Batteries and pumped-hydro: Pooling for synergies in the frequency response provisioning

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***Abstract*—Battery electric storage systems (BESS) are characterised by their fast ramping, pumped-storage plants (PSP) by their relatively larger storage capacity. In this paper the pooling of PSP (with ternary set) and BESS for the common provision of frequency containment reserve (FCR, primary reserve) is analysed. For this, different joint operation modes have been studied and their power output and energy flows have been simulated on a second-wise resolution. It is shown how common FCR provisioning and volatility reduction in PSP by pooling with BESS is possible. The main benefit of volatility reduction is the lifetime extension of wearing parts in the PSP. It could be shown, that a PSP and BESS aggregate operated in dual mode to provide FCR and volatility reduction at once is more profitable compared to respective individual stand-alone PSP and BESS FCR provisioning.**

Keywords—pumped-storage, hydro power, ternary set, battery, BESS, cycle lifetime, pooling, frequency containment reserve, primary reserve, frequency response

I. Introduction

Jacobsen [1] outlined that there is no technical or economic barrier to transitioning the entire world to 100 % clean and renewable energy with a stable electric grid at low cost. Nevertheless, as already seen today, with an increasing share of fluctuating renewable infeed, the dynamics and complexities in operating the power supply infrastructure increase [2-5].

The rapid growth of wind power and solar photovoltaic drives the need for high-capacity as well as rapid-response energy storage technologies to smoothen intermittent generation (e.g. [6]). Storage can help to limit the need for investments in grid capacity, to reduce operation costs of generation facilities and to increase the reliability of the supply.

One important prerequisite for stable grid operation is the provision of sufficient Frequency Containment Reserve (FCR). Traditionally, FCR is provided mainly by thermal power plants, and here most prominently by coal power plants.

However, in the last couple of years, Battery Electricity Storage Systems (BESS) increasingly provide FCR. E.g. in Germany, BESS with more than 200 MW are actively taking part in the FCR market, which makes up for approximately one third of the entire German market volume.

Also pumped-storage plants (PSP) equipped with ternary sets (three-machine type units), consisting of a motor-generator and two hydraulic machines, such as a separate turbine and a separate pump, can provide FCR capacity if operated in so-called hydraulic short circuit mode.

The principle of this operating mode is based on the idea that only the difference between the constant pump load and the flexible turbine output, both rotating on one common shaft, is exported to the grid. Full regulating capability exists in both the generating and the pumping mode operation, from 0 to 100 per cent of the unit output.

Compared with a PSP, even with ternary sets, BESS can react much faster as a result of the absence of moving parts and the dependency on only the power electronics as well as the cell chemistry. The BESS can fulfil the ramping requirements of FCR provisioning with almost no delay. If the PSP and the BESS are jointly controlled by a single controller, the respective benefits of each technology can be brought in, so that the control aggregate can benefit from maximized ramping functionality of the BESS and high storage capacity of the PSP.

The aim of this paper is to discuss possible modes of cooperation between a ternary set PSP and BESS for their joint provision of FCR. These operation modes are analysed from a techno-economic perspective. Furthermore, their economics are also contrasted with the provision of FCR in a stand-alone BESS.

II. Methodology

A model is conceptualised to mirror the operation of a BESS to deliver FCR in cooperation with a PSP operating with a ternary set under the objective to reduce costs deriving from BESS replacements and the replacement of electro-mechanical components of the PSP. The BESS and PSP's specifics are based on a project conducted by ENGIE in Pfreimd. The model is applied on two exemplary weeks. With selected frequency indicators for the period from 2017-2018 the simulated outcomes have been used in a regression analysis to be applicable to one entire model year. Market trends for the BESS replacement costs, charging costs and FCR tender prices were assessed to apply the model outcomes on a long-term scenario to enable an in-depth observation of the impact of the replacement costs of the BESS and the PSP's wearing parts in an economic analysis which is presented in section "Economic evaluation".

For the outlined long-term scenario in which a BESS is used to provide FCR, two baseline strategies are assessed to compare different operation modes within the PSP-BESS-system.

The *baseline strategies* are selected to present cooperative and noncooperative behaviour of a BESS in a system with a PSP with a ternary set. The strategies are specified as:

- *S1: noncooperative*, the BESS and the PSP with a ternary set are independent stand-alone entities.
- *S2: cooperative*, the BESS and a PSP with ternary set are operated in combination to reduce the impact of the power output volatility on the PSP.

The strategies are subjected to the same BESS and PSP features and the same techno-economic environment. The utilisation of the BESS follows in both strategies the main objective to maximise revenue. In both cases income is generated by providing FCR. The amount of FCR supplied is the same for both strategies. The operation mode for the BESS is in both strategies subjected to a reduction of SOC deviations from an optimum level which is set to 50 %. In the noncooperative strategy this is achieved by utilising liberties left by the regulator called degrees of freedom (DoFs). The DoFs enable the circumvention of instantaneous FCR provision. They are presented in section “technical definition” and implemented in the model to reflect the optimum behaviour of a BESS in the FCR market. The BESS response is consecutively extended from a direct response to the frequency deviations to the behaviour which uses most DoFs to reduce the daily cycles.

In the cooperative strategy S2, the BESS' added value is generated by reducing the power deviations which the PSP is subjected to. In this case the BESS is almost exclusively charged or discharged by the PSP, not having to rely on market prices for the required energy.

The underlying trade-off between the aspects of the utilisation of the BESS in both baseline strategies S1 & S2 is between the reduced operation cost of the PSP and the overall lifetime of the BESS in which FCR is provided and no substitution is needed.

With the aim to address a compromise between the two presented strategies to utilise a BESS for FCR provision, two additional *mixed strategies* are modelled. They combine both baseline strategies, S1 & S2, by separating the overall usable prequalified power and energy of the BESS into two equally sized segments, where each segment is subjected to either the volatility minimisation baseline strategy (S2) or the strategy where the degrees of freedom are fully exploited (S1):

- *S3*: combines S1 and S2. Both baseline strategies react to the SOC deviation of the aggregated energy capacity
- *S4*: combines S1 and S2. The BESS is virtually split into two independent entities, adjusting their behaviour exclusively in consideration of the SOC of their respectively designated energy capacities.

The strategies are simulated for a representative summer week and one representative winter week in 2018.

With selected frequency indicators for the period from 2017-2018 the weekly simulated outcomes are transferred to one year with the help of a regression analysis to form the basis for an economic evaluation. The economic evaluation is based on the strategy specific outcomes including the daily absolute energy flow of the PSP, the daily absolute energy flow of the BESS and the volatility of the PSP power output. To enable a critical evaluation of the assessed economic parameters of the resulting behaviour a concept to determine the economic efficiency LVOS of the strategies is introduced.

III. Preconditions for the supply of FCR

A. FCR power demand

The contract partners decide on a set of a rules which have to be applied to different technologies which supply frequency containment reserve. In Europe ENTSO-E, the European Network of Transmission System Operators for Electricity grids which represents the TSOs, is the main institution to offer guidelines and rules according to this matter.

With a preparation of a general agreement [7] the transmission grid operators specified the framework: FCR is to be continuously supplied according to the determined frequency deviations Δf. The FCR which has to be supplied is set as the entire contracted prequalified FCR, if Δf is larger than the maximum permissible quasi-steady-state security margin Δf_{max} which is set to +200 mHz for positive frequency deviations and −200 mHz for negative deviations. FCR has to be delivered proportionally to the frequency deviations. This relation is described with the relation [9]:

$$\frac{\Delta f}{\Delta f_{max}} P_{pq} = P_{FCR} \tag{1}$$

The share of the frequency deviation of the quasi-steady-state security margin from the nominal frequency with the prequalified FCR power sets the power which has to be continuously provided. FCR has to be consistently and entirely activated within 30 seconds for every quasi-stationary frequency deviation which is larger than ±200 mHz. The same maximum activation velocity applies for smaller frequency deviations [8]:

$$\max(\Delta P_{FCR}) = \frac{P_{pq}}{30s}. \tag{2}$$

B. BESS sizing

The German TSOs (50 Hertz, Amprion, TenneT and TransnetBW) have implemented guidelines [10] which define the sizing of BESS which participate in the FCR market. The guidelines [10] differentiate between to subsections: the operation of batteries with limited energy capacity or batteries in a system without limited energy capacity. The latter would be a battery in connection with a larger consolidated system including stationary operating plants. The sizing regulation offered by the German guidelines for systems with limited energy capacities follows the main rule of a minimum continuous operation time of the BESS for at least 30 minutes (30-min-criteria). This time period has led to discussion since the usual interval for conventional power plants is set to 15 minutes (15-min-criteria) [11]. Without consideration of either of the criteria the TSOs set the minimum ratio of the usable energy E_{BESS} and the prequalified power P_{pq} as [10]:

$$\frac{E_{BESS}}{P_{pq}} > 1 \quad (3)$$

The 15-min-criteria, ensuring additional 15 minutes of positive or negative FCR supply by the providing technical entity with limited energy capacity, reduces the range of the admissible two directional residual energy capacity. The BESS is restricted by its energy to prequalified power ratio as illustrated in Figure 1.

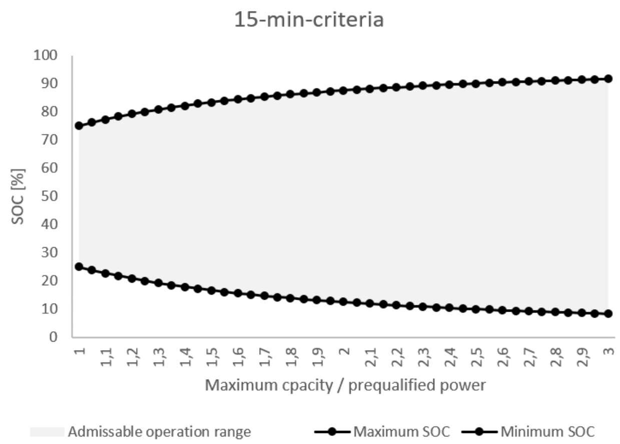

Figure 1: Admissible SOC range according to the 15-minute-criteria

The SOC limits for the BESS which ensure continuous operation according to the 15-min-criteria as shown in Figure 1 are defined by the regulator in [10]:

$$SOC_{max,reg} = \frac{E_{BESS} - 0.25h\, P_{pq}}{E_{BESS}} \quad (4)$$

$$SOC_{min,reg} = \frac{0.25h\, P_{pq}}{E_{BESS}} \quad (5)$$

To get clearance to connect to the grid the FCR provider has to successfully complete the prequalification process of the transmission grid operator [7]. This process determines the prequalified power usable to provide negative or positive FCR considering the determined period.

The prequalified power and the necessary BESS' capacity are further subjected to a categorisation of operational modes. The TSOs define in [10] the frequency interval in which standard operation is assumed as not given, meaning the BESS can differ from its regulatory boundaries, if:

1. Frequency deviations exceed $\pm\, 200\, mHz$
2. Frequency deviations exceed $\pm\, 100\, mHz$ and for a period longer than 5 minutes
3. Frequency deviations exceed $\pm\, 50\, mHz$ for a period longer than 15 minutes.

If the frequency resides within the standard operation interval the BESS has to be designed to stay within the admissible operation range. For any instance where the frequencies standard operation interval is left, the BESS can intercept and leave the admissible operation range [10]. To ensure a continuous PRC delivery for normal frequency deviations in the range of $\pm\, 50\, mHz$ balancing power trades have to be initiated which account for at least 25 % of the prequalified power [10]. To enable simultaneous trading and FCR delivery the power conversion system (PCS) has to be dimensioned with a factor of 1.25 [11]. The responsible TSO has to be informed if the power dedicated for FCR is changed or the degradation of the battery leads to losses [10].

The calculations were conducted for a BESS with 12.5 MW and a capacity of 13 MWh. The prequalified FCR power of the BESS is set to 10 MW and the prequalified power of the PSP is set to 32 MW based on the PSP Reisach in Pfreimd operated by ENGIE. A power band of 2.5 MW is reserved for trading.

IV. BESS & PSP Pooling

A. *Technical definition of the baseline strategies*

a) Noncooperative

The noncooperative strategy utilises the liberties deriving from the technically feasible FCR provision and the regulatory framework to reduce the BESS' daily cycles and increase its lifetime. The BESS and the PSP operate separately and supply the FCR power according to their respectively prequalified power.

The elaboration of the rules follows the given environment of conventional power plants which are not able to follow the frequency deviations with countermeasures completely consistently and instantaneously [11].

The differences between the technologies such as conventional power plants and batteries and their common application to frequency stabilisation lead to technology specific degrees of freedom which can be exploited to assure economic feasibility.

For BESS multiple degrees of freedom are exploitable, which are explained in the following [12]:

Deadband

It is possible to deviate the FCR supply within the band of $\pm\, 10\, mHz$ around the nominal frequency of $50\, Hz$ to support the battery's energy management system (EMS) [7]. A moving deadband and its set values can be negotiated with the transmission system operator [13].

The procedure of utilising the deadband for power management purposes can only be executed if system conformity is ensured. The battery can only charge or discharge if the frequency is in the corresponding negative or positive frequency deviation [12].

The deadband provides a power interval in which the BESS can operate according to its optimisation target function, if system conformity is assumed.

This power output within the deadband is defined as:

$$P_{DB}\, \epsilon \left\{-\frac{10\, mHz}{200\, mHz} P_{pq}, 0, \frac{10\, mHz}{200\, mHz} P_{pq}\right\} \quad (6)$$

The resulting power output of the BESS $P_{FCR,BESS}$ is adjusted in regard to the deadband and the SOC. If the frequency deviation intercepts the deadband interval the BESS utilises the freedom to choose the power output in this interval to minimise its daily cycles. If the SOC deviates from the optimum level at 50 % and the frequency deviation intercepts the deadband, the BESS adjusts its power output to the most beneficial power level.

$$P_{FCR,BESS}(P_{FCR}) = \begin{cases} P_{DB}\ , -10\ mHz \leq\ \Delta f \leq\ 10\ mHz \\ P_{FCR},\ for\ else \end{cases} \tag{7}$$

Overfulfilment

With the utilisation of the degree of freedom deriving from overfulfilment a BESS operator can deviate from the original power curve up to 20%. An under-fulfilment is not permitted [12].

Overfulfilment is only applied outside of the deadband interval. The overfulfilment parameter $\phi(SOC)$ is either 1 or 1.2 according to the SOC. For a power demand parallel to the BESS' preferred power direction the parameter is 1.2.

$$P_{FCR,BESS}(P_{FCR}) = P_{FCR}\phi(SOC) \tag{8}$$

Gradient

The prequalified primary control power has to be supplied proportionally to the system frequency deviations within a 30 second delay [14,19]. The provision gradient ΔP_{FCR} is also subjected to the requirements of the appointed TSO and therefore needs to be parametrisable [12]. The gradient can be increased to improve SOC control [14]. The most beneficial power gradient is subjected to the resulting deviation ΔSOC from the optimum $SOC_{50\%}$. The power output is either set to the admissible maximum if it is beneficiary to SOC of the BESS or to the admissible minimum if the contrary is the case.

$$P_{FCR,BESS}(P_{FCR}) = \begin{cases} \max(P_{FCR})\ ,\ \frac{\Delta f}{\Delta SOC} < 0 \\ min(P_{FCR}),\ \frac{\Delta f}{\Delta SOC} > 0 \end{cases} \tag{9}$$

Delay

The delay is introduced to consider the response time of conventional power plants [11].

The Union for the Coordination of Transmission of Electricity (UCTE) sets the admissible response time to reach 50% of the prequalified FCR power to a maximum of 15s [15]. Furthermore, the activation of FCR deployment should start within a few seconds [15]. For entities which can provide the demanded power faster, a degree of freedom arises.

This additional response time is continuously considered at each time step resulting in a further broadening of the possible operation limits.

b) Cooperative

The cooperative strategy's main objective next to adding revenue by increasing the prequalifiable FCR power is the decrease of the power output volatility of the PSP. The shift of the objective considered for the noncooperative strategy leads to the neglection of the DoFs for the BESS in this strategy. The PSP and the BESS are operated as a combined system.

The power distribution between the entities is depending on the allocation parameter $\lambda(t)$. The allocation parameter assigns a fraction of the gradient $\Delta P_{FCR}(t)$ which has to be supplied by the respective entity and is given with:

$$\lambda(SOC, P_{FCR}) = \rho_{load}(SOC)\frac{z\beta(P_{FCR,BESS})}{\Delta P_{FCR}} \tag{10}$$

The BESS is assigned a fraction of the demanded FCR power gradient depending on its state of charge, the power output it already generates and the residual power capacity. The residual power capacity $\beta(P_{FCR})$ is the power the BESS can deliver considering the power it already supplies. Figure 2 visualises this concept.

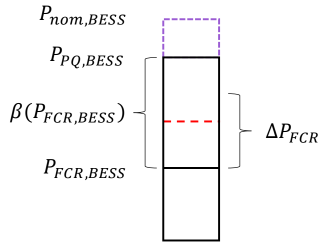

Figure 2: Concept of residual power capacity

The impact factor z reduces the residual power capacity and is experimentally set to achieve a feasible daily discharge cycle amount.

$$\beta(P_{FCR}) = \gamma(P_{FCR})P_{pq,BAT} - P_{FCR,BESS} \tag{11}$$

$\beta(P_{FCR})$ can range between 0 and $2P_{pq,BESS}$. The parameter $\gamma(P_{FCR})$ reflects changes of direction of the demanded power gradient ΔP_{FCR}.

$$\gamma(P_{FCR}) = \begin{cases} 1\ ,\ \Delta P_{FCR} \geq 0 \\ -1,\ \Delta P_{FCR} < 0 \end{cases} \tag{12}$$

The alternating residual power capacity reserve parameter $\rho_{load}(SOC)$ sets the fraction of the residual power capacity $\beta(P_{FCR})$ which is reserved to absorb power demand gradients. The parameter is subjected to the prevailing SOC and the maximum SOC_{max} of the BESS and alternates between an interval between 0 % to 25% for gradients which are not beneficiary for the optimum SOC retention and between 75% and 100% if the gradient is beneficiary for the optimum SOC retention. For positive power demand gradients ΔP_{FCR} the resulting residual power capacity reserve parameter increases the power fraction delivered by the BESS if the SOC deviation from the optimum $SOC_{50\%}$ is positive.

$$\rho_{load}(SOC) = \begin{cases} \alpha\frac{SOC}{SOC_{max}},\ \Delta SOC \leq 0 \\ 1-\alpha(1-\frac{SOC}{SOC_{max}}),\ \ \Delta SOC > 0 \end{cases} \tag{13}$$

For negative power demand gradients, the residual power capacity reserve parameter amounts to:

$$\rho_{load}(SOC) = \begin{cases} 1-\alpha\frac{SOC}{SOC_{max}},\ \Delta SOC \leq 0 \\ \alpha(1-\frac{SOC}{SOC_{max}}),\ \ \Delta SOC > 0 \end{cases} \tag{14}$$

The charging factor α can be varied to increase or decrease the amount of the power demand gradient which is absorbed by the BESS. This parameter has been experimentally adjusted to ensure feasibility. Figure 3 visualises $\rho_{load}(SOC)$ for $\alpha = 0.5$.

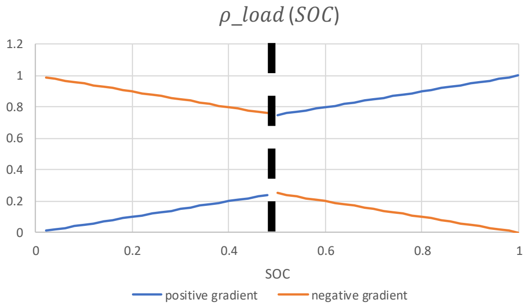

Figure 3: $\rho_{load}(SOC)$ *for* $\alpha = 0.5$

B. *Operation of the cooperation strategies*

a) Baseline noncooperative strategy (S1)

This strategy consists of a BESS using all admissible DoFs and a PSP supplying FCR without any interference.

The daily absolute energy flow is calculated for the utilisation of all DoFs for one summer week and one week in February 2018. The power output of the PSP was calculated without taking any effects of a BESS into account.

To show the impact of the DoFs the energy profiles for 02.02.2018 are shown in Figure 2:

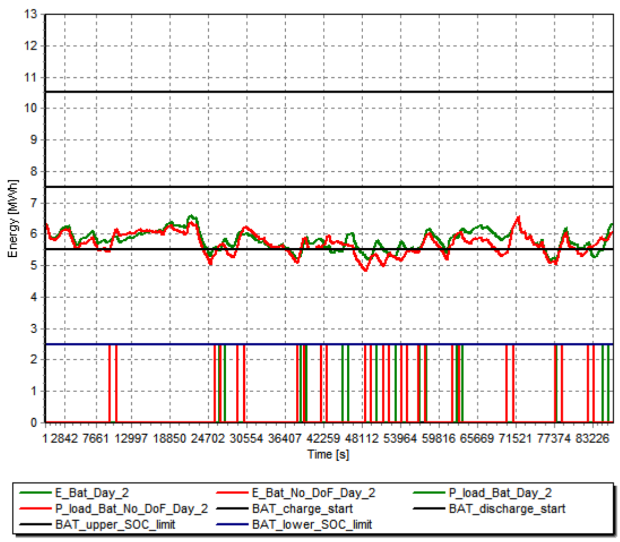

Figure 4: Energy profile of a stand-alone BESS (S1) over the period of one day

The green profile shows the energy levels of the BESS which uses all admissible DoFs, the red profile shows the energy levels for a BESS which uses no DoFs. The columns at the bottom of the graphic show the recharging measures. On this particular day, there were 9 recharging measures for the BESS with the operation mode using DoFs (case 1) and 13 recharging measures for the operation mode using none (case 2).

The absolute energy flow without charging measures is slightly lower for case 1 than for case 2 due to the utilisation of the DoFs.

The charging measures accumulate to absolute energy amounts of 5.6 MWh and 8.1 MWh on this particular day and show the impact on the techno-economic improvement capabilities of the utilisation of the DoFs.

The reduction of the necessary corrective energy of 30 % could reduce the power trading costs in the same scale.

Considering the EPEX spot index prices for each half hour the charging costs accumulate for case 1 to 203.8 EUR and for case 2 to 341.9 EUR. On this day, the market prices enhanced the cost effect for about 10 % resulting in an overall price relation between the two cases for corrective energy trades of about 40 %. The BESS had to recharge at times with high prices, and this more often in case 2, leading to charging costs 40% higher than in case 1 as opposed to only 30% if the charging costs would be the same at every hour.

The impact of the DoFs is essential for the corrective energy flow which is needed to keep the SOC in the admissible limits.

The number of recharging events clearly exceeds the number of discharging events. This effect can be partially explained with the efficiency increasing the effective energy flow for discharging and decreasing the effective flow for charging events. Furthermore, the average frequency in February was negative. This implies a slight overhead of negative frequency deviations, resulting in a higher power supply of the BESS.

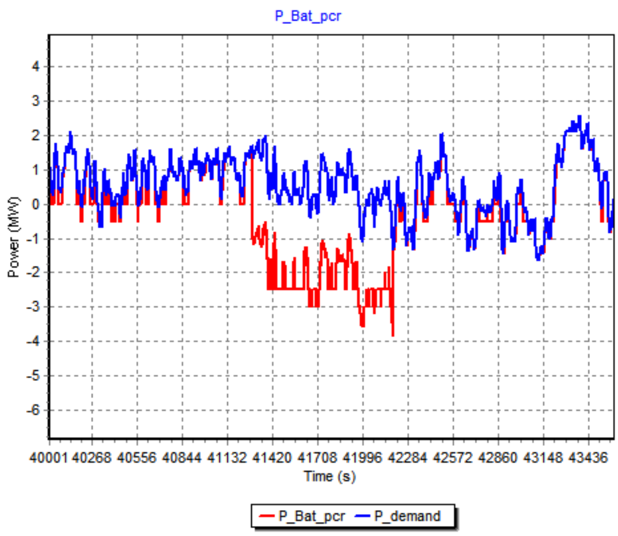

Figure 5: Power profile of a stand-alone BESS over the period of 30 minutes

The power profile of the BESS for the 01.06.2018 over the period of 30 minutes is shown in Figure 5. The power demand depicted in blue is in direct relation to the frequency and determines the power the BESS has to provide. The red profile shows the actual FCR supply by the BESS. The BESS uses the degrees of freedom. The DoF "deadband" is easily observable as the deviation of the red profile settles either on 0.5 MW, 0 MW or -0.5 MW. These are the limits of the deadband according to the regulator in proportion to the frequency for a BESS with 10 MW prequalified FCR.

The larger deviation of the BESS' power profile is the result of a charging event. The BESS adds on its current FCR supply bought power to restore a SOC around 50%.

b) Baseline cooperative strategy (S2)

In this strategy the BESS is used as a support system for the PSP. This strategy enables a reduction of the impact of the changes in the power demand on the PSP's equipment.

With a higher impact of the BESS the power volatility of the PSP is decreasing. The effect of the BESS' impact is shown in Figure 6 for the period of one day.

The assessment of the theoretically possible volatility reduction with a 10 MW BESS on a 32 MW PSP with a ternary set leads to very high volatility reductions but to an economically infeasible amount of daily discharge cycles of the BESS. A variation of the impact effect is achieved by reducing the residual power capacity to absorb power deviations by the BESS with the introduced impact factor z, which would otherwise have to be delivered by the PSP.

The profiles in Figure 6 (light blue line: PSP output; dark blue line BESS SOC) correspond to a 30% constant reserved residual power capacity ($z = 0.3$) for the high impact case and to a 50% constant reserved residual power capacity (z = 0.5) in the extra high impact case over a 30 minute period (orange line: PSP output; red line BESS SOC).

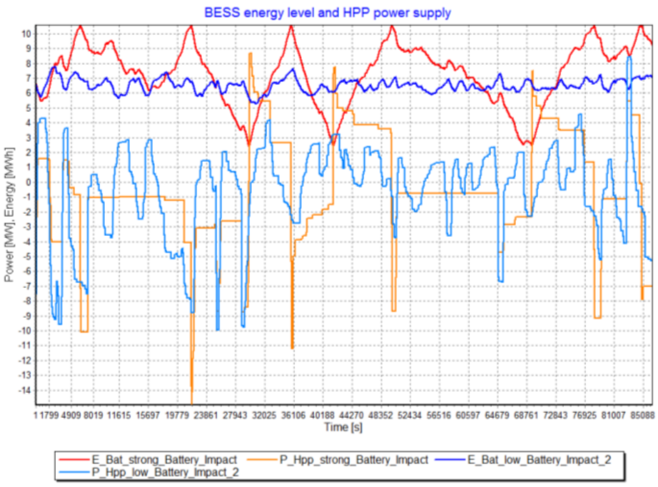

Figure 6: Effects of PSP volatility reduction

Figure 7 depicts the PSP power output volatility reduction in S2 compared to the volatility in S1. The green line visualises the relative frequency of PSP power output changes in S1, the red line for S2 for the high impact case (z = 0.3)

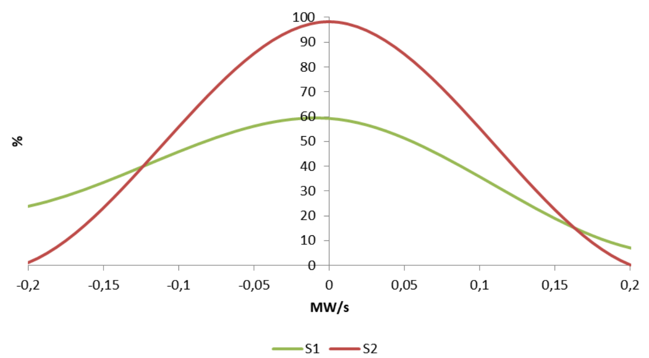

Figure 7: Histogram of PSP power output volatility in S1 and S2 for high impact case with constant z = 0.3

These cases with constant residual power capacity are not affected by the present SOC. With the introduction of a SOC sensitive parameter which only reserves a fraction of the residual power capacity ($\rho_{load}(SOC)$) the daily cycles are reduced and the deviations from the optimum $SOC_{50\%}$ are reduced.

The trade-off between the power output of the BESS and the PSP can be observed in Figure 8 for a BESS setting with an alternating reserved residual power capacity $\rho_{load}(SOC)$ between 0-25% and 75-100%, depending on the present SOC of the BESS, and an impact factor of z = 0.5 as the other constant reserved residual power capacity settings (30 % and 50%) were wearing down the BESS too fast as to be economically feasible.

The black line represents the power demand proportionate to the frequency deviations, the blue profile the BESS response and the red line the power profile of the PSP. It is clearly observable that the PSP's response is slightly smoother in comparison to the power demand. The differences are internalised by the BESS. This operation mode has the side effect that the power supply of the entities can quasi contradict each other. This leads to a higher absolute energy flow of the two entities. The BESS only takes into account its SOC and the amount of power it has to substitute from the PSP. The BESS operation point is not bound to the algebraic sign of the PSP's power supply/intake.

The cooperative baseline strategy could reduce the volatility for about 25% in comparison to a strategy where the PSP supplies FCR independently.

If the BESS' impact factor z was increased to a constant 30% of the residual power capacity $\beta(P_{FCR})$ the impact on the volatility would increase by the factor 25.

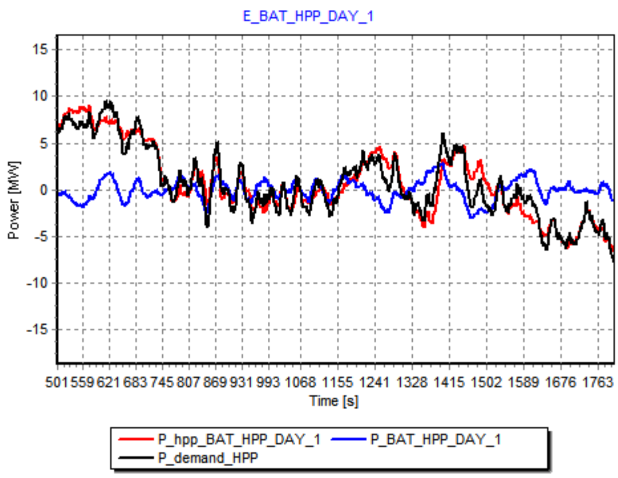

Figure 8: Sample S2 operation over the period of 30 minutes

Since the BESS restores its preferred state of charge exclusively with the PSP the opportunity costs of the PSP are used to determine the charging costs. The volatility smoothing and the connected charging lead to incidents were the power profile of the BESS is positive and the profile of the PSP is negative or vice versa which can be observed in Figure 8. If the balance is positive, the BESS discharges into the PSP and if it is negative the BESS is charged from the PSP. If the BESS discharges into the PSP, it loses the opportunity to sell the given amount to the market. If the BESS is charged from the

PSP, the PSP would have had to buy this amount on the market. The traded energy volumes between the two entities to recharge the BESS account in average for 0.21 MWh per day in June and in 1.78 MWh per day in February. Resulting in average daily charging costs of 11.5 EUR in summer and 79.6 EUR in this particular winter week reducing the charging costs with the factor 3 in comparison to baseline strategy S1.

a) Mixed strategies (S3 & S4)

To address a compromise between the baseline strategies to utilise a BESS for FCR provision two additional mixed strategies are modelled. They combine both baseline single strategies by separating the overall usable prequalified power and energy of the BESS into two equally sized segments, where each segment is subjected to either the volatility minimisation baseline strategy (S2) or the strategy where the degrees of freedom are fully exploited (S1). The difference of the strategies is, how the SOC deviation minimisation is addressed. The mixed strategy *S4 "separated compound strategy"* virtually separates the BESS in two independently acting parts each reacting to their own SOC. In the mixed strategy *S3 "combined compound strategy"* both baseline strategy compounds react to the SOC of the entire energy capacity. The stand-alone compound has to follow the frequency deviation proportionally and is therefore forced to supply FCR in a direction which might be strongly disadvantageous to its SOC even after the DoFs are applied. This leads to necessary market transactions for S4 to restore a favourable SOC. With S3 the volatility smoothing compound can react with great effect on the retention of the $SOC_{50\%}$. The volatility smoothing compounds' power output continuously annihilates the effect of the stand-alone compound's power output and uses the residual power amount to smoothen the PSP's gradient. The stand-alone strategy therefore weakens the possible impact of the BESS on the PSP, increasing the absolute energy flow of the PSP since less gradient fractions can be substituted. Due to the continuous minimisation of SOC deviations, the combined compound's (S3) absolute energy flows are higher than the separated compounds (S4) daily absolute energy flows. For strategy S3, the deviations of the SOC of the BESS as a whole are lower than the deviations from the aggregated SOC of the strategy S4. A trade-off between the absolute energy flows of PSP & BESS as well as the volatility reduction and the reduction of the deviation from the optimum $SOC_{50\%}$ is therefore observable. The recharging costs for S3 are slightly lower than the recharging costs for S4.

V. Benefits of Pooling

The profitability of the project is essentially depending on:

- Capital expenditures,
- Frequency of the replacement costs of the BESS over the project lifetime,
- Charging costs,
- Other operational expenditures,
- Benefits generated by the extension of the lifetime of the wearing parts of the PSP,
- Income from weekly FCR tenders and
- Interest rate used as the discount factor.

For the comparison a discount factor of 12 % is used [16].

To assess the profitability of an extension investment of a ternary set PSP with an added BESS, the project lifetime period was set to 60 years. This long consideration period has been chosen to allow for consideration of lifetime extension effects. To enable an analysis of this project the calculated values for the two simulated weeks were applied to the project's lifetime.

The exemplary winter and summer weeks were used for the simulation. To fit the project lifetime, the daily charging costs (including interference costs between the entities) were repeated weekly for each season and incorporated in the economic evaluation. A price degradation was applied on the charging costs. The daily energy flow of the PSP and the BESS were repeated equally frequent for a whole year but were fitted to each month's frequency indicators. A correlation between the frequency's standard deviation, the absolute average frequency gradient and the absolute average of the frequency with the absolute energy flows of the entities and the volatility was assumed. The monthly values for the indicators were assessed and the energy flows and volatilities according to the indicators adjusted for each month. The resulting absolute energy flows of the BESS resulting from the regression are depicted in Figure 9.

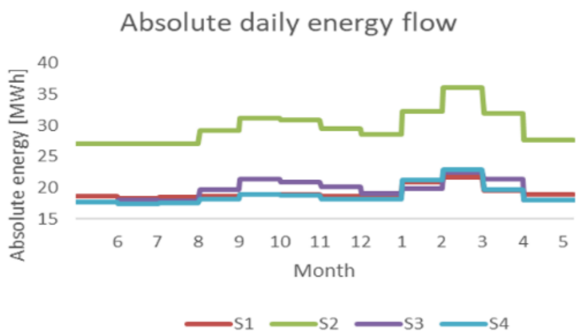

Figure 9: Absolute daily energy flows per month for the cooperation strategies S1-4

Based on the absolute energy flows, the lifetime of the BESS could be assessed and thus necessary BESS replacement investments could be triggered.

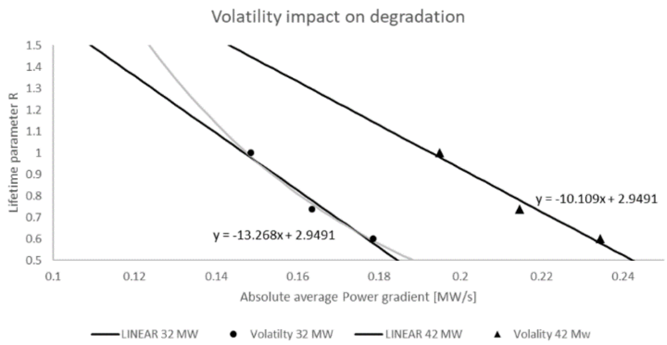

Figure 10: Volatility impact on degradation of the electro-mechanical parts of a PSP (source: own assessment based on [17])

In literature no sources for the direct effects of power output volatility reduction on the lifetime of electro-mechanical equipment of PSPs could be found. However, VGB Powertech conducted a large study assessing the impacts of modified operational conditions on the technical lifetime of more than 100 mechanical components of PSPs [17]. The findings of this study have been used as a proxy to determine the effects of volatility reduction on the technical lifetime.

For this, the component lifetime assured by optimum utilization is adapted to the varying circumstances with the degradation factor R as a function of the absolute average power output gradient. The found relation is depicted in Figure 10.

The lifetime of the electro-mechanical equipment (the cost of which accounts for approx. 520 kEUR) for regular ternary set PSP operation is considered with 40 years. Regular operation is considered for the average absolute power gradient of 0.149 MW/s (for only PSP) and of 0.195 (for PSP together with BESS) based on absolute average second-wise frequency gradient of the period June 2017 until July 2018 of 0.93 mHz/s. Operation strategies which bring down the average absolute power gradient can thus extend the lifetime up to 60 years, which represents the calendar lifetime, after which the equipment has to be replaced anyways.

The average of the power volatility in each strategy was used with the relation depicted in to calculate the lifetime of the wearing parts.

As current FCR prices 2,000 EUR/MW/week is retained. With ongoing measures to stabilize the grid and the still growing number of participants in the FCR market it is very likely that the power price remains adjusting downwards [18]. This of course could be contradicted by an increasing growth rate of the share of renewables for electricity generation. The compound annual growth rate of the FCR price over the observed last 5.3 years is around -8% [19] and is assumed to progress to reach half the price level of today over the next 30 years, after which it is considered to remain stable.

The nominal volume weighted average EPEX spot market prices (approx. 45 EUR/MWh) relevant for re- and discharging show a slight downward shift. The compound average growth rate for the day ahead market prices over a 14 years period is -1.05% [20]. The price level is again assumed to progress to reach half its level in 30 years, after which it is considered to remain stable.

The current costs for a lithium-ion BESS incl. PCS is considered with 480 EUR/kW at an autonomy of 1.05 hours [16]. The capital costs for the different lithium-ion battery chemistries are estimated to drop between 50% and 70% [21]. The compound average growth rate of the capital costs over the last five years was -8% [16]. This annual rate was used as a prognosis for the second year of the project's lifetime and was annually reduced to reach 50 % of the today's cost level in 30 years, after which the cost level is considered to remain stable.

A. Cost Comparison

The BESS replacement costs are clearly dominating the total project's costs. The BESS has to be replaced equally often for the strategies S1, S3 and S4. For S2, the BESS has to be replaced 6 times (approx. 7.9 MEUR) over the course of 60 years against 4 times (approx. 7.0 MEUR) for the other strategies. For the strategy S2 the replacement costs take the highest share compared to the other strategies at 92%. The baseline strategy S2 "volatility smoothing" has also the lowest share in charging costs.

The discounted charging costs over the full project lifetime for each strategy amounts to 499.9 kEUR for S1, 124.2 kEUR for S2, 346.3 kEUR for S3 and 342.2 kEUR for S4.

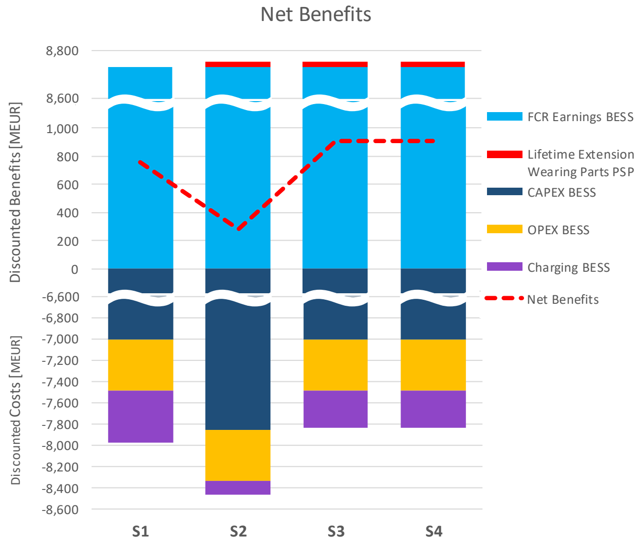

Figure 11: Net benefit comparison

B. Benefit Comparison

The maximum PSP wearing parts' lifetime of 60 years was achieved by all strategies except for S1. The average lifetime of the wearing parts of 40 years was improved with S2 to 174%, by S3 to 153% and by S4 to 154%. For strategy S1 a decrease of the lifetime would amount down to 84 %. The discounted benefit of the wearing part lifetime extension by introducing a BESS into a system with a PSP is therefore 10.7 kEUR for S2-3.

However, the largest benefit of the project for all strategies is the additional FCR earnings due to the increase of the prequalified power from 32 MW to 42 MW, which accounts for approx. 8.7 MEUR. Figure 11 visualises the total discounted costs and benefits.

C. Project Profitability Comparison

All strategies show positive net present values (see Figure 11 curve "Net Benefits") for the project's lifetime. The most profitable strategy is S4 with an NPV of 909.8 kEUR closely followed by S3 (905.8 kEUR). The least profitable strategy is S2 with an NPV of 276.9 kEUR. The baseline strategy "stand-alone" (S1) has an NPV of 757.3 kEUR without any benefit generated by extending the lifetime of electro-mechanical parts of the PSP.

Figure 12 shows the discounted costs and benefits for S1 for each year for a third of the projects lifetime. The first time the project is breaking even is in year 10. With the next capital expenditures to replace the old BESS system after its calendar lifetime of 12.5 years, the project is in deficit for a short period. After year 14, the replacement costs do not bring the balance into negative values again.

Since the recharging costs for S2 are the lowest, the break-even point for this strategy would have been approached the fastest, if the energy consumption was not making an early replacement necessary. The disadvantage of S2 is the high amount of annual discharging cycles reducing the lifetime to 9.3 years. It takes until year 16 to regain profitability after the replacement in which period the other strategies were already making profit. The annual balances are shown in Figure 13.

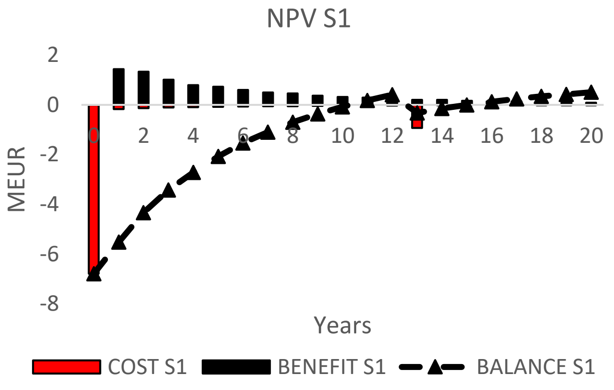

Figure 12: NPV progression of S1 over the period of 20 year

The strategies S3 and S4 are plotted together for legibility. Both strategies gain profitability in year 9 with S4 reaching the break-even point slightly faster, due to lower recharging costs.

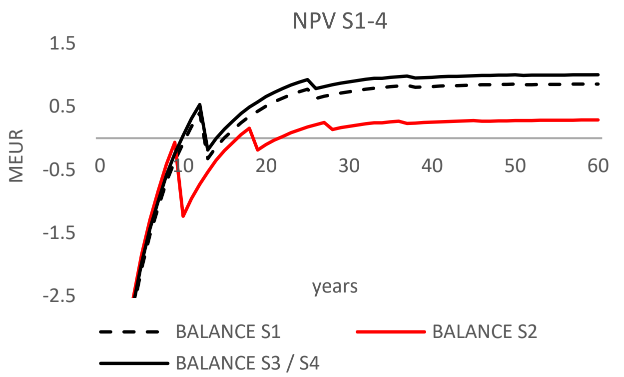

Figure 13: NPV progression over a period of 60 years for strategies S1-4

The internal rate of return (IRR) for S1 is 14.5%, for S2 13.1%, 15.1% for S3 and S4. If there are alternative investments which yield higher rates than the IRR of each strategy, the alternative should be chosen.

D. *Levelised Value of Storage*

The profitability assessed with the NPV takes the provided storage energy into account only to a certain extent. To assess how efficient the stored energy of the PSP and BESS combined were exploited the Levelised Value of Storage (LVOS) is used. The LVOS is calculated by dividing the NPV of each strategy by the discounted absolute energy flow of both FCR providing entities as shown in eq. 15. The analysis with the LVOS regards the two entities as one system and adds all values of the model PSP and the BESS. The model PSP has only costs generated by the wearing parts and a very high income due to the prequalified power for the FCR market. The values of the LVOS of the system are therefore only acceptable to compare the efficiency of the strategies.

$$LVOS = \frac{NPV_{SYS}}{\sum_{n=1}^{N} E_{abs,SYS}\,(1+r)^{-n}} \tag{15}$$

Figure 14 shows the accumulated absolute energy flows over the period of one year.

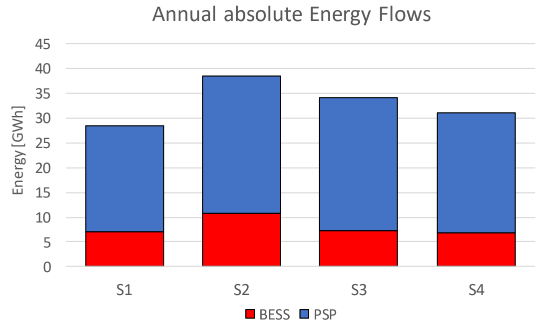

Figure 14: Annual absolute energy flows

The absolute energy flow for the strategy S1, where the PSP and the BESS function as separate entities has the lowest absolute system energy flow. There are no instances, where the supplied power of the entities contradict each other. The other strategies which have at least a partial volatility smoothing compound are subjected to higher absolute energy flows due to the independence of the BESS from the frequency deviation proportionality. With the degree of impact of the volatility smoothing compound of the strategies, the absolute energy flow decreases. The daily energy flow of the BESS in Strategy S1 accounts for 18.6 MWh, in S2 for 27.5 MWh, in S3 for 19.5 MWh and in S4 for 17.5 MWh. The daily energy flow of the PSP in Strategy S1 amounts to 58.7 MWh, for S2 to 75.8 MWh, for S3 to 73.9 and for S4 to 66.2 MWh. With the discounted income generated by a PSP with a prequalified power of 32 MW and a BESS with a prequalified power of 10 MW, the capital expenditures for electro-mechanical parts, the operational costs and the charging costs over the lifetime, the LVOS for each strategy amounts to: 90.27 EUR/MWh for S1, 65.18 EUR/MWh for S2, 75.66 EUR/MWh for S3 and 83.19 EUR/MWh for S4. If the overall absolute energy was provided today, it would thus generate a benefit of 90.27 EUR/MWh for the stand-alone case (S1) with a highly profitable model PSP. The calculation shows that the energy is utilised in the most efficient way in the stand-alone strategy S1 followed by S4 and S3 leaving the baseline strategy S2 still as the least efficient.

VI. Conclusion

This analysis compared different approaches for the provision of FCR: BESS standalone and BESS pooled with a ternary set PSP. It can be concluded that with the given market environment FCR provision with the utilisation of a lithium-ion BESS in stand-alone mode is profitable.

Furthermore, it has been shown, that BESS and PSP can be operated in a joint mode, where the aggregate can provide the overall prequalified FCR – as in stand-alone mode by BESS and PSP separately – and additionally can reduce the volatility in the PSP. The main benefit arising from the volatility reduction is the lifetime extension of wearing parts in the PSP.

A. *Volatility reduction*

Depending on the level of volatility reduction in the PSP, the BESS has to perform a certain number of daily cycles. For this, at a given time, the BESS reaches its end of life and has to be replaced. The larger the targeted volatility reduction, the more frequent the BESS has to be replaced. It has been found, that smaller levels of volatility reduction are sufficient for wearing parts lifetime extension up to 60 years (compared to 34 years if operated in stand-alone FCR provisioning mode), when they have to be replaced anyways.

The most profitable mode of joint operation is the Strategy S4 “Separate Compound”, in which the BESS virtually is separated into two BESS: one only working in volatility reduction mode, and the other one in the provision of FCR, as if it was a standalone BESS. In this operation mode, the volatility reduction is lower than in the pure “volatility reduction mode” S2. However, it is sufficient to extend the wearing parts’ lifetime up to their calendar lifetime, when they have to be replaced anyways. Also, due to the relatively lower level of volatility reduction, the BESS cycling is less extensive and comparable to the standalone strategy S1. As a result, the costs for S1 and S4 are almost the same, but the benefits of S4 outweigh those of S1 due to the volatility reduction, though only to a small extent. Generally speaking, the optimum for the BESS energy utilisation is given when the calendar lifetime and the cyclic lifetime are almost the same.

B. Levelised Value of Storage

The different operation modes show different quantities of overall energy flows of the BESS and the PSP, which are needed for the provision of FCR, for balance the SOC of the BESS and to reduce the volatility of the PSP’s production levels. S1 has the lowest overall energy flows, followed by S4 and S3. S2 has the largest overall energy flows.

The Levelised Value of Storage (LVOS) is a measure of the techno-economic efficiency of the storage system which puts the economic net benefits into relation to the (therefore needed) overall energy flows. When comparing the LVOS, it can be seen, that S1 shows the highest value, followed by S4 and S3, S2, having the lowest. Thus, compared to the order of NPVs/IRRs, S1 is here ranked first, which can be explained by its lower level of overall energy flows.

Generally speaking, existing or new build pumped hydro schemes provide the potential for being extended by container-based BESS as the techno-organisational infrastructures can be shared. Apart from the technological infrastructure (high voltage installations with grid interface as well as the control, communication and monitoring systems), the required marketing and energy trading competences are already available.

C. Outlook

The domain of pooling PSP with BESS is still a relatively new field, for which few experiences are known. Hence, the quantification of benefits of volatility reduction in ternary set PSPs had to be based on the existing information given in literature. With more reliable data, the accuracy of the estimation of a degradation factor for FCR providing systems which are exposed to high volatility can be increased. In general, this problem is addressed since 2010 by a project group funded by the VGB committee TC Hydro Power Plants [22]. The main task of the group is to develop a guideline for design and operation of high strained components in hydro power plants. An exhaustive fatigue analysis could be used to explicitly specify the effects of volatility on lifetime curtailment.

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