Optimized Operation and System Design of an Energy Storage Device for Post-feed-in-tariff Sales of Wind Energy at the Spot Market

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Summary

The relevance of energy storages as important flexibility technology for the prospective energy supply system has been discussed in many projects and studies during the last years. In the context of the project “Netzintegrierte Stromspeicher”[1] Fraunhofer UMSICHT has developed a deterministic optimization model for storage commitment, named GOMES – **G**eneric **O**ptimization **M**odel for **E**nergy **S**torage. It has the purpose to compare and evaluate different storage applications both technical and economical. Due to its generic nature GOMES is applicable to different storage technologies as well as different markets. Moreover it possesses the particularity that a simultaneous participation in different markets is feasible. Its modular design allows an easy and fast modelling of new scenarios. GOMES applies a rolling horizon to restrict the perfect foresight to a predetermined timeframe. The optimization determines the most beneficial and economical storage commitment and delivers therefore information about the maximal reachable revenue of the examined storage application. This allows to calculate break-even capital costs and to determine the optimal storage plant design.

In this case study GOMES is used to evaluate the profitability and the systemic effect of a hybrid power plant consisting of a wind farm (older than 20 years → post-feed-in-tariff) and an electric energy storage device. Exemplarily a redox flow battery was applied as electric energy storage. Two cases were examined: in the single-market operation mode the hybrid power plant only sells the generated wind energy at the spot market. In the multi-market operation mode the storage device is additionally allowed to trade at the spot market itself.

In the single-market operation mode the optimal storage design from an economical point of view tends to be very small (storage power of 0.4 MW which equals 2% of the installed wind farm power, capacity of 6 full load hours). This has the consequence that the systemic effect is also very small. Wind energy is only shifted in 6.7% of the hours of the year. The calculated break-even capital costs for the redox-flow battery lie with 2 200 €/kW in the lower range of today’s capital costs for redox flow batteries. The multi-market operation mode has several consequences: the storage device performs more cycles and gets a little higher annual revenue. Nevertheless the break-even capital costs slightly decrease to 2 100 €/kW. This results from the shorter lifetime (17.2 instead of 19.2 years because the maximum numbers of cycles of 10 000 is reached earlier) and the therefore shorter amortization period. Simultaneously even less wind energy is shifted from low load to peak load hours.

To conclude, selling the generated wind energy with the support of a storage device at the spot market could be an interesting alternative for wind farms that are no longer subject to the feed-in-tariff in the near- to midterm future. A single-market operation mode is both more economic for the operator of the hybrid power plant and more advantageous for the system (however on a low level). Nevertheless future studies should compare the here described strategy to other direct market strategies.

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1 Motivation

The relevance of energy storages as important flexibility technology for the prospective energy supply system has been discussed in many projects and studies during the last years [1][2][3]. Possible applications for energy storages are:

- balancing of the fluctuating feed-in of wind or photovoltaic plants,
- provision of control reserve,
- smoothing of the load curve,
- deferral of investments in the transmission and distribution grid or
- balancing between generation and consumption of electricity.

However precise descriptions as well as detailed, temporal high resoluted techno-economic evaluations of the services that can be performed by energy storages are rarely.

2 GOMES

In the context of the project “Netzintegrierte Stromspeicher” Fraunhofer UMSICHT has developed a deterministic optimization model for storage commitment, named GOMES – **G**eneric **O**ptimization **M**odel for **E**nergy **S**torage. It uses mixed integer linear programming and has the purpose to compare and evaluate different storage applications both technical and economical. Due to its generic nature GOMES is – through parameterization – applicable to different storage technologies as well as different markets. Moreover it possesses the particularity that a simultaneous application to different markets is feasible. Its modular design allows an easy and fast modelling of new scenarios. Figure 1 shows the existing modules, e.g. modules for renewable power plants (wind, photovoltaics), modules for different markets (remuneration by fix tariff according to German renewable energy sources (RES) feed-in act, day-ahead spot market, control reserve market) and modules for different types of energy storages (stationary and mobile electric energy storage, thermal energy storage, intelligent household appliances).

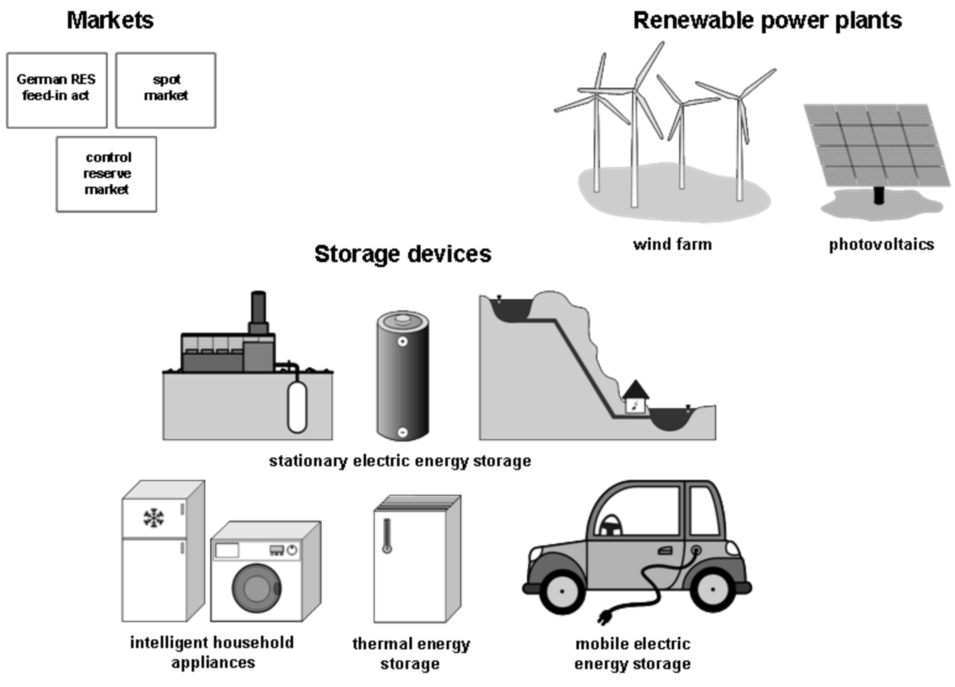


Fig. 1 Modules of GOMES

The optimization determines the most beneficial and economical storage commitment and delivers therefore information about the maximal reachable revenue of the examined storage application. Hence it is possible to calculate break-even capital costs or to compare the fitting of different storage technologies for a specific storage application. By carrying out a variety of optimization runs with different input parameters for the storage design it is possible to determine the optimal storage plant configuration (e.g. ratio of installed charging to discharging power, ratio of installed power to installed storage volume). Besides GOMES delivers characteristic figures on operational regime e.g. number of performed cycles, number of performed start-ups or the average stand-by period [4]. Figure 2 demonstrates exemplarily the functionality of GOMES. A description of the necessary input parameters, time series and the achievable results in detail follows in the case study in chapter 3.

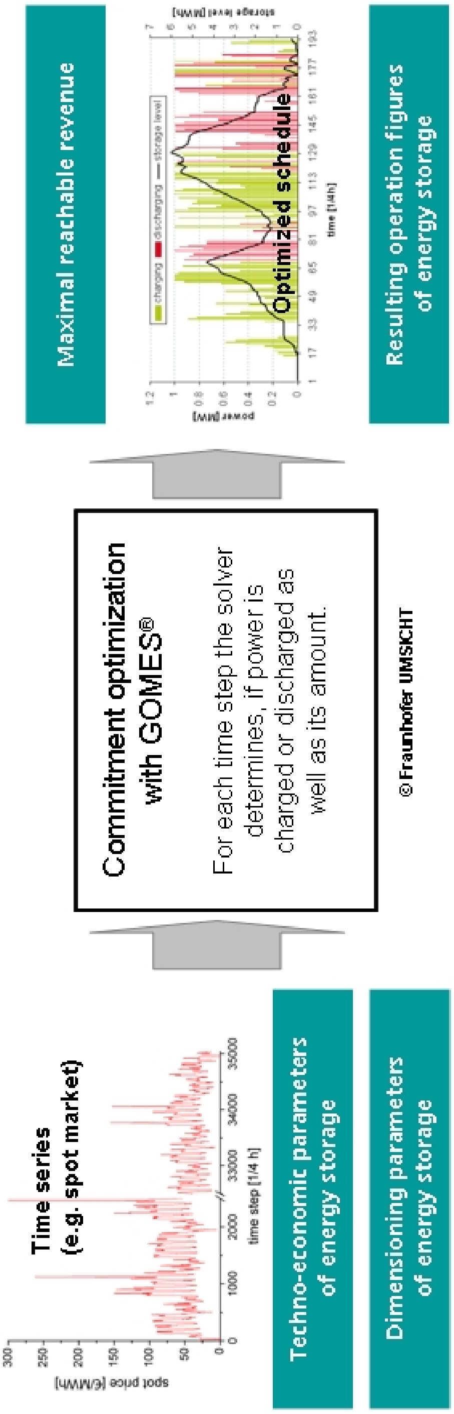


Fig. 2 Functionality of GOMES – input parameters, commitment optimization and achievable results

GOMES applies a rolling horizon to restrict the perfect foresight to a predetermined timeframe. In the discussed scenario runs, the foresight was determined to 24 hours (plus additional 12 hours of preview to prevent total emptying of storage at the end of each day). The applied time series have a resolution of 15 minutes and comprise a whole year. For the evaluation of storage applications it is important to examine high resoluted time series of complete years. The calculation basing on single type days or average values does not capture the complexity of storage processes.
Besides the optimization core, which consists of the model formulation in GAMS and the linear solver CPLEX, GOMES possesses an in- and output structure in Excel-VBA. The results of the optimization runs are stored in a SQL data base. The in- and output structure allows an automated computation of a multitude of scenario variations.

3 Case Study: Post-feed-in-tariff Sales of Wind Energy at the Spot Market

Initial situation

The initial situation is illustrated in figure 3: a stationary electric energy storage is installed close to a wind farm so that an operation as hybrid power plant is possible. The size of the wind farm is determined to 20 MW. The feed-in time series representing the wind farm originate from a wind farm in southern Germany and comprise the years 2007-2009. The hybrid power plant shall sell the wind energy to the day-ahead spot market at the German power exchange EEX. Therefore the spot price time series also derive from the years 2007-2009. The electrical grid is assumed to be a copper plate. This means the power flows are not restricted. Storage technologies that are applicable in combination with a wind farm are redox flow or sodium sulfur batteries. They have a fast response and start-up time and suit well to the determined wind farm size.
The following research questions shall be answered:

- Is it economic to sell the wind power at the day-ahead spot market with the support of an electric energy storage? It is not the goal to compare the selling of wind power at the day-ahead spot market to other direct marketing strategies (e.g. green electricity privilege).
- Which storage size (storage power, storage capacity) is optimal?
- Which are the specific break-even capital costs for the storage device?
- How do the results change if the storage is additionally allowed to trade energy at the spot market independent of the wind farm?

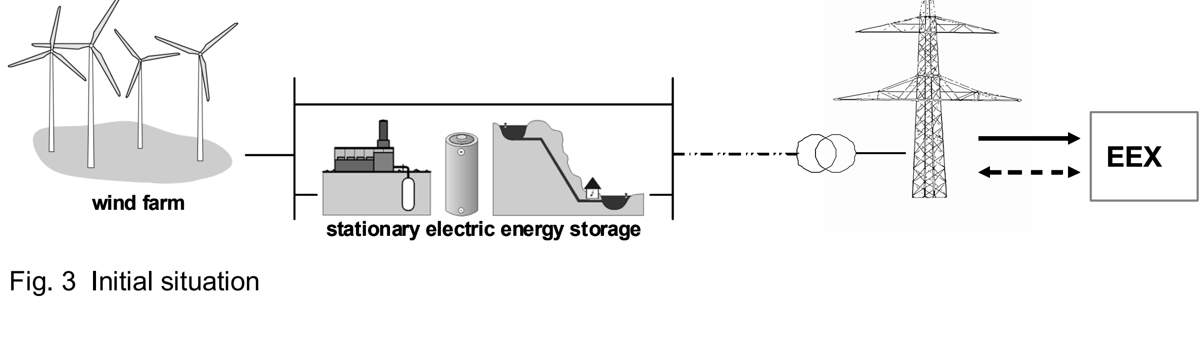
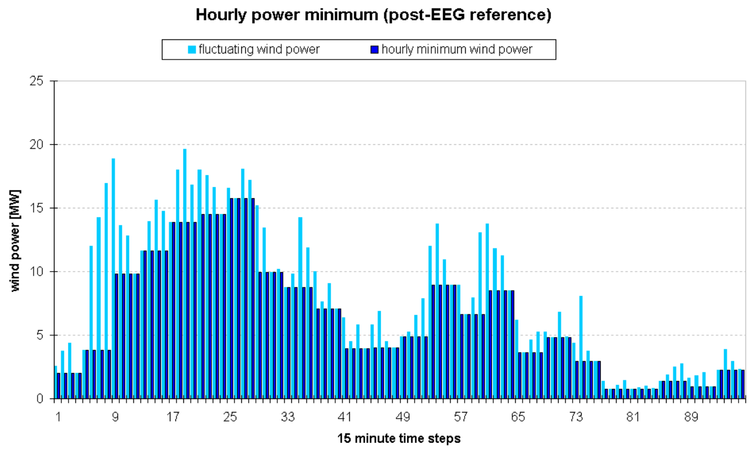
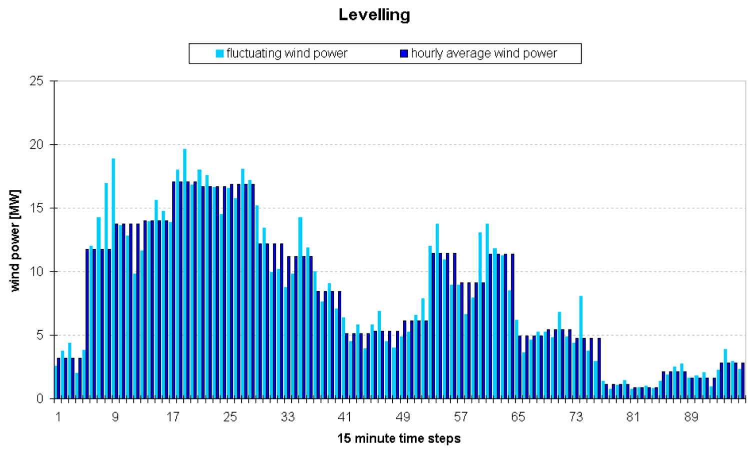


Fig. 3 Initial situation

Storage Services

The first question to be answered is how much wind power can be sold in the reference case. There, the age of the wind farm has to be differentiated. Wind farms younger than 20 years obtain a feed-in priority, independent of the fluctuations and can choose to be remunerated by a fix feed-in tariff. Wind farms older than 20 years have to sell their energy directly to the market. One possible market is the day-ahead spot market at the EEX. The market demands the feed-in of constant hourly power blocks. Therefore the fed-in wind power has to be smoothed. Assuming a perfect prognosis it is possible to sell the minimal occurring power of each hour. The rest of the wind energy has to be discarded. This is depicted in figure 4 (above). With the support of a storage device, it would be possible to sell the average power of each hour instead of the minimum. So smoothing the fluctuating wind power to an hourly average is the first service of the storage. This is illustrated in figure 4 (middle). The second storage service is the shifting of the wind energy from hours with low spot prices to hours with high spot prices (see figure 4 (below)). On the one hand this increases the revenue for the operator of the hybrid power plant. On the other hand it is useful for the electrical grid, because the energy is shifted from low load to peak load hours.





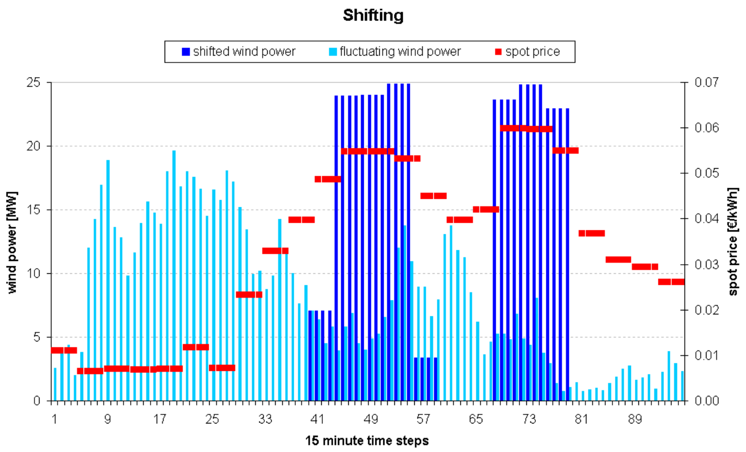


Fig. 4 Feed-in time series for the wind energy (fluctuating feed-in vs. storage controlled feed-in)

Why only Post-feed-in-tariff Sale?

Figure 5 shows the average annual revenue of the hybrid power plant for the years 2007-2009. For the simulation runs a very large (power = 20 MW, capacity = 300 MWh) and ideal storage device was applied. Ideal means a storage that has an efficiency of 100% and no variable costs. This was done to avoid an impact of the chosen storage technology and storage size on the economical result.
The horizontal lines show the three reference revenues:

- the annual revenue if the wind farm would get the initial feed-in tariff according to German RES feed-in act,
- the annual revenue if the wind farm would get the basic feed-in tariff according to German RES feed-in act or
- the annual revenue if the wind farm sells its hourly minimum energy to the spot market (post-feed-in-tariff reference).

The annual revenue of the hybrid power plant selling its energy to the spot market exceeds the reference for the basic feed-in tariff, but does not reach the reference of the initial feed-in tariff. But the latter is the decisive reference because the here examined wind farm would be remunerated with the initial feed-in tariff over the whole funding duration of 20 years (because of the below average wind situation). As long as this wind farm gets the feed-in tariff it is not economic to choose the here described direct marketing strategy; even if the ideal storage would have capital costs of 0 €/kW. In contrast, the annual revenue of the hybrid power plant exceeds the post-feed-in-tariff reference significantly. In the following it is possible to calculate the break-even capital costs for profitability.

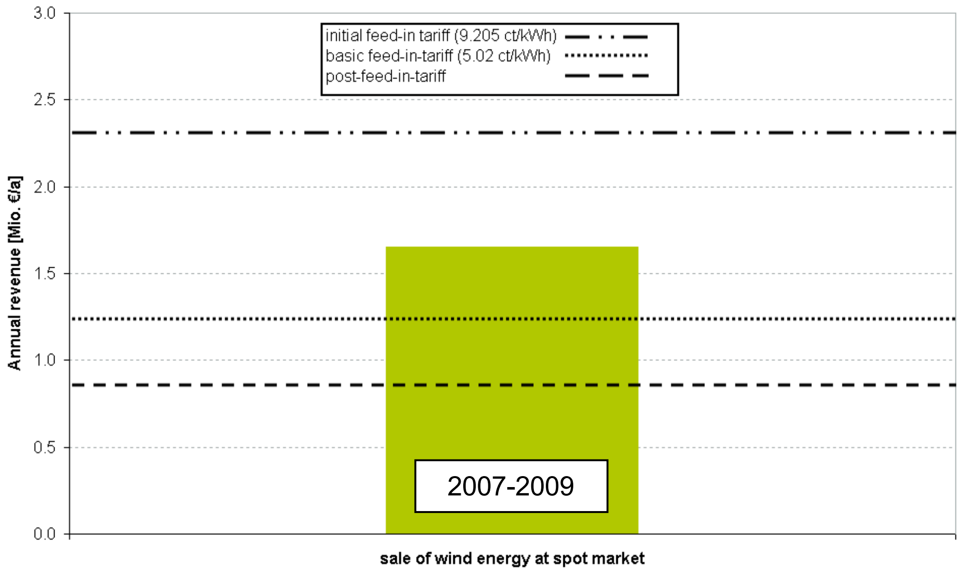


Fig. 5 Comparison of annual revenue of the hybrid power plant and the reference revenues

Evaluation of Optimal Design and Break-even Capital Costs

For the evaluation of the optimal design a multitude of optimization runs with different input parameters concerning the installed storage power and the installed storage capacity[2] was carried out. As storage technology now a redox flow battery was exemplarily applied[3]. The second step of the method was to calculate the specific break-even capital costs. For this purpose a technology specific characteristic number (ratio of capital costs for storage capacity to total capital costs) was used.[4]
It is always important to distinguish the different referencing modes if dealing with specific capital costs of storages. There exist two widely-used referencing modes:

- Total capital costs related to installed power [$€_{total}$/kW] respectively total capital costs related to installed capacity [$€_{total}$/kWh]
- Additive capital costs, divided into capital costs for the storage power [$€_{power}$/kW] and capital costs for the storage capacity [$€_{capacity}$/kWh].[5]

In figure 6 the calculated specific break-even capital costs[6] are plotted against the storage design. The right graphic covers the range from 1 to 5 MW installed storage power, the left graphic comprises the range from 0.1 to 1 MW. The installed storage capacity in both graphics reaches from 1 to 9 full load hours. It can be seen that over a wide range the break-even capital costs increase significantly with decreasing storage power.

[2] Installed capacity = installed power * number of full load hours
[3] Parameterization of the redox flow battery: AC-AC-efficiency of 75%, lower part-load limit of 10%, self-discharge rate of 0.3% per day, variable operating costs of 0.1 €/MWh, variable start-up costs of 1 €/MW
[4] Related to the total capital costs for a redox flow battery, the capacity-related capital costs are assumed to have a share of 16%.
[5] $€_{total} = €_{power}/kW * kW + €_{capacity}/kWh * kWh$
[6] Additive referencing mode. Due to the above mentioned technology specific number the plot basing on the power-related capital costs has the same developing as the capacity-related capital costs (only the absolute values on the z-Axis would vary).

The global maximum can be found in the left graphic at the point 0.4 MW (2% of the installed wind farm power) and 6 full load hours. This correlates with total specific capital costs of 2 200 $€_{total}$/kW. According to [5], today's capital costs for redox flow batteries range between 1 500 and 4 000 €/kW. This means that the here examined direct marketing strategy is at the lower scope of profitability.

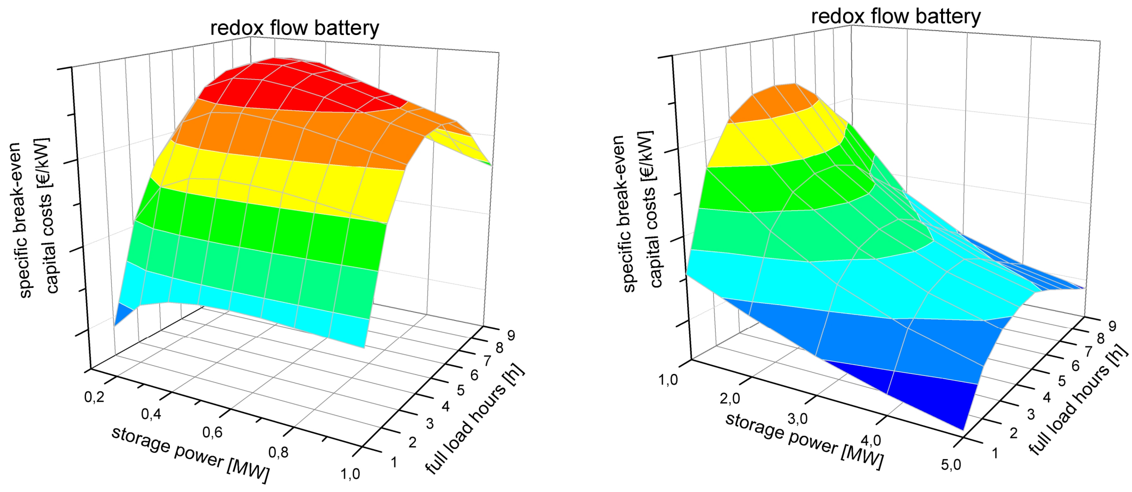


Fig. 6 Specific break-even capital costs for a redox flow battery depending on storage design

There exists a conflict of aims concerning the optimal design of the storage device. From an economical point of view the above mentioned design is optimal. But if one wishes to realize a noteworthy systemic effect (shifting of big amounts of wind energy from low load to peak load hours), an installed storage power of several MW would be needed. For the following analyzes the characteristic number of "share of hours with shifted wind energy" is used. In the above found optimal point wind energy is shifted in 6.7% of all hours.

Changes due to Multi-market Operation Mode

In this paragraph the storage device is allowed – besides its services for the wind farm – to trade at spot market by itself. This has the goal to enable a better utilization of the installed storage power and capacity and therefore to afford a higher revenue.

Assuming the same storage design (0.4 MW; 6 h) – which again is the optimal point – this new strategy has two significant impacts:

- The number of cycles carried out by the redox flow battery increases from 522 to 581 cycles. This goes hand in hand with a slight increase of the annual revenue. Nevertheless the break-even capital costs slightly decrease from 2 200 €/kW to 2 100 €/kW. This results from the shorter lifetime (17.2 instead of 19.2 years because the maximum numbers of cycles of 10 000 is reached earlier) and the therefore shorter amortization period.
- The number of hours with shifted wind energy decreases from 6.7 to 4.6%. This means the systemic effect gets more and more unimportant.

So, it is not useful to operate the redox flow battery simultaneously at different markets (smoothing fluctuations / shifting wind energy as well as trade at the spot market by itself), because the additional revenue of the spot market does not compensate the faster degradation of the battery.

4 Conclusion and Outlook

To conclude, selling the generated wind energy with the support of a storage device at the spot market could be an interesting alternative for wind farms that are no longer subject to the feed-in-tariff in the near- to midterm future. The calculated break-even capital costs for the redox-flow battery lie with 2 200 €/kW in the lower range of today's capital costs for redox flow batteries.

The optimum storage size – from an economical point of view – was found at an installed storage power of 0.4 MW (2% of the installed wind farm power) and an installed storage capacity of 6 full load hours. If one wishes to realize a noteworthy systemic effect (shifting of big amounts of wind energy from low load to peak load hours), an installed storage power of several MW would be needed.

As operation mode the single-market operation mode should be selected. It is both more economic for the operator of the hybrid power plant and more advantageous for the system. However the systemic effect in terms of shifted wind energy from load to peak load hours lies on a low level.

Nevertheless future studies should compare the here described strategy to other direct market strategies (e.g. green electricity privilege).

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