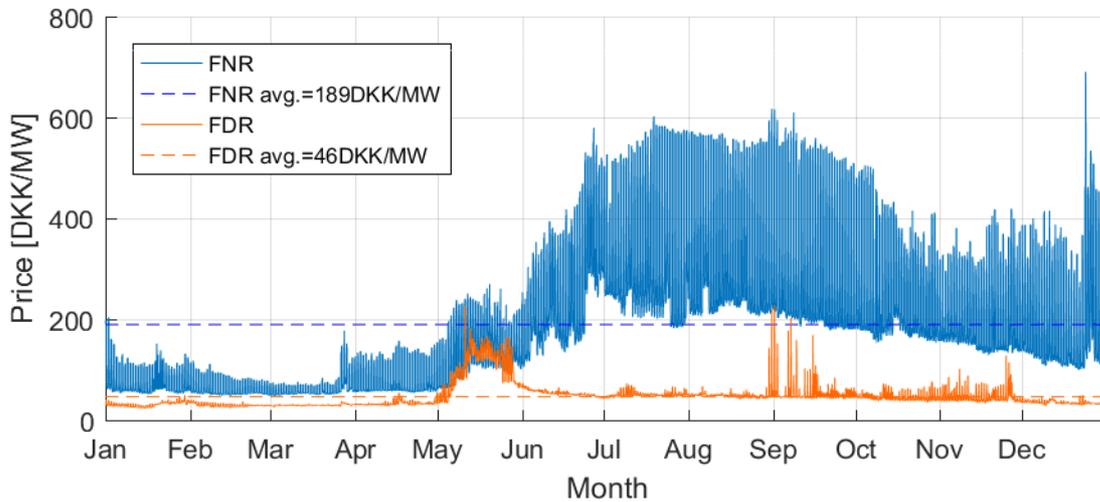


Figure 4: The availability payments for FNR and FDR in 2016

The reason FNR is interesting, is that it has the highest availability payments of the two frequency reserves in DK2. Figure 4 shows the difference in the prices between FNR and FDR. The average FDR price is 46 DKK/MW while the average FNR price is 189 DKK/MW. From an economic standpoint, FNR would be preferred due to the increased availability payments.

There are two main issues with the BESS providing the FNR service for all hours of the year: 1) It is energy limited and therefore risks being either fully charged or discharged in connection with providing regulation and 2) it has a sub-optimal efficiency and therefore cannot uphold an acceptable SOC over time.

The first issue is caused by the fact that the BESS is a limited energy source, and when it is either fully charged or fully discharged, it cannot provide downward or upward regulation respectively. FNR must be supplied continuously over the contracted period (minimally 1 hour), meaning the BESS could be required to provide either upward or downward regulation for a full hour of operation. Since it is a bidirectional service, its SOC must be maintained around 50%, and therefore the energy capacity available for each direction is only half of the BESS's actual energy capacity. The BESS rated power is greater than its energy capacity, it will discharge or charge completely 50% SOC within an hour, if the full power capability is offered for FNR. Consider the worst-case scenario, where the starting

SOC is 50% (230 kWh) and the BESS is fully activated for up regulation for the full hour. If the bid was 630 kW, the battery would be drained in just over 20 minutes.

The efficiency losses also prevent continuous operation. Assuming the frequency deviations have a mean of zero and switches between over- and under-frequency often, the BESS would still become depleted due to efficiency losses. When the BESS charges, it requires more energy than is transferred to the cells and when discharging more energy is lost than is delivered to the grid. Therefore, over time, the BESS will have a declining average SOC.

Table 1: Relevant frequency characteristics for to FNR operation considering 2016 data.

Aspect	Value	Unit
Mean time below 50 Hz	83.89	Seconds
Mean time above 50 Hz	81.34	Seconds
Maximum time below 50 Hz	4.28	Hours
Maximum time above 50 Hz	11.74	Hours
Standard deviation for time below 50 Hz	4.32	Minutes
Standard deviation for time above 50 Hz	4.66	Minutes
Total time of frequencies at 50 Hz in 2016	74	Hours

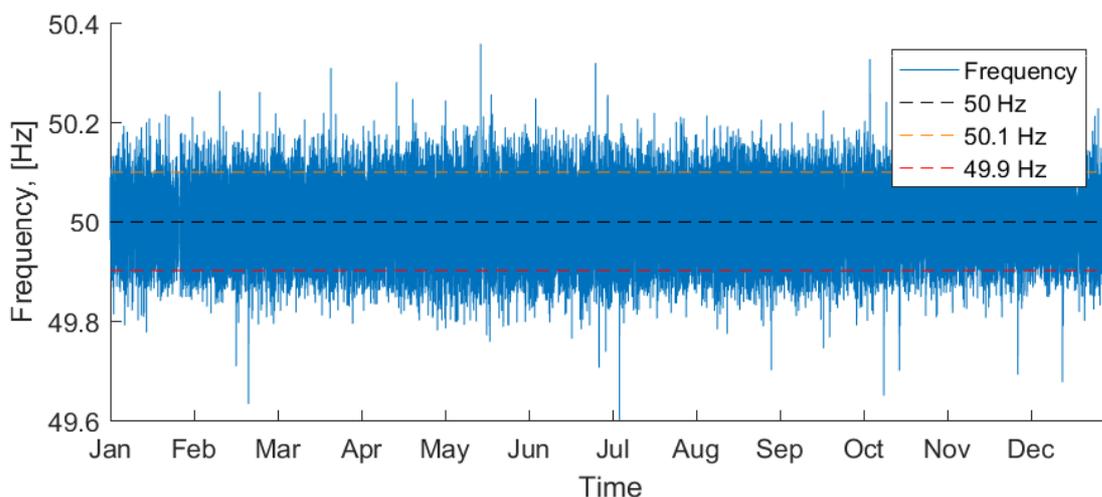


Figure 5: The frequency for 2016.

Table 1 shows the relevant frequency characteristics for FNR operation. Figure 5 shows the system frequency of 2016. The mean frequency in 2016 was 49.9995 Hz. FNR is active whenever the frequency is not 50 Hz, which is the case for all hours of the year except approximately 74 hours. For the remaining 8,686 hours, the BESS is delivering frequency regulation to some degree. On average, over- and under-frequencies have a duration of almost 1.5 minutes and a standard deviation of about 4.5 minutes. There are deviations which lasted many hours. Therefore, there is a high probability that the BESS will become charged or discharged during continuous operation unless the power bid is very low.

To achieve reliable delivery, the bids must be reduced and the BESS cannot participate continuously. Equation 1 shows a simple calculation for the maximum power bid if it should be able to provide for a full hour without the risk of failure (not including the efficiency). SOC_{max} is the maximum SOC, SOC_{min} is the minimum allowed SOC, E_{BESS} is the BESS energy capacity and t_{hours} is the number of consecutive hours for provided FNR.

$$P_{bid,max} = \frac{(SOC_{max} - SOC_{min})E_{BESS}}{2 t_{hours}} \quad 1$$

For $SOC_{min} = 0\%$, $SOC_{max} = 100\%$, $t_{hours} = 1 \text{ hr}$, the BESS could offer a maximum bid of 230 kW. The FNR power bids must be above 300 kW [3], but for the purposes of this thesis, it is assumed that the BESS can still participate with a lower bid. This would of course drastically decrease the availability payments received.

When the BESS is not able to supply its contracted regulation, it will not receive the affected hour's availability payment. Furthermore, the BESS owner must cover any costs Energinet.dk should contract new reserves, meaning the BESS owner must pay for the next FNR bid in the merit order. The cost can vary, but for simplicity it is assumed that the cost is always 100% more than the availability payment the BESS received.

Clearly, the BESS may have difficulty providing the FNR service without drastically decreasing revenues under current regulations, and therefore several different cases are simulated, which test different changes to the FNR and how they improve the BESSs ability to participate as an FNR. Some of the changes are inspired by PFR in DK1. The 5 different situations simulated are:

1. (Base case) Continuous operation with current regulations and a 630 kW offer.
2. Continuous operation providing unidirectional regulation.
3. Continuous operation including a deadband.
4. Discontinuous operation with blocks of 1 hour.

5. Continuous operation including a deadband, and taking breaks to re-establish when necessary.

The first case is the base case where the BESS participates continually with full power capacity under the current regulations. The remaining cases try to improve this base case.

In point 2, the effect of participating in either up or down regulation only is investigated. In Western Denmark, it is possible to participate in unidirectional frequency regulation. This enables the BESS to dedicate its full energy capacity to a single direction of frequency deviations and therefore it should be able to handle the deviations better, with less failures.

Point 3 investigates the effect of including a deadband, as is implemented in Western Denmark. When the frequency is in the deadband, it is assumed that the BESS can attempt re-establish its SOC. Therefore, the BESS gets more control over its SOC, instead of only depending solely on the frequency to keep the SOC at 50%.

The risk of supply failure can be decreased by participating discontinuously. Point 4 therefore investigates the effect of block operation instead of continuous operation. This means the BESS participates for a block of hour(s), and between the blocks there is a single hour to re-establish the SOC. Of course, this will automatically decrease the availability payments, but increases reliability.

Point 5 tests the effect of the BESS taking breaks when it is either fully charged or discharged, so it can properly re-establish the SOC. Of course, the BESS receives a penalty for these breaks, but it may create a more reliable and predictable service. To decrease penalties, the breaks have a length of 15 minutes unless the remaining time in the hour is less than 15 minutes. In this case, it takes a break for the rest of the hour, instead of carrying the break into the next hour and receiving the penalty for that hour too. If the break causes the BESS to receive a penalty in the following hour, it defeats the purpose of trying to quickly re-establish.

Only point 1 and 4 is within the current regulations in Eastern Denmark. Point 2 requires that upward and downward regulation are separated as they are in Western Denmark. Point 3 and 5 require that a deadband is introduced as it is in Western Denmark. All simulations assume that the TSO is tolerant for some degree of supply failure and that the FNR availability payments are unchanged.

4. Method for simulations

The FNR operation is simulated using Matlab. The power output of the BESS is determined from the frequency using a linear droop.¹ The droop is created using the Matlab function “polyfit”, which fits a polynomial to the input points. The droop for normal FNR operation is simply a linear function between the two points ($50.1 \text{ Hz}, P_{offer}$) and ($49.9 \text{ Hz}, -P_{offer}$). For the cases where the deadband is included, the droop is a discontinuous line and two separate linear functions are created; one for up regulation and one down regulation. For simulating unidirectional service, the linear function is created for one direction of frequency deviations. The Matlab function “polyval” is used to convert any frequency value into the corresponding BESS power output. A vector for the power output, P_{out} , is created in 1-second resolution using the 2016 frequency data. For point 4, blocks where the BESS is not participating in FNR, the power output is forced to 0, no matter the frequency.

The SOC for each time step is calculated in a loop running through the power vector, where the SOC is updated using the BESS power for each time step. If the calculated SOC is higher or lower than 100% or 0% respectively, then it is set to the respective upper/lower limit. If the SOC reaches either 0% or 100%, it is classified as a supply failure, because the BESS cannot provide the regulation in one direction any more. An additional vector is created which shows whether a failure occurred in each time step.

A second power vector is created while calculating the SOC. This vector is the power used for re-establishing the SOC. Re-establishing can only take place when the FNR power output is 0. Re-establishing power attempts to bring the SOC back to the goal SOC (In this case 50%).

For point 5, the length of the breaks is set to 15 minutes, unless the remaining time in the hour is less than 15 minutes. In this case, the BESS takes a break until the hour ends. In Matlab, a function finds the minimum of either 15 minutes or the time left in the hour.

The breaks are only implemented for one direction. For example, if the BESS is completely discharged from providing up regulation, providing down regulation helps the BESS remedy its SOC. Therefore, the BESS only stops providing up regulation in the break.

¹ Droop is the linear relationship between a frequency deviation and the change in a unit's power output.

5. FNR Results

The following section describes the results of simulations for FNR operation using the Nordhavn BESS. Table 2 shows the results of the most important simulations run. The cases are as follows:

- Case 1: Current regulations, 630 kW bidirectional power offer
- Case 2: Up regulation only with 630 kW power offer
- Case 3: Down regulation only with 630 kW power offer
- Case 4: Down regulation only with 350 kW power offer
- Case 5: Including a ± 20 mHz deadband with a 630 kW power offer
- Case 6: Including a ± 20 mHz deadband with a 350 kW power offer
- Case 7: 1 hour block operation with a 630 kW power offer
- Case 8: 1 hour block operation with a 230 kW power offer
- Case 9: 1 hour block operation with a 300 kW power offer
- Case 10: Continuous operation taking breaks to re-establishing when necessary with 630 kW power offer
- Case 11: Continuous operation taking breaks to re-establishing when necessary with 400 kW power offer

Table 2: The results from key FNR simulations. (*): The economic values for cases 2-4 are not be comparable with the rest.

Case	Offer kW	NPV Mio. DKK	Revenue '16 kDKK	Cyc. Ageing %	Cal. Ageing %	Life Years	Failed occurrences	Unavailable %
1	630	-8.95	-716	2.85	1.42	5	36347	25.15
2	630	-2.54*	629*	2.88	1.83	5	3563	5.21
3	630	-1.56*	753*	2.71	1.18	6	1779	3.25
4	350	-1.08*	551*	1.35	1.12	9	163	0.46
5	630	-3.02	454	2.43	1.45	6	5222	5.35
6	350	-1.87	491	1.29	1.50	8	844	1.29
7	630	-4.87	106	5.56	1.38	3	3761	3.12
8	230	-3.88	187	1.57	1.52	8	0	0.00
9	300	-3.74	241	2.29	1.48	6	19	0.01
10	630	-3.07	522	3.53	1.38	5	2067	3.77
11	400	-2.12	545	1.84	1.46	7	668	1.19

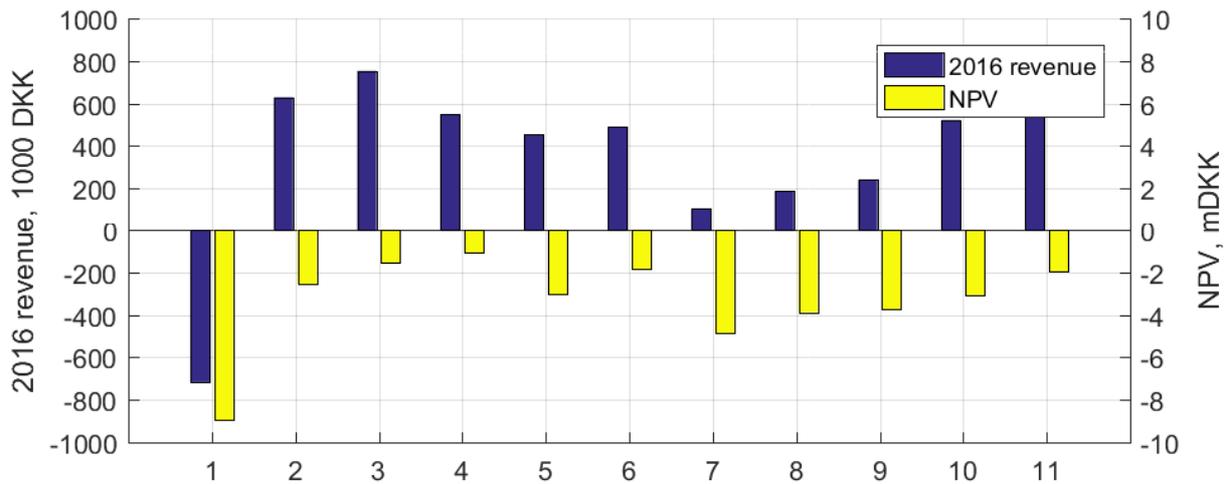


Figure 6: The 2016 revenue and NPV of the different FNR strategies.

Figure 6 is a visualisation of the economic results. The parameters which used to compare the different simulations are:

- NPV: Shows the profits over the course of the BESS lifetime. The project is only feasible if the NPV is positive.
- 2016 revenue: Shows the theoretical revenues, including the availability payments, energy settlement and penalties. It is independent of the degradation.
- Cyclic and calendar ageing: Quantitative estimation of the ageing components.
- Life: The total estimated lifetime in full years
- Failure occurrences: A count of number of individual failures, unaffected by length of failures.
- Unavailability: The percentage of time where the BESS is not able to fully provide FNR (SOC at either 0% or 100%).

5.1 Base case: Continuous FNR operation with current regulations and 630 kW bid

To begin, the base case is simulated. The base case is the when the BESS offers its full power capabilities, 630 kW, continuously for all hours. It does so in the current FNR regulatory framework as described in Chapter 2.

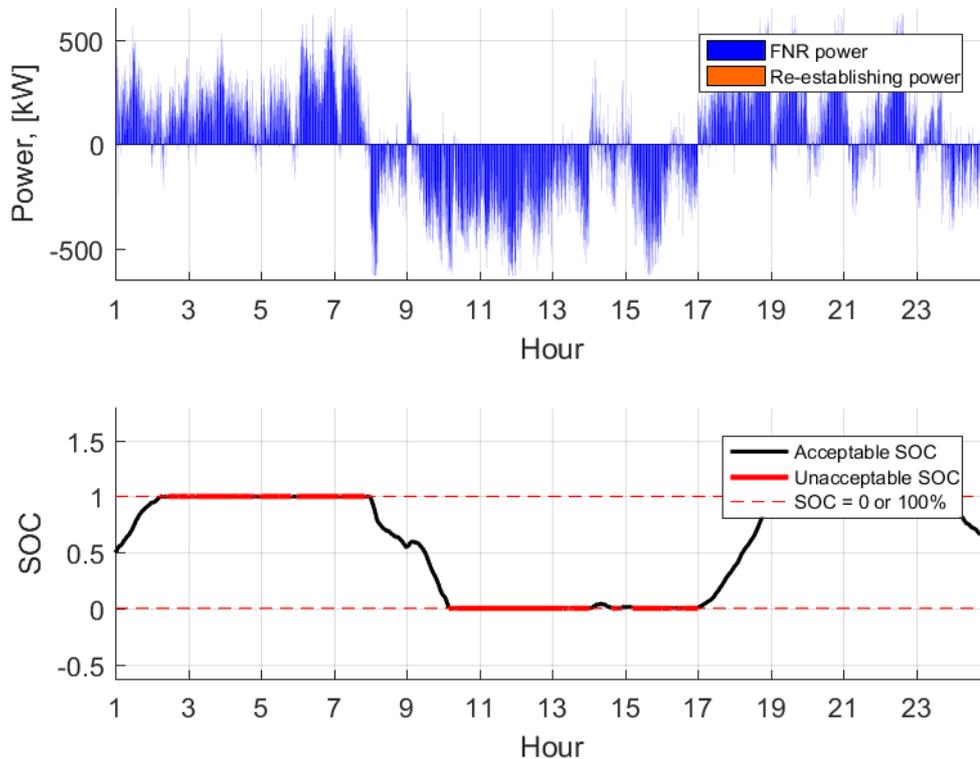


Figure 7: The BESS power and SOC over the first day of 2016 with continuous FNR operation and a power bid of 630 kW.

Figure 7 shows the resulting operation and SOC for the first 24 hours when the BESS continuously offers 630 kW. Already within these 24 hours, the SOC of the BESS reaches both 100% and 0% and it is quite clear that the power offer is simply too large for the available energy capacity. The required FNR power often approaches the maximum BESS power and a frequency deviation in the certain direction easily lasts a couple hours.

The BESS failures account for about 25% of the time and there are on average almost 100 individual occurrences of failures every day. From the TSO's perspective, this is unacceptable. The TSO contracts reserves to ensure the balance between production and consumption, and the reserves must therefore be reliable. This simulated operation is far from reliable.

Economically, the operation results in a NPV of almost -9 million DKK, and the revenue in 2016 is estimated at -718,000 DKK. The large losses are due to the penalties. The BESS fails in a large portion of the operation hours, meaning it loses the availability payment and receives a penalty of double the availability payment.

The estimated lifetime is only 5 years, where the annual cyclic ageing is 2.85% and the annual calendar ageing is 1.42%. The cyclic ageing is the dominating factor, because FNR operation results in deep, frequent cycles. The calendar ageing is caused by the BESS being 'stuck' with a SOC of either 0% or 100% and by the existence of very small cycles transferred to calendar ageing.

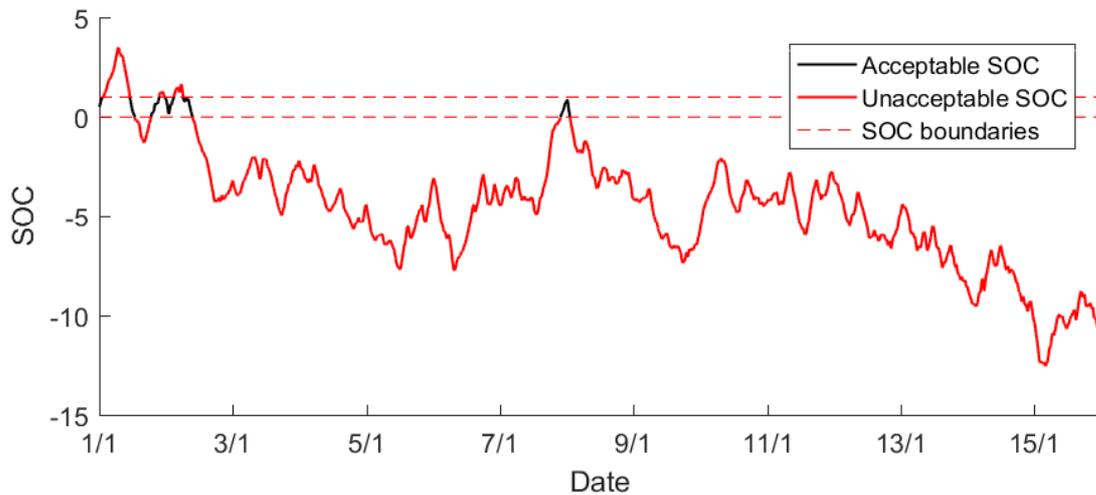


Figure 8: The theoretical SOC over the first 15 days of 2016 with continuous FNR operation and a power bid of 630 kW

Chapter 3 discussed how efficiency loss would result in a decreasing SOC over time, no matter how the frequency behaves. Figure 8 shows the first 15 days of operation and illustrates that this is indeed the case. The simulation removes the SOC boundaries, so the SOC can exceed 100% and 0%. Of course, in reality the SOC cannot exceed 100% or 0%. The frequency is relatively centred around 50 Hz over the course of the year, but since the BESS has efficiency losses, it requires more energy to charge the same energy that was discharged. It therefore cannot maintain the SOC over time, and it is not possible to provide FNR continuously without failures.

The following simulations aim to investigate how various alterations to the operation could affect the BESS's ability to supply FNR.

5.2 The effect of unidirectional service

When participating in a bidirectional service such as FNR, the energy capacity is split between up and down regulation in its re-established state. Offering only up or down regulation, means the full energy capacity is dedicated to a single direction and may lower the number of failures. This type of unidirectional service is possible for PFR units in Western Denmark.

5.2.1 Only up or down regulation with 630 kW bid

First, the BESS operation was simulated when it only provided up regulation. Figure 9 shows 2 days of the simulated operation. As expected, the failures are drastically reduced compared to the base case. The failures are reduced to approximately 3,500 individual occurrences, corresponding to an average of 9-10 failures per day, and a total unavailability of about 5%. The improvement can be explained by two main reasons: 1) when there is an over-frequency, the BESS can attempt to re-establish itself and 2) it has

more energy capacity available for the service and can therefore provide the service for longer.

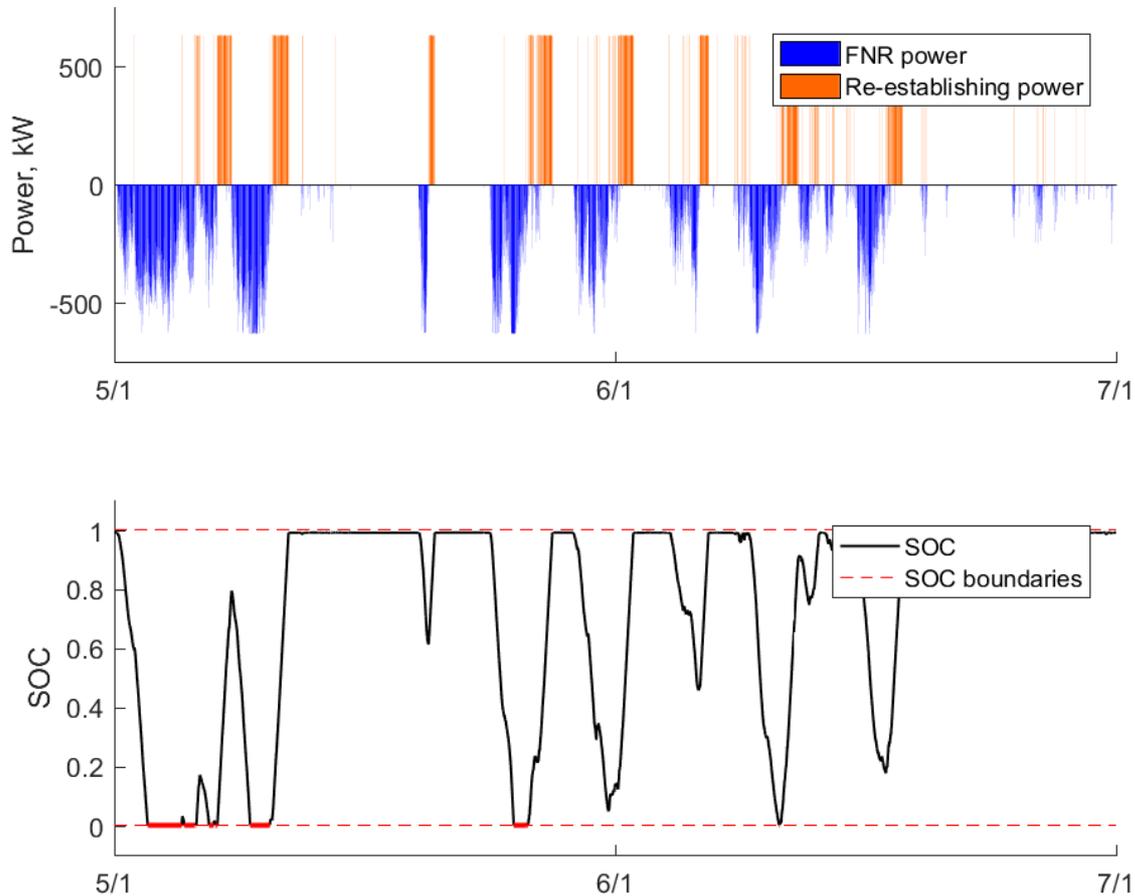


Figure 9: The simulated operation when only providing up regulation for FNR for 5-7 January 2016.

The reduction of failures is seen directly in the NPV and 2016 revenue, which are -2.54 million DKK and 629,000 DKK respectively. The operation is still not feasible.

The cyclic ageing is approximately the same as the base case, which might seem odd when considering the BESS only operates during under-frequencies now. This can be explained by the increased cycle depths. In the base case, the largest cycles are typically 50% of the energy capacity, where in this case, the largest cycles are 100% of the energy capacity. The fact that the cycles are deeper outweighs the fact that it performs less cycles. The calendar ageing is also higher, because during periods of over-frequency, the BESS will re-establish itself and then be idle instead of cycling. The lifetime is still approximately 5 years.

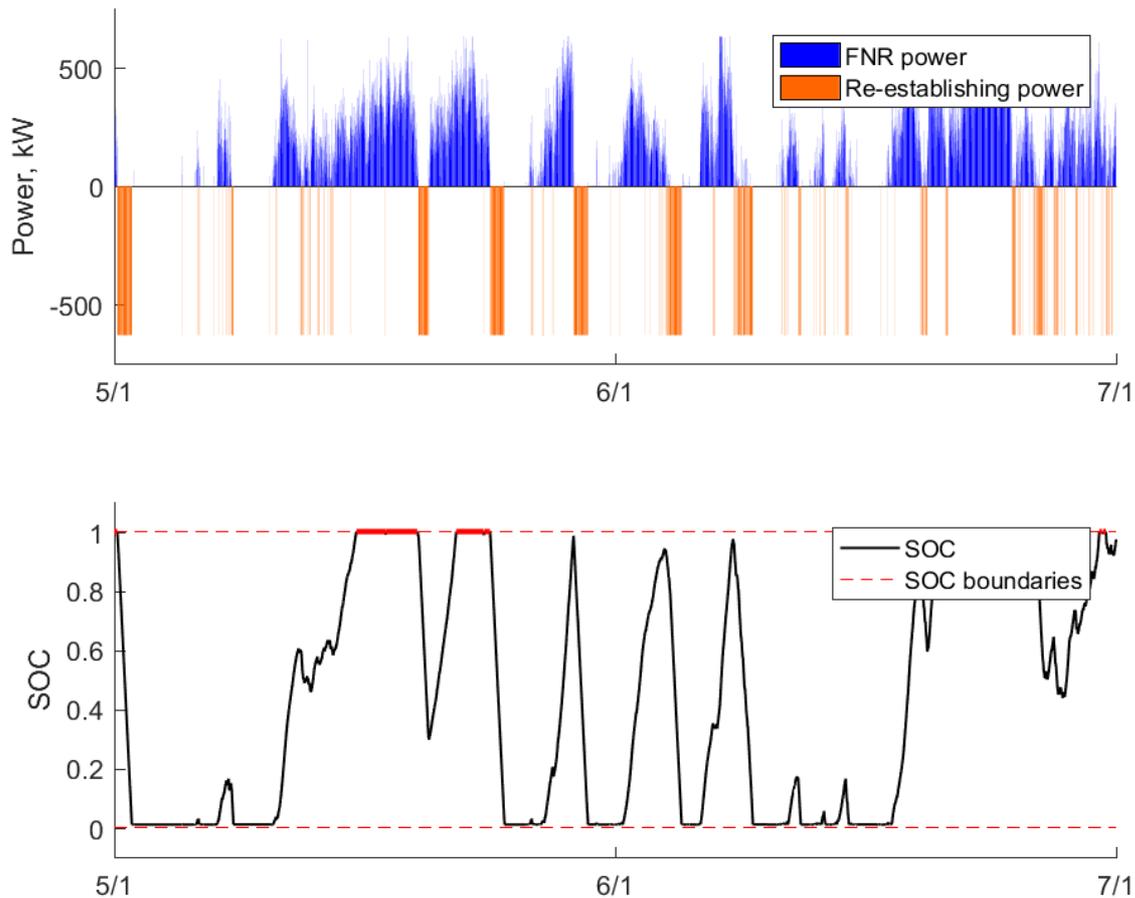


Figure 10: The simulated operation when only providing down regulation for FNR for 5-7 January 2016.

Next, down regulation with a 630 kW power offer is considered instead. The resulting operation can be seen in Figure 10. There are significantly less failures compared to only providing up regulation. There are about 1,800 failures corresponding to about 4-5 failures per day and the total unavailability is a slightly less than 3.5%. This indicates that periods of up regulation are more energy demanding than the periods of down regulation.

The NPV is higher than only providing up regulation at -1.57 million DKK, simply because the penalties are lower. The lifetime is extended by a single year. Overall, these results suggest that for the possibility of a unidirectional FNR service, the BESS should choose down regulation.

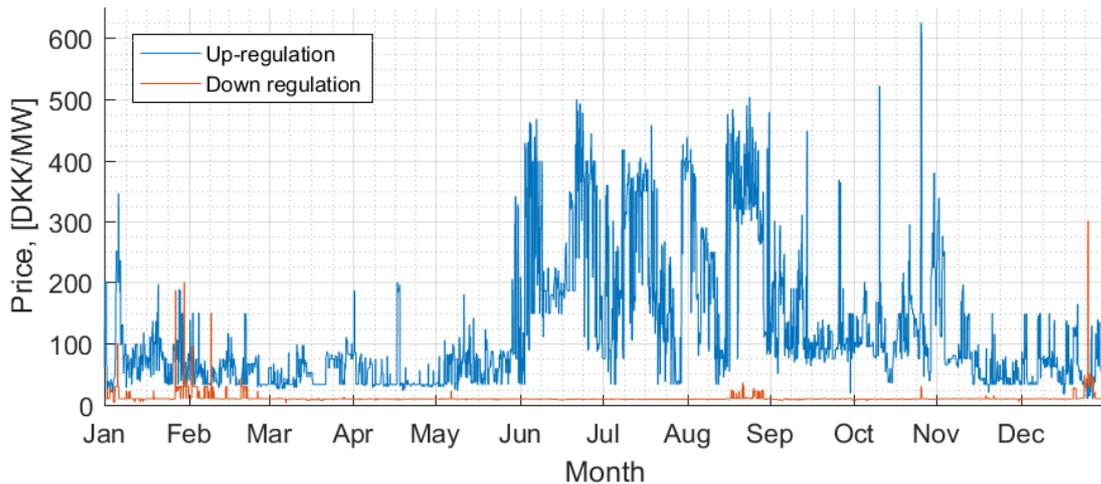


Figure 11: PFR prices

Of course, the economic calculations assume that the unidirectional services receive the same availability payment as providing the full FNR service. This is most likely not the case. For PFR, up and down regulation are separate, and the prices are lower than the FNR as seen in Figure 11, which indicates that this would also be the case if implemented for FNR. Furthermore, the PFR up-regulation prices are much higher than the down regulation prices. Therefore, the NPVs and revenues related to unidirectional FNR presented are unreliable and not comparable with the other simulations. Nonetheless, it shows that separating the services gives a more reliable operation.

5.2.2 Optimal offers for unidirectional service

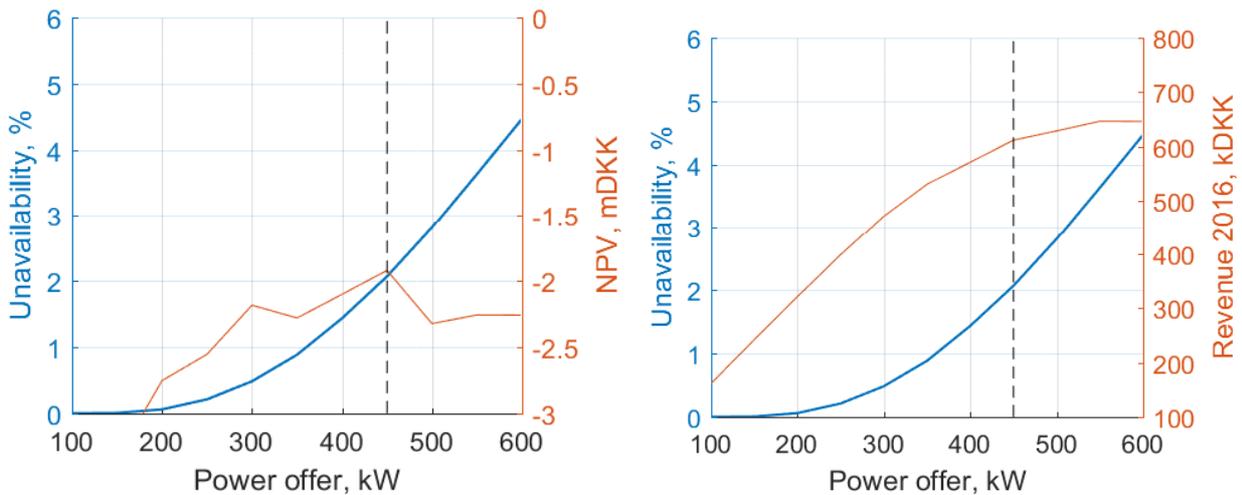


Figure 12: Up regulation offer optimisation

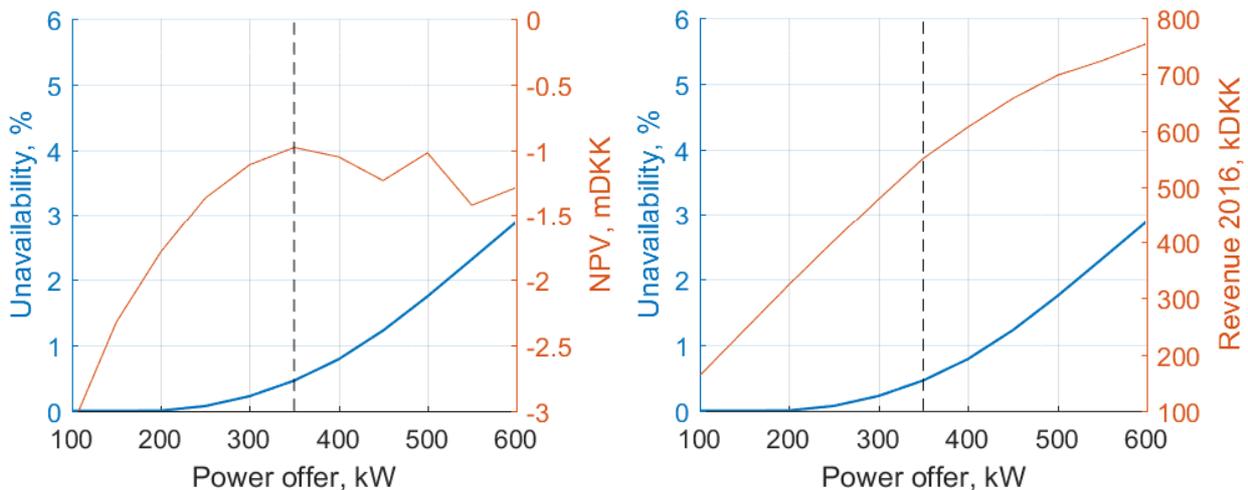


Figure 13: Down regulation offer optimisation

Offering the full power capabilities of the BESS for either up or down regulation still results in an unavailability of 3-5%. Logically this can be improved by decreasing the power offer. From the system's perspective, the aim is to maximise reliability while from the owner's perspective, the aim is to maximise the NPV. Decreasing the power offer naturally increases reliability. On the other hand, it also decreases the availability payment, but increases the total lifetime, meaning the NPV could both increase or decrease. To better understand effects of changing the power offer on both the reliability and the revenues, the simulation is run for various power offers. Figure 12 and Figure 13 show the total unavailability, NPV and 2016 revenue as functions of the power offer for both up and down regulation. The dotted lines indicate where the maximum NPV is.²

The NPVs have a parabolic tendency, with peaks at 450 kW and 350 kW³ for up and down regulation respectively. To the left of the NPV peaks, the contribution of the increased availability payments outweighs the decreased lifetime and penalties. To the right of the NPV peaks the lifetime is shortened, decreasing the availability payments, while the penalties are increasing. The total revenues for 2016 increase with the power offer, but start to flatten as the power offer increases, because the penalties are also increasing.

Offering 350 kW for down regulation gives the highest NPV and reliability. A visualisation of the operation can be seen in Figure 14. Case 4 in Table 2 shows the results for this case. Offering 350 kW for down regulation gives a reliability of about 99.5% which is very high. It is desirable to find a compromise between the owner's profits and the TSO's reliability requirement, but ultimately it is the TSO who decides what is acceptable. They will not contract reserves which they believe to be too unreliable. If Energinet.dk requires a reliability very close to 100%, the power offer should be as low as 100 kW, where the

² To ease the simulation computations, the total lifetime is estimated from the 1st year of operation and degradation in the individual years is not included. Therefore, the NPV may be slightly off compared to the full simulation.

³ With a resolution of 50 kW

unavailability is essentially zero. Overall, it is unlikely that Energinet.dk will implement unidirectional FNR service in the near future.

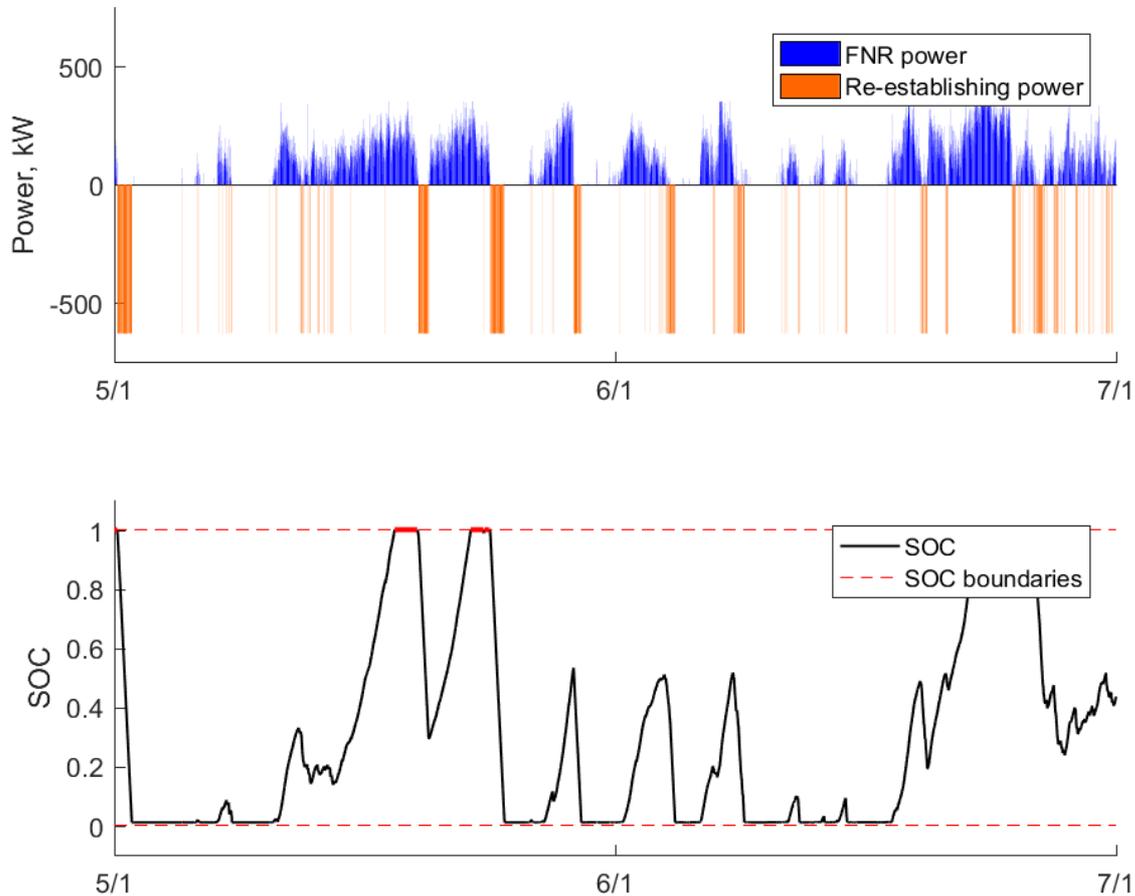


Figure 14: The simulated operation when providing 350 kW down regulation for FNR for 5-7 January 2016.

5.3 Effect of a deadband

The following section presents the effect of introducing a deadband in FNR. Again, continuous, bidirectional bids are considered, but now including a deadband. The PFR units in Western Denmark receive a ± 20 mHz deadband and this deadband is applied to FNR. It is assumed that within the deadband, the BESS can re-establish itself in either direction.

5.3.1 Maximum power offer, 630 kW

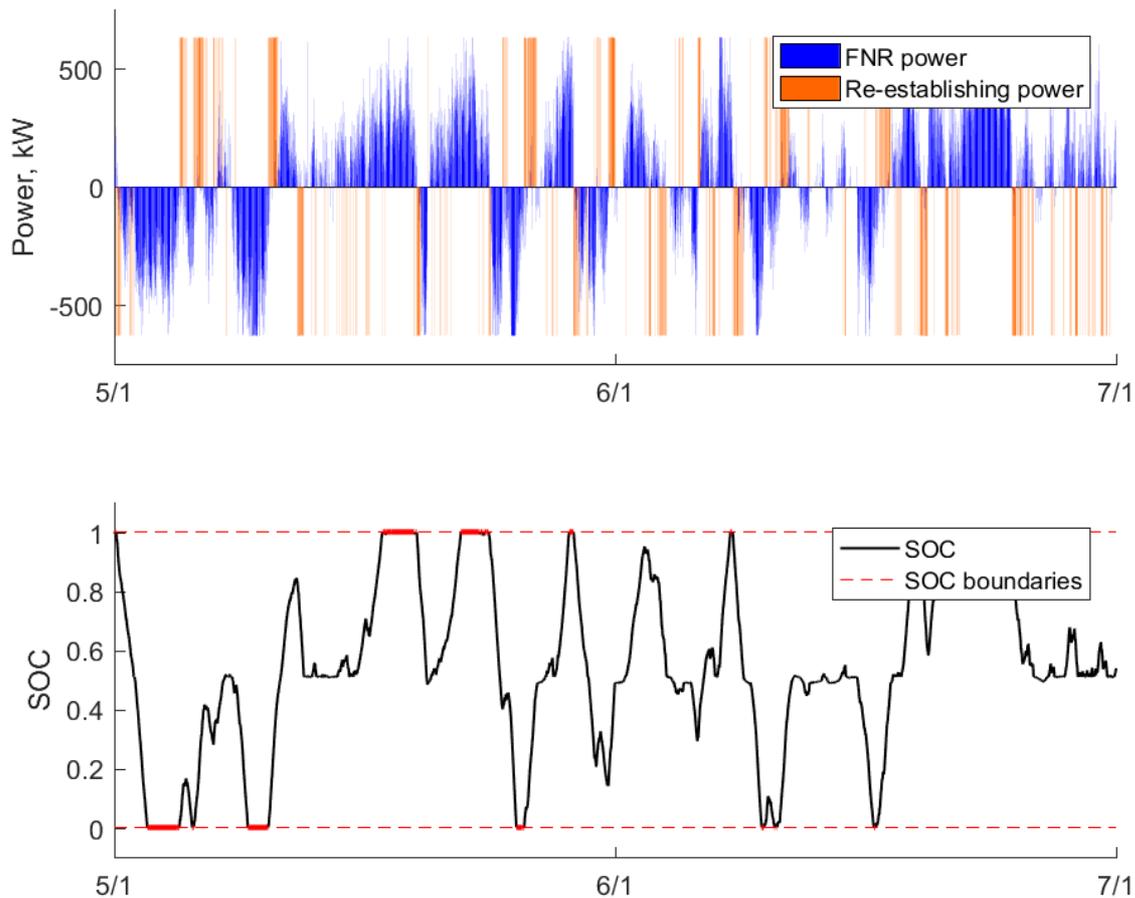


Figure 15: The simulated operation when providing 630 kW continuously for FNR including a +/- 20 mHz deadband for 5-7 January 2016

The power offer is set as 630 kW, to investigate whether the BESS can participate with its full power capacity when given a deadband. Figure 15 shows two days of operation. The total number of failures is vastly decreased compared to the base case. There is an average of 14-15 failures per day. The percentage of time which the BESS is unavailable is about 5.5%. Due to the decrease in failures, the 2016 revenue is positive at 453,000 DKK and the NPV is -3.03 million DKK.

The deadband causes both a large decrease in failures and a vastly increased revenue compared to the base case, showing how helpful the deadband is for helping the BESS re-establish a SOC of 50%.

The cyclic ageing is lower compared to the base case. The deadband removes or decreases the depths of cycles when the frequency is close to 50 Hz. Also, it breaks large cycles into smaller cycles. For example, consider the case where the frequency is 49.95 Hz for an extended period, but increases to 49.98 Hz for some time, and then returns to 49.95. When the frequency increases to 49.98, the BESS with a deadband can charge,

meaning it gives a discharge-charge-discharge cycle sequence. Without the deadband, the BESS would constantly discharge and the period would have been one large cycle.

The calendar ageing is approximately the same as the base case. The calendar ageing in the base case was primarily caused by being idle at 0% or 100%. In this simulation, it is caused by the deadband introducing idling periods for frequencies close to 50 Hz. The estimated lifetime is increased by approximately 1 year compared to the base case.

If Energinet.dk decides to change the FNR regulation, it is not unlikely they will consider the implementation of a deadband. For this reason and because the deadband is very helpful for the BESS, it was included when investigating the effect of actively taking a break from FNR when fully charged or discharged.

5.3.2 Optimal offer when including deadband

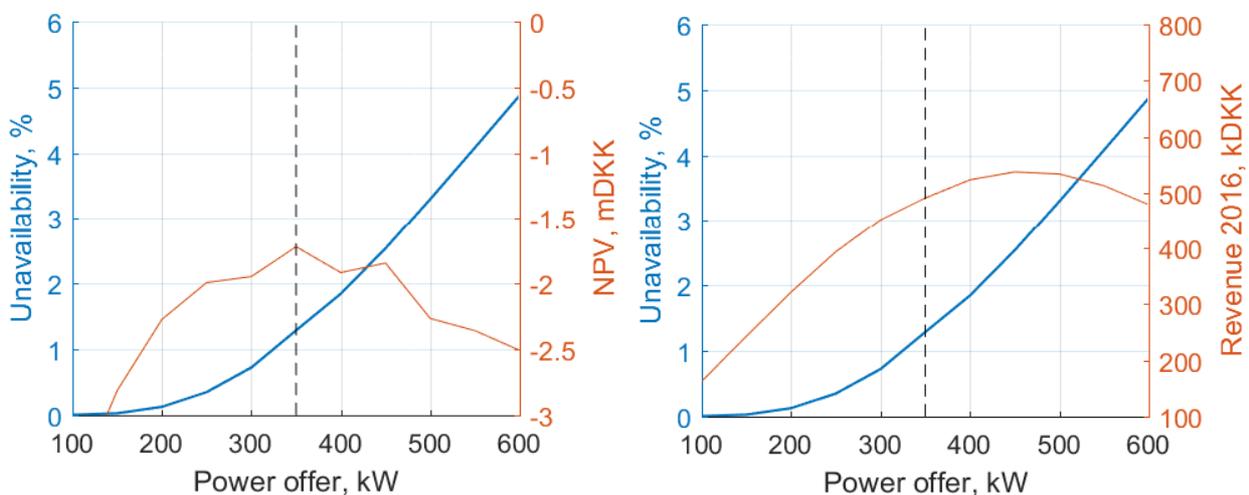


Figure 16: The unavailability and NPV as a function of the power offer for FNR service including the +/- 20 mHz deadband.

Figure 16 shows the NPV, 2016 revenue and unavailability percentage as a function of the power offer. Clearly, offering 630 kW, is neither optimal for the TSO desiring reliability or for the owner desiring high profits. The maximum NPV occurs at 350 kW, where the unavailability is reduced to about 1.3%. If a reliability of 98.7% is acceptable for the TSO, then this would be the optimal power offer. Figure 17 shows the resulting operation when offer 350 kW.

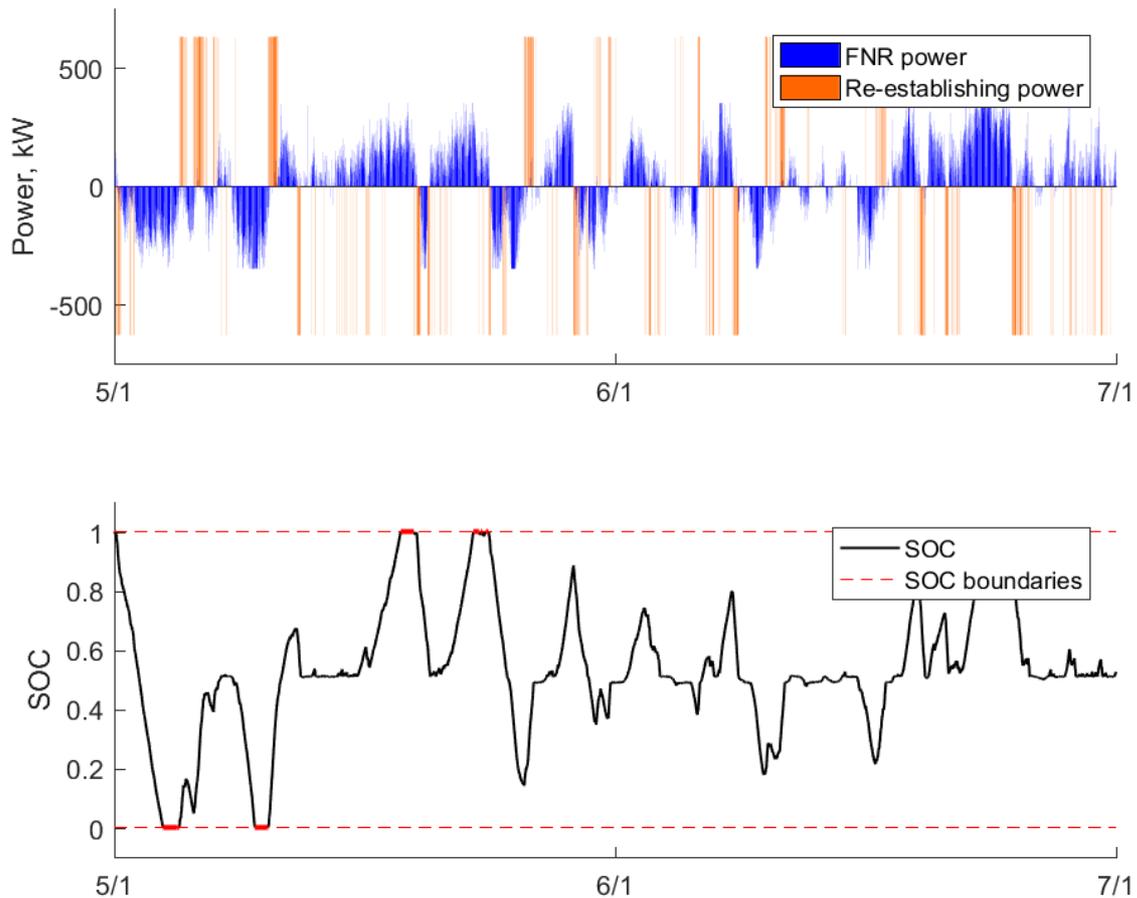


Figure 17: The simulated operation when providing 350 kW continuously for FNR including a +/- 20 mHz deadband for 5-7 January 2016

5.4 Effect of block operation

As also shown in the previous simulations, the main issue is the lack of energy capacity compared to the size of the power capabilities. A possible solution to this problem is to participate in FNR in blocks instead of continuously. Between the hours of operation, the BESS can re-establish itself to 50% SOC. The deadband is not included.

5.4.1 1 hour blocks

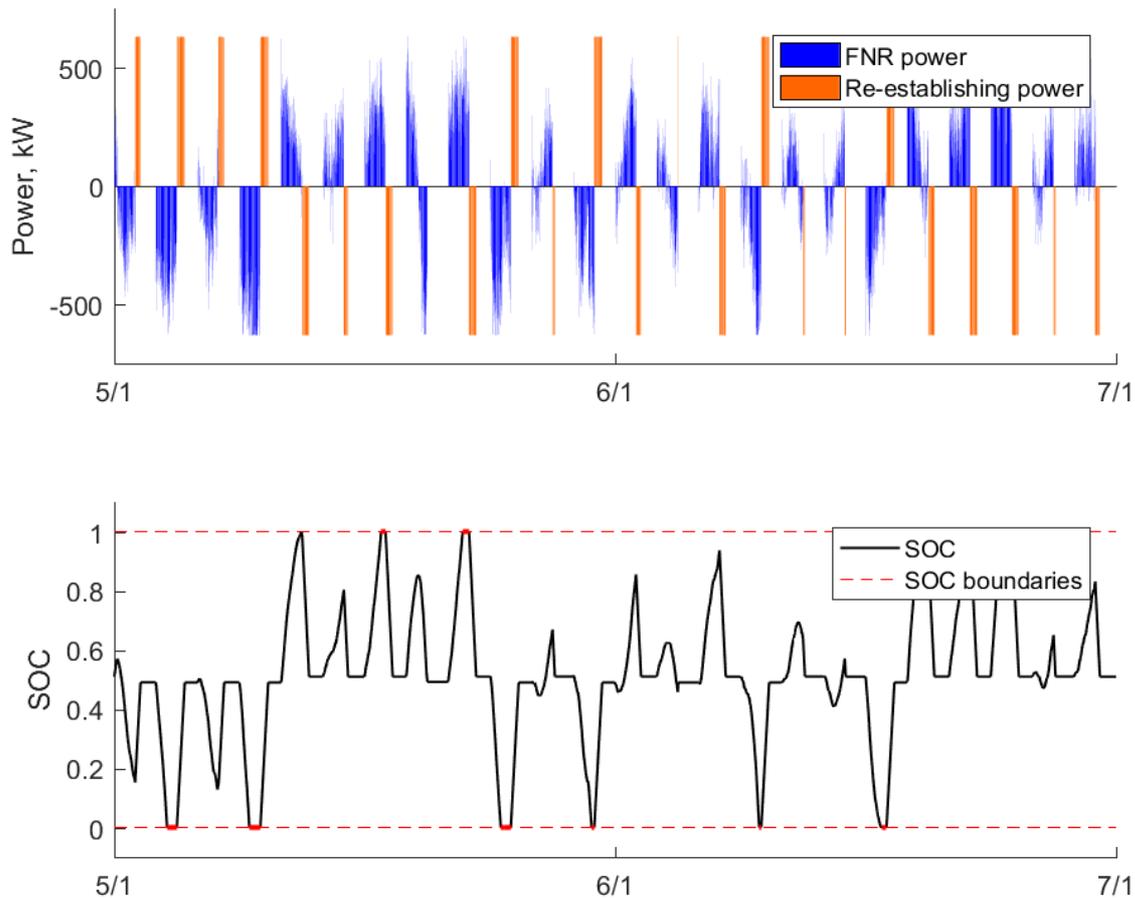


Figure 18: The BESS operation for 5-7 January 2016 with single hour 630 kW FNR operation (Does not include deadband)

FNR is contracted by the hour, and therefore 1 hour is also the shortest possible operation length. To begin, the simulation is therefore run for 1-hour blocks with a power offer of 630 kW. Figure 18 shows the operation for 2 days in 2016. The on/off behaviour of the FNR operation is clearly seen and the SOC is returned to 50%, in the hours in-between operation.

The number of failures is reduced and the unavailability is about 3.1%. The 2016 revenue is 106,000 DKK. Compared to the base case, this is a large improvement, and creates positive revenues even though it only participates half the number of hours. The NPV is the lowest of all the cases presented so far (except for the base case), simply because the annual revenue is the lowest and the lifetime is shorter. The advantage of this strategy is that it does not require a change in the regulations.

From an ageing perspective, this strategy is not recommended. The cyclic ageing is much higher, because the BESS almost always cycles 50% of its capacity every other hour. The calendar ageing is similar to the base case, but where the base case calendar ageing is caused by being "stuck" at a SOC of 0/100%, for this strategy the calendar ageing mainly

occurs in the non-FNR hours after the BESS has re-established. Overall, the lifetime is estimated at 3 years.

The power at which the BESS re-establishes its SOC in the hours between FNR participation could be reduced such that it uses the full hour to re-establish, because this would decrease ageing. The degradation calculations do not take charging rate into account.

5.4.2 Preventing failures completely

Block operation is the only strategy which can guarantee no failures, because it specifies an exact period the BESS should be able to supply full power. It is possible to calculate the necessary power offer expressed as:

$$P_{bid,max} = \frac{(SOC_{max} - SOC_{min})E_{BESS}}{2 t_{hours}}$$

For single hour block operation, $SOC_{max} = 1$, $SOC_{min} = 0$, $E_{BESS} = 460 \text{ kWh}$, the power bid is $P_{bid,max} = 230 \text{ kW}$. As mentioned in Chapter 2, a FNR bid must be at least 300 kW according to Energinet.dk's current requirements. It is assumed that the BESS can still participate.

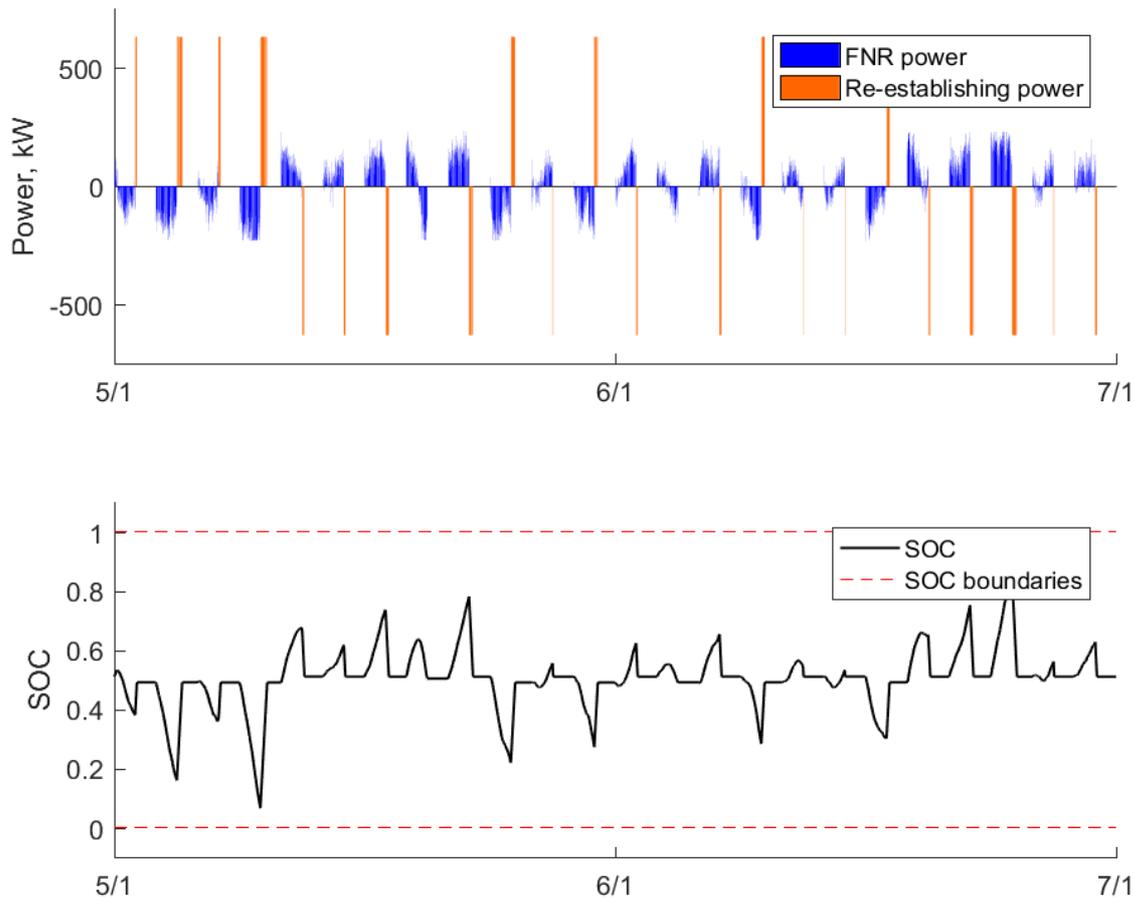


Figure 19: The BESS power and SOC for 5-7 January 2016 with single hour blocks and a power offer of 230 kW (Does not include deadband).

The power offer is dependent on the lengths of the blocks. If the block is extended to 2 hours, the power offer must be halved. For single hour blocks, the BESS participates in $\$8760/2=4380\$$ hours and for 2-hour blocks, the BESS participates in $8760 * \frac{2}{3} = 5840$ hours. Since the number of operation hours is not doubled when doubling the block length, the best block length is 1 hour. Note, the power offer is decreased as the BESS degrades in the simulations.

Figure 19 shows the operation for 2 days with a power offer of 230 kW. The minimum SOC for the full year is 6% and the maximum SOC is 93%, which, as expected, shows that the power bid is set in such a way that the BESS does not violate its SOC limits.

The NPV for this strategy is higher compared to offering the full power capabilities due to the decreased penalties. The NPV is -3.88 million DKK. The 2016 revenue is 187,000 DKK, where there are 0 DKK penalties.

The cyclic ageing is greatly reduced to 1.57% per year, because the cycles are much smaller. The calendar ageing is higher due to two reasons: 1) The BESS does not need as much time to re-establish the SOC and therefore spends more time being idle in the non-FNR hours and 2) some cycles become so small that they are transferred to calendar ageing instead. The lifetime is estimated at approximately 10 years.

Overall, this strategy gives the highest reliability at 100%, but the profits are still not sufficient.

5.4.3 Optimal offer for block operation

The optimal power offer for single hour block operation is presented here. Figure 20 shows the NPV, 2016 revenue and unavailability as a function of the power offer. The highest NPV occurs at 300 kW and is approximately -3.74 million DKK. This NPV is not nearly as high as the optimum power offers for the previously investigated strategies. On the other hand, the reliability is very high for all power values (above 99%), so if the desire is to consistently ensure a reliable operation, block operation recommended.

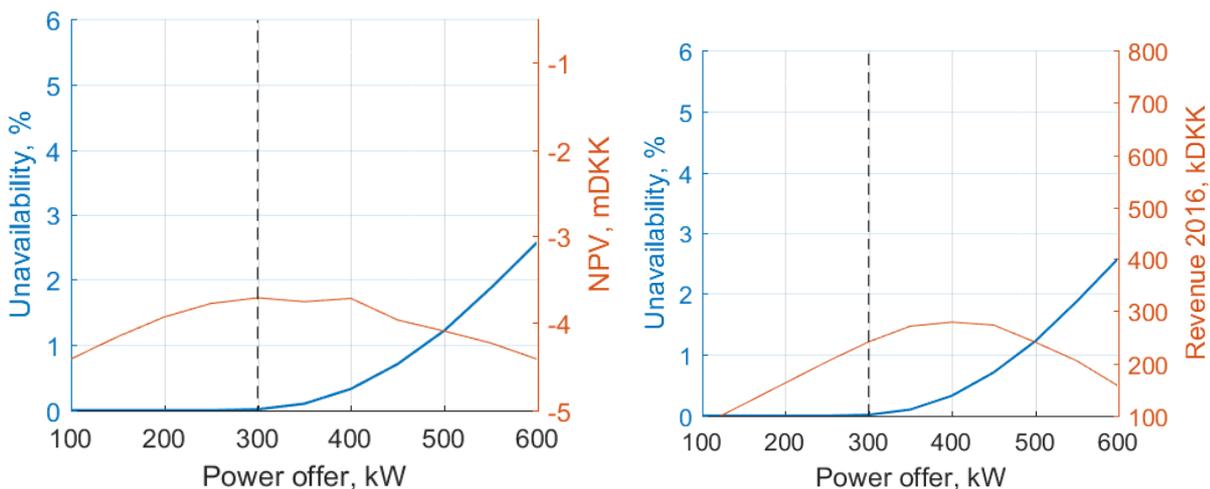


Figure 20: The unavailability and NPV as a function of the power offer for block participation (Does not include deadband).}

5.5 The effect of taking time to re-establish

In the following simulations, the effect of actively remedying the SOC, if it reaches either 0% or 100% was investigated. The break is activated as soon as the SOC reaches one of its boundaries. The deadband from case 5 is also included in these simulations.

Of course, during the break the BESS is not fulfilling its duties as a reserve, and therefore it receives the penalty. The aim is to introduce controlled and predictable periods of failure, which both helps the BESS handle future frequency deviations and may be more acceptable for the TSO.

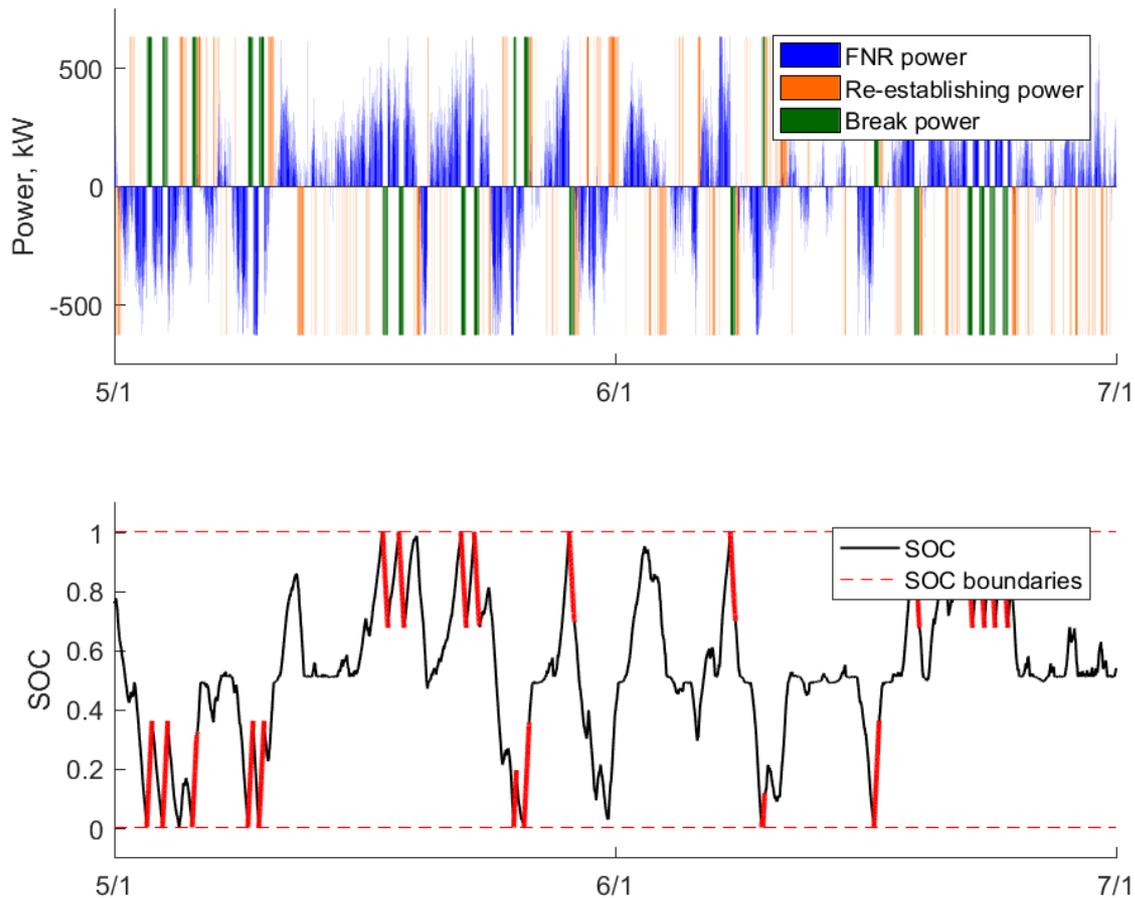


Figure 21: The BESS power and SOC for 5-7 January 2016, when taking 15 min breaks every time the SOC reaches 0/100%. Including the +/- 20 mHz deadband.

Figure 21 shows two days of the operation when offering 630 kW. A red SOC curve indicates both failures and when the BESS is taking a break. The operation is identical to the continuous case including the deadband (case 5 in Table 2), but instead of waiting for the frequency to re-establish the SOC, the BESS takes a break to remedy the SOC. Therefore, the results of these two strategies are compared.

The number of failures is more than halved, from 14-15 failures per day to 5-6 failures per day. The total unavailability is decreased from 5.4% to 3.8%. The breaks are included in the failures, which shows that the controlled breaks managed to prevent or alleviate future failures.

Compare again Figure 21 to the operation without the breaks (with deadband) in Figure 15. It is clear that the number of cycles is increased. The annual cyclic ageing is therefore increased from 2.43% to 3.53%. The calendar ageing is slightly decreased because the BESS does not remain idle at 0% and 100% anymore. The estimated lifetime is only 5 years.

The 2016 revenue is about 70,000 DKK higher than the strategy without the breaks, due to reduction of failures. This increase in annual revenue and the reduced lifetime outweigh each other, and therefore the NPV is nearly unchanged.

5.5.1 Optimal power offer when including 15 min breaks

Like in the other investigations, offering 630 kW may not be optimal for either the BESS owner or the TSO. Therefore, the NPV, 2016 revenue and unavailability are determined as functions of the power offer. Figure 22 shows the result with a power resolution of 50 kW. The optimal power offer is 400 kW, which is slightly higher than Case 5.

When running the full simulation with 400 kW, the estimated NPV is -1.97 million DKK, which is very similar to the optimal offer of the case without the breaks (Case 6 in Table 2}. On the other hand, the failures are reduced slightly to 1.2% compared to 1.3%. Figure 23 shows the operation with the optimised power offer.

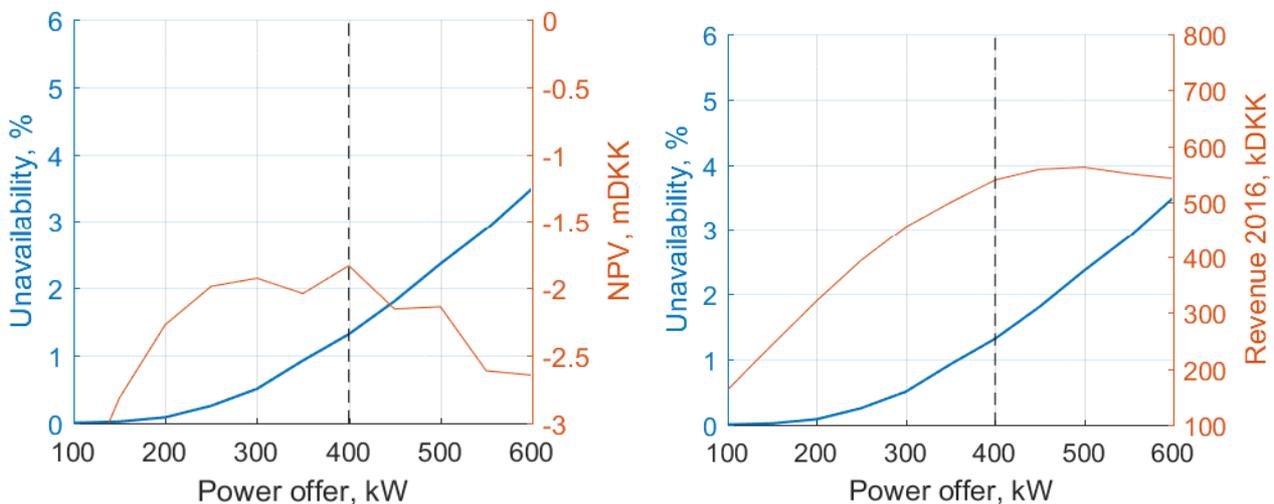


Figure 22: The unavailability and NPV as a function of the power offer for FNR service when allowed to take breaks (including the deadband).

Since the NPV is similar and the reliability increased, this strategy is preferred compared to the case with the deadband, but no breaks. In the case without the breaks, the BESS failures and SOC are at the mercy of the frequency and therefore the delivery of power is unpredictable. In other words, the TSO does not know when the BESS can return to operation. When controlled breaks are introduced, the TSO knows exactly when the BESS will return to the service again and can therefore plan accordingly. This characteristic may make the TSO more likely to accept some degree of unavailability.

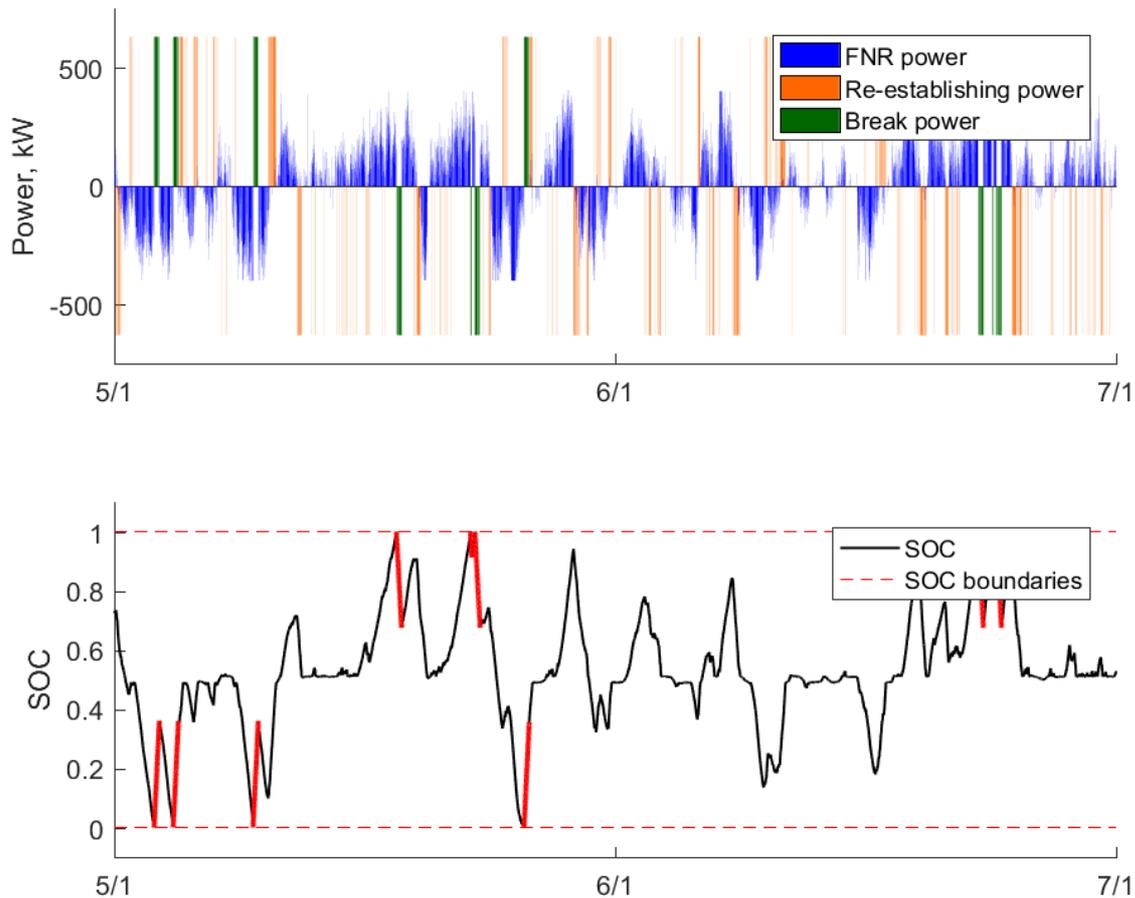


Figure 23: The BESS power and SOC for 5-7 January 2016, when taking 15 min breaks every time the SOC reaches 0/100% and offering 400 kW. Including the +/- 20 mHz deadband.

6. FNR conclusion

Participating in FNR has the highest potential for revenues for units in DK2. Unfortunately, the simulations concluded that with the current regulations, the BESS cannot participate continuously in FNR. There are no mechanisms which help the BESS maintain its SOC. The BESS operation is completely at the mercy of the frequency. To achieve a reliable operation, the BESS must participate in 1-hour blocks, separated by 1 hour of re-establishing the SOC and it cannot offer 630 kW. Of course, this drastically decreases the revenues. A power offer of 230 kW gives 100% reliability, but according to regulations FNR offer must be at least 300 kW. This strategy is less profitable than participating in FDR.

Several different changes to FNR operation were investigated, including the implementation of unidirectional service, a deadband and actively taking time to remedy the SOC when necessary. For future changes to FNR regulations it is recommended to consider a deadband for units with a limited energy reservoir, allow them to take a break when they require it or define a certain time frame the BESS must be available. It would be most beneficial if FNR was changed so it resembles PFR in DK1 or the regulations in Germany. When simulating the effect of the deadband for FNR, it was assumed that the BESS can re-establish its SOC in either direction when the frequency was in the deadband. In reality, the BESS may only be allowed to re-establish itself in the deadband, if it helps the system balance. Since the FNR operation was already rather unreliable, and this restriction was not enforced in this simulation.

7. References

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