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Influence of technical limitations and operation on sizing of an offshore energy storage connected to an offshore wind farm

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Abstract

This paper aims to investigate the sizing of an offshore energy storage unit operated in conjunction with an offshore wind farm. The storage unit is evaluated with technical limitations to reveal the parameter sensitivities when coupled with a wind farm. The main interest is the sizing of the storage unit for capacity firming purposes.

A storage unit in combination with a large offshore wind farm has been simulated in time domain over the course of one year. The storage unit has been operated with the goal of firming the wind power capacity within each bid period. Different constraints have been introduced to show parameter sensitivity of the storage unit. The constraints were both technical and control oriented. An important prerequisite for the simulation was that the combined wind power plant and the storage operate in a market where the imbalance between bid and delivered energy is measured and penalized.

Results show that there are several important parameters regarding storage sizing. Storage sizing is shown to be very dependent on the production forecast error and market bid length. Furthermore, technical constraints in the shape of ramping rates and power reversal dead time can be countered by choosing an appropriate control strategy. No control strategy gives significantly more reduction in grid power imbalance than the constant, fixed mode control strategy. The same reduction can however be obtained, with somewhat less energy routed through the storage by applying an alternative control strategy.

Keywords: energy storage; wind; control; capacity firming; offshore

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1. Introduction

An increasing number of concepts for offshore energy storage have been explored over the last few years, some of which have been realized in prototypes or grid integrated on a reduced scale [1-6]. Some suggestions also try to integrate the energy storage onto the renewable energy harvester as a single unit, which would increase total efficiency [6, 7].

A possible use for these offshore solutions could be in combination with variable renewable sources like wind power. A lot of work has been done on sizing and optimal operation of combined wind power and pumped hydro storage in a deregulated market [8]. Often, the storage sizing and operation is based on price data from a specific market and the optimization is solved through various techniques. An aspect that is not taken into consideration in these investigations are technical constraints, hence these operating strategies could allow operation outside the limitations of storage devices.

The offshore energy storage unit, similar to the onshore version, can be connected to a grid and operated in the related market structure. As with the former work on wind and pumped hydro storage (PHS), the optimal solution would differ according to the implemented financial mechanism and the absolute price values. However, an offshore energy storage unit may also be connected to an offshore grid that can be connected to multiple grids (e.g. North Sea offshore grid [9]) or to isolated/regulated markets. Thus, it would be relevant to investigate the performance of an offshore energy storage decoupled from the monetary stream.

This research aims to investigate the performance of an offshore energy storage unit operated in conjunction with an offshore wind farm. The two units share a single cable onto shore. The storage unit is evaluated with technical limitations to reveal the parameter sensitivities when coupled with a wind farm. The main interest is the sizing of the storage unit for capacity firming purposes. Capacity firming can counter two characteristics related to wind power production: wind variability and production forecasting error. The former originates from natural variation in wind, while forecasting error is a result of our inability to correctly anticipate the average wind over a bid period a certain time in advance of production [10]. Additional capacity can be added to the storage for arbitrage, long-term storage purposes or even short-term frequency control purposes. However, this is outside the scope of this paper.

The technical constraints of the storage unit stem from physical and regulatory limitations. Understanding how these constraints could affect the final sizing of the storage is important at a design stage and should therefore be investigated. Such constraints include ramping limitations and dead time with zero power associated with each power flow reversal.

In addition to technical constraints, the effect of choosing an operating strategy will be investigated. Five different control strategies will be implemented. The first strategy aims at ensuring constant power output, which would bring the apparent behaviour closer to a traditional power plant. The second strategy aims at securing the committed energy for the bid period. This strategy is better suited for certain market structures as they exist today. The remaining three strategies are variants of the second strategy that aim at mitigating some of the technical constraints.

Nomenclature

PHS   pumped hydro storage
DRW   Dogger Bank reference wind farm

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2. Method

A time domain simulation model in Matlab is used for this work. Simulations are run for one year of operation. The details about the modelling are presented in the subsequent subsections.

2.1. Wind farm output using the Dogger Bank reference wind farm

The Dogger Bank reference wind farm (DRW) is a publicly available offshore wind farm design for the Dogger Bank area, UK [11-13]. DRW information was used to produce a realistic power output from a very large offshore wind farm. As a first approximation, the wind series from a single offshore measurement station was used. The wind series was recorded at 90m hub height from 01.11.2009 to 31.10.2010. To obtain the output from the wind farm, the wind farm was simulated with the wind series passing over the farm with the yearly average speed of the wind series. Wake effects for DRW were included by terms of turbine spacing. Hence, the wind direction information is of less importance, and the single wind speed measurement could be used. Verification of the model showed a capacity factor of 37.27% with the single wind series compared to an expected 36.7% from earlier simulations with DRW. Hence, the wind farm power output was verified.

Table 1. Characteristics of the wind power series.

Wind farm	Dogger Bank 1.2GW reference wind farm
Capacity factor	37.27%
production hours $P < 1\%\ P_{max}$	980.5h
production hours $P > 95\%\ P_{max}$	1078.6h

2.2. Production forecast error

Forecast error is not straightforward to model since the error depends on the methods and tools used to perform the forecasting. There will be variation due to local conditions and natural variations over the year. At some locations it is easier to get good quality forecast, at other locations it is more difficult. The accuracy of the forecasting will also differ for high and low production. Moreover, the forecasting horizon (minutes to days) will have the largest impact on the forecasting error. Furthermore, the forecast error for one period will be correlated to the error of the previous and the next period as discussed in [14]. Consequently, it is more likely that production is higher (or lower) than forecasted for several bids in a row.

The objective of this work is to show the general impact of technical limitations and operation of the storage. Hence, a simple model of the forecast error was chosen. For the sizing of at a specific site it will certainly be recommended to use much more sophisticated models adapted to the location and forecasting methodology.

In simulation, the error is introduced to each new bid period by adding an error to the exact forecast, which is the average wind power production for the next bid period. The added error is a random error, Gaussian distributed with zero mean value with a standard deviation in percent of rated wind farm power production. This implies that the forecast error in this work is independent of the forecast error of previous and next bid intervals as well as independent of production level. This method will in some intervals give forecasts that are less than 0 or larger than rated wind farm production, in which case the forecast for these periods are set to zero and rated plant power respectively.

In most real markets today production forecasts are made in advance of production, e.g. day-ahead markets. The forecast error of each imbalance period will then typically be smaller in the first periods, and then increase toward the end of the forecast interval. The standard deviation of the simple model used in this work will in such cases be considered as a representative value for the whole production forecast interval.

2.3. Imbalance market operation

To evaluate the performance of the storage unit, a market mechanism related to imbalance was implemented. The wind power plant places a bid in the market for the following bid period, and the bid is always accepted. After the bid period is over, the wind power plant is benchmarked according to its own bid. Any mismatch in delivered

energy compared to the bid is recorded as an imbalance. In several markets today such an imbalance mechanism exists. The resulting imbalance is traded on a balance market and represents a penalty to the wind power plant.

For the simulation presented in this paper, new bids are placed every 15, 30 or 60 minute based on the forecast of the next 15, 30 and 60 minute respectively (the exact forecast plus the independent forecast error). The bid can be modified by the applied control strategy (Section 2.4) or by the energy balancing strategy (Section 2.5).

Energy cost and imbalance cost are not modelled in this work since focus is on technical and operational aspects. Instead, focus is set on the total aggregated imbalance between bid and actual production over a year. Furthermore, only imbalance in energy is recorded. It is assumed that variation in instantaneous power is accepted as long as the average for one period, i.e. the energy, complies with the bid. This is in compliance with most markets today.

2.4. Storage operating strategies to compensate forecast error and firming capacity

Since variations in the instantaneous power output is not penalized, several approaches for control strategies open up that aim at avoiding imbalance at minimal effort. Reference [15] presents some alternative control strategies for the same goal. In this work, five other operating strategies are used, which are explained further in following subsections:
1. Constant and fixed set-point for grid power in each bid period.
2. Constant set-point for grid power with recalculation of set-point during bid.
3. Strategy 2 with linearly increasing storage max-power limitation.
4. Strategy 2 with a linearly decreasing dead-band for storage power command.
5. Min-max operation aiming at unidirectional storage power-flow within each bid period.

The main goal of all strategies is to prevent or reduce the imbalance between bid and actual delivered energy in one bid. Technical limitations in the storage system may however prevent the storage system from 100% goal fulfilment.

2.4.1. Constant grid power in each bid period
The energy storage is controlled to counter any instantaneous deviation between bid and wind power throughout the whole bid period. The goal is to make the power flow constant when seen from the grid side. This strategy makes the combined wind farm and storage unit output similar to a traditional power plant.

2.4.2. Constant grid power with recalculation of set-point during bid
On the contrary to the constant fixed power output strategy, this strategy allows for the actual grid power to change during the bid period. The set-point for the storage is recalculated during the bid period to compensate any aggregated error. This will be beneficial if the storage, due to some technical or operational restrictions, has not been able to follow the set-point in first part of bid (e.g. due to insufficient power rating). Similarly, this minimizes the energy that passes by the storage by possibly allowing for the wind variation to cancel itself out.

2.4.3. Increasing storage max- power limitation and decreasing dead-band for storage power command
The two first strategies are set to compensate from the beginning to the end of the bid period. While imbalance only considers the energy it is uncertain if it will be necessary to use the storage until one approaches the end of the bid period. Hence, any storage activity in the beginning of the period might be wasted. Thus, it seems appropriate to try a "wait and see" approach from the beginning of the bid. One possible implementation of such strategy is to use the previous strategy with a restriction on the maximum allowed storage power flow. The maximum allowed
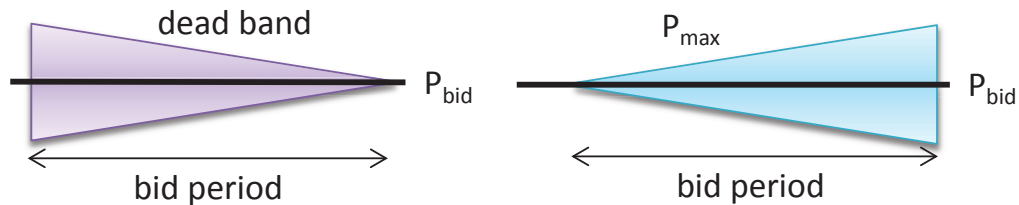
Figure 1. Variations of the recalculated set point strategies. The left figure shows the dead band decreasing along the bid period. The right picture shows how the maximum power band increases along the bid period.

storage power flow is zero at beginning of the bid and increases linearly to the rated storage power at the end of the bid period. A second attempt of such a strategy is to introduce a dead-band on the storage power command. The storage power flow is kept at zero as long as the commanded storage power flow from strategy explained in 2.4.2 is less than the dead-band. The dead-band starts at rated storage power and decreases linearly to zero towards the end of the bid period. Both of these strategy variations are visualized in Figure 1.

2.4.4. Min-max

The min-max strategy was used for controlling a battery storage system together with a solar plant in [16]. The goal of this strategy is to minimize the number of zero power crossings by setting the bid higher or lower than the forecasted instantaneous power plant output. In this way, a unidirectional power flow should be secured through the bid period. However, for batteries the increased power flow led to lower lifetime. For mechanical storage technologies, lifetime is less affected by the absolute power flow and rather the power flow reversal might be associated with(?) cost and short-time stops in power output. Therefore, the min-max strategy is included here to investigate the effect of fewer power flow reversals.

In this strategy the bid is based on the forecasted minimum or maximum wind production instead of the average. A "maximum bid" implies that storage will discharge throughout the bid, while a "minimum bid" will cause a net charging. However, the forecasting may cause the opposite to happen, since the minimum and maximum production in next bid is not exactly known in advance.

One free variable of the min-max strategy is the criteria for changing from a "minimum bid" to a "maximum bid" This influences on the number of power flow reversals. Fewer reversal results in longer periods of power flow in each direction, which in turn increases the need for storage energy capacity. To clarify the possible advantages or disadvantages of the min-max strategy, reversal is allowed at the start of every bid period. A "minimum bid" is used if stored energy is above 50% of rated, and a "maximum bid" is used if stored energy is below 50% at the time the bid is placed. This is expected to minimize the storage capacity needs.

2.5. Storage energy balancing (state of charge control)

In this work energy storage capacity is included as a constraint. The stored energy needs then to be monitored and there must be a strategy to maintain the stored energy at a desired level such that the storage is able to compensate the variation in wind power. For this model, each bid is based on the forecasted wind power production plus an offset that with zero forecast error will give 50% stored energy at the end of the bid. The actual stored energy at end of the bid period will still typically differ from 50% due to the forecast error, but by using this strategy one ensures that the storage remains close to 50% at the end of most of the bids.

2.6. Technical constraints

2.6.1. Zero storage power when shifting between storing and generating mode (reversal dead-time)

For mechanical storage concepts, there can be a certain dead-time associated with changing between storage and generation modes. During this time the power output would be zero. Examples from existing plants in Britain

indicate that the dead-time can vary from seconds up to several minutes [17]. This phenomenon is modelled by limiting the output to zero power for a certain time period before power can start flowing in the opposite direction.

2.6.2. Storage power flow ramp limitations

Ramp limitations indicate the rate at which the power output of the storage device can change. Such limitations could be the result of a technical limitation, e.g. grid codes, or it could be the result of the responsiveness of the control and mechanical system. The simulation model allows for limitations of the rate of change of the storage power flow.

3. Simulation

Table 2. Overview of the different conditions for simulations that were made. Each case or group of cases are aimed at performing a sensitivity analysis of a certain parameter.

| Case	Conditions
Base case	Storage power rating: 0 to 40% of plant power rating
	Storage energy rating: 8% of plant power rating times 1 hour
	Control strategy: Constant and fixed grid power set-point (strategy 1 in see section 2.4)
	Forecast error standard deviation: 10% of plant rating
	Imbalance calculation: Imbalance in energy calculated every 15 min
	Imbalance reference: calculated in percent of total wind power production
	All losses in storage system are ignored
	No limitation in rate of change in storage power flow
	Storage target state of charge: 50%
	Power reversal: Instant with zero dead time
	Storage can be utilized from 0 to 100%
A	**Effect of storage power and energy rating**
	Energy rating: 2, 3, 5, 8, 12 percent of plant power rating times 1 hour
	(Remaining as base case)
B	**Effect of storage power and energy rating with 60 minute bid**
	Variant of A
	Imbalance calculation: Imbalance in energy calculated every 60 min
	(Remaining as base case)
C	**Effect of bid intervals**
	Deviation calculation: Imbalance in energy calculated every 15, 30 and 60 min.
	(Remaining as base case)
D	**Effect of different standard deviation in production forecast error**
	Production forecast error standard deviation: 2%, 5%, 10%, 15%, 25% and 30%
	(Remaining as base case)
E	**Effect of maximum ramp rate of storage power flow**
	Limitation in rate of change in storage power flow (maximum % change in power flow per seconds): 100, 1, 0.5, 0.4, 0.3, 0.2
	(Remaining as base case)
F	**Effect of time used for storage power flow reversal**
	Dead-time associated with each storage power flow reversal (seconds): 300, 240, 120, 60, 0
	(Remaining as base case)
G	**Effect of time used for storage power flow reversal (average control strategy)**
	Variant of case F:
	Control strategy: Constant with recalculated set-point (strategy 2 in see section 2.4)
	Dead-time associated with each storage power flow reversal (seconds): 300, 240, 120, 60, 0
	(Remaining as base case)
H	**Effect of control strategy**
	Control strategies: Strategy 1, 2, 3, 4 and 5 (see section 2.4)
	(Remaining as base case)

4. Results
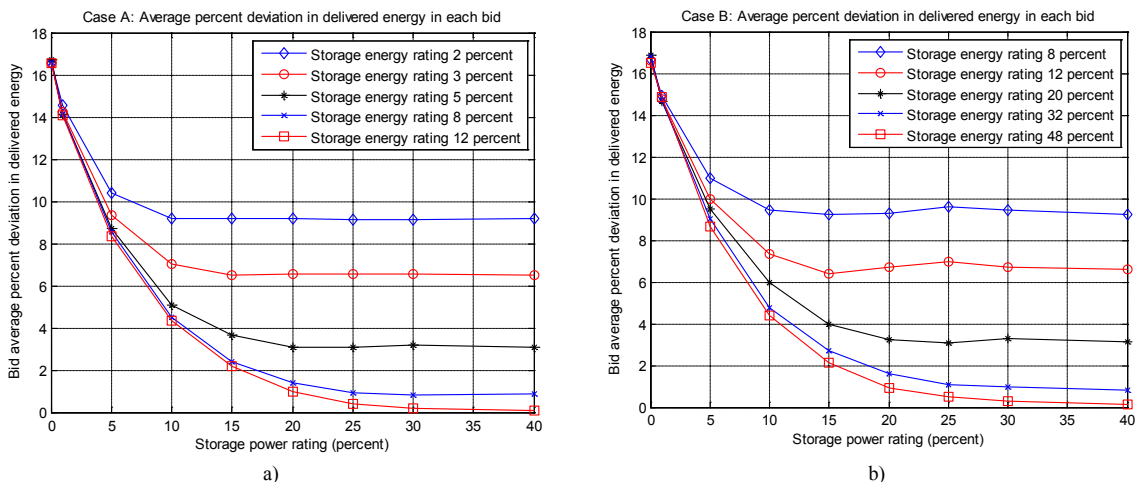
Figure 2. The variation in imbalance is shown as a function of storage capacity for different energy rating scenarios. a) Bid length equal to 15 minutes. b) Bid length equal to 60 minute and storage capacities four times larger.

Figure 2 shows the results of case A and B, where yearly energy imbalance is shown for different energy storage sizes and for different bid lengths. The results show that the optimal dimensioning of the power and energy capacities is correlated, i.e. increasing just one of the parameters does not necessarily cause a performance increase. Additionally, the length of the bid has a large impact on the needed energy capacity.

To limit the number of simulation cases, the remaining simulations uses a forecast error of 10% and the energy rating was chosen to 8%. Depending on the power rating, 1% yearly deviation can then be achieved.
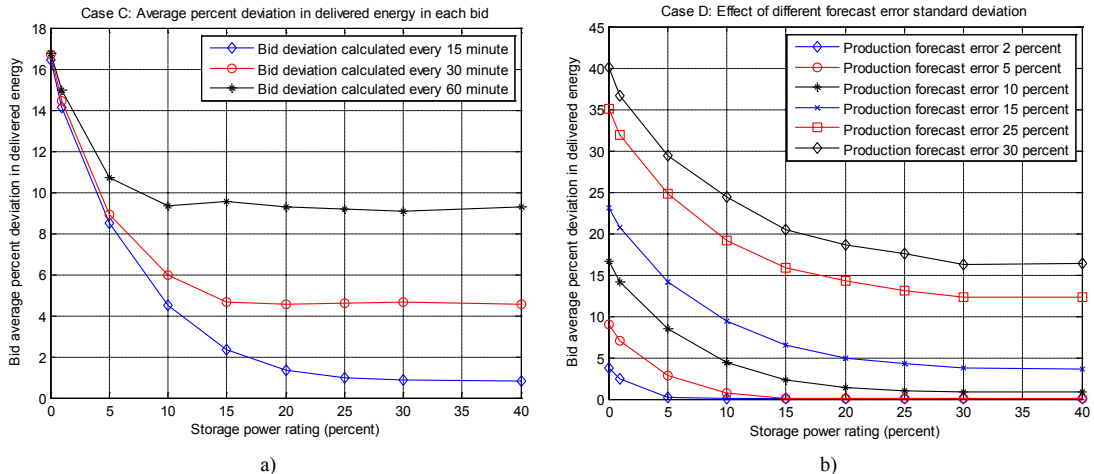

Figure 3. Two external factors are varied to show impact on yearly imbalance. a) Bid length is varied between 15, 30 and 60 minutes. b) The production forecast error is varied between 2-30%.

Figure 3 shows the results of case C and D. As seen in Figure 3a, smaller bid lengths result in smaller imbalances. This would be an advantage for both the producer and the grid operator. The producer suffers fewer penalties and the operator could consider the market bids to be more dependable and fewer reserves are needed. This results in decreased reserve requirements and, consequently, smaller system cost. Figure 3b shows that with close to perfect forecast and with a market structure that only penalizes energy imbalances over the bid period

there would be little incentive to firm the capacity. Consequently, any improvement in forecasting would be beneficial and a perfect forecast would eliminate the need for energy storage solutions for the given market.

The next steps show the results of including technical constraints. In Figure 4 a maximum ramp rate of the storage unit is enforced. A maximum ramp rate of 100%/sec represents an unhindered case and the theoretical maximum performance that can be achieved. The graph shows that only with very severe ramping limitations of the equipment will this affect the storage's ability to firm the capacity. In Figure 5 a dead-time is introduced after each power reversal. Figure 5a shows that the dead-time has a clear impact on the storage performance. Yet, by choosing a different operating strategy, this negative effect can be almost nullified. In Figure 5a the constant power output strategy was implemented, while Figure 5b shows the increased performance with the recalculated set point strategy.
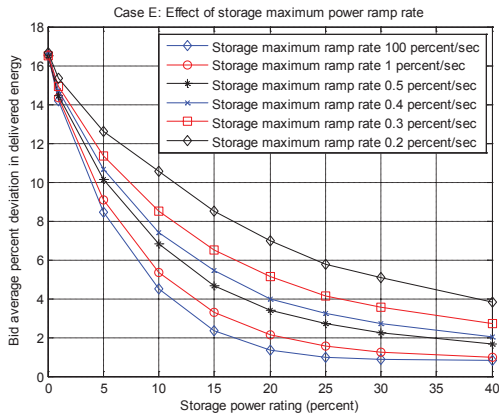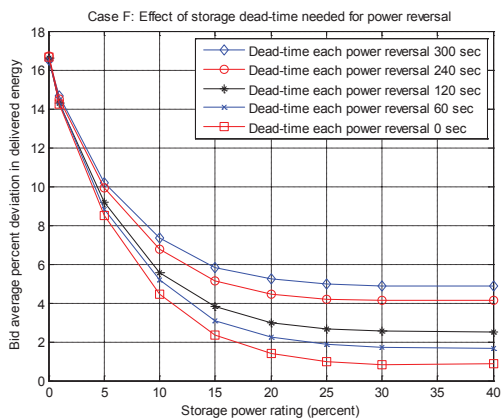

Figure 4. Impact on yearly imbalance by variation in maximum ramp rate of the storage unit.

The last set of results concerns the benchmarking of the different control strategies. Figure 6 shows different results for case H, where the energy capacity is locked to 8% and the bid length is 15 minutes. As seen in Figure 6a, 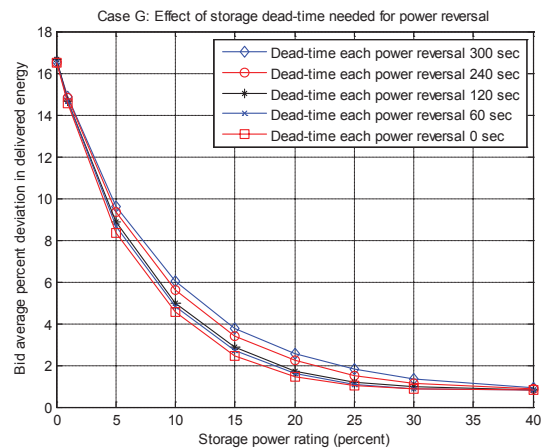the different strategies achieve approximately the same yearly imbalance except for the strategy with a power band and the min-max strategy. The former has the worst performance. In Figure 6b the average number of power flow reversals per hour is shown. Usually, there is a cost related to start and stop actions, hence, a lower value is better. There are clearly two groups present in the results. The first group has a tendency toward 4 reversals per hour and consists of constant power, recalculated set point and power band strategies. The second group tends towards more than 2 reversals per hour and consists of the dead band and min-max strategies.

The final figure, Figure 6c, shows the amount of delivered energy which passes through the energy storage before it is delivered to the grid. This number represents a cost which is dependent on the storage unit efficiency. Regardless of efficiency, a lower value is better. The power band strategy has the lowest values in this case. However, this strategy also had a higher yearly imbalance as shown in Figure 6a. The min-max strategy has a slightly higher energy flow

a)

b)

Figure 5. Impact on yearly imbalance by variation in dead-time after a power reversal. a) Constant power strategy (strategy 1 in section 2.4). b) Constant power with recalculated set-point strategy (strategy 2 in section 2.4).

through the storage, which is according to expectation. The rest of the strategies have approximately the same result. From these three simulations, a slight advantage is observed for the power dead-band strategy. It has a comparable yearly imbalance as the other strategies; yet, it gives fewer power reversals and has a lower power flow through the storage than the min-max strategy. The higher imbalance and lower power flow through storage of the power band strategy is not easily interpretable, and its possible advantage cannot be determined without establishing further benchmarking goals.

5. Conclusion

A storage unit in combination with a large offshore wind farm has been simulated in time domain over the course of one year. The storage unit has been operated with the goal of firming the wind power capacity within each bid period. Different constraints have been introduced to show parameter sensitivity of the storage unit sizing. The constraints were both technical and control oriented. An important prerequisite for the simulation was that the storage would operate in a market where the imbalance between bid and delivered energy is measured and penalized.

Results show that there are several important parameters regarding storage sizing. Storage sizing is very dependent on the production forecast error and market bid length, where lower values are better for both parameters. Furthermore, technical constraints in the shape of ramping rates and power reversal dead time can be countered by choosing an appropriate control strategy. No control strategy gives significant reduction in grid power imbalance than the constant, fixed mode control strategy. Yet, the same reduction in yearly imbalance can be obtained with less energy routed through the storage by applying alternative control strategies. However, using such control strategies to counter the constraints allows for the power flow seen from the grid side to vary approximately with the same amplitude as the variation in wind production. This is the cost of not using a constant power control strategy. It would be up to the grid operator to decide if this behavior is acceptable.

Future work should include alternative forecast error models to improve the investigation of storage sizing. Furthermore, the control strategies should be further studied to identify optimized versions.
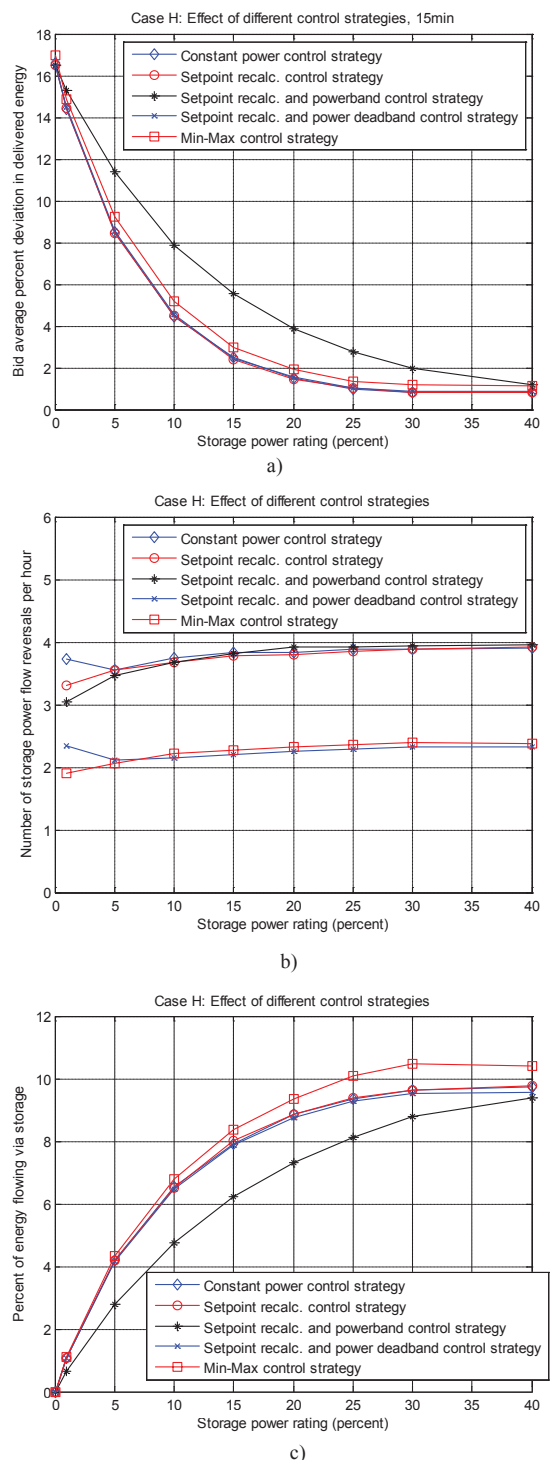
a)

b)

c)

Figure 6. Benchmarking of the different control strategies. a) Variation in yearly imbalance b) Average number of power reversal operation during one hour. Four reversals translate to one reversal per bid period. c) Percent of the energy delivered to the grid which has passed through the storage unit.

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