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Optimizing Storages for Transmission System Operation

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Abstract

A growing amount of congestions is expected for future operation of electrical transmission grids in Europe. Within this context, storages can be used to assist transmission system operators in daily operation and to avoid costly redispatch measures. In this paper, a research methodology to evaluate impact and interdependencies between market operation of storages and participation in redispatch measures is presented. Furthermore, a methodology for the evaluation of benefits by storages solely administrated by TSO is introduced. The methods are evaluated in a case study for the German electricity system in the year 2020.

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Keywords: Storages; SCOPF; Redispatch, Transmission System Operation; Congestion

1. Motivation and background

In the future an increased share of renewable energy sources is predicted [1]. This will result in two major challenges. The first challenge is keeping the electrical energy system including volatile feed-in balanced, which will entail a need for flexible generation or energy storage. The second challenge is transporting the intermittent energy produced at remote locations, which will lead to a growing amount of congestions in the transmission grid. These congestions are relieved by transmission system operators (TSO) due to affecting dispatch ("redispatch") or curtailing renewables, but could also be tackled using storages.

Today storages are operated in the market, e.g. pumped storage hydro power plants mainly exploit price spreads. Therefore storage limitations are not optimized to minimize congestions but maximize profit. This utilization scheme affects the availability of storages for use in redispatch measures due to limited basin levels.

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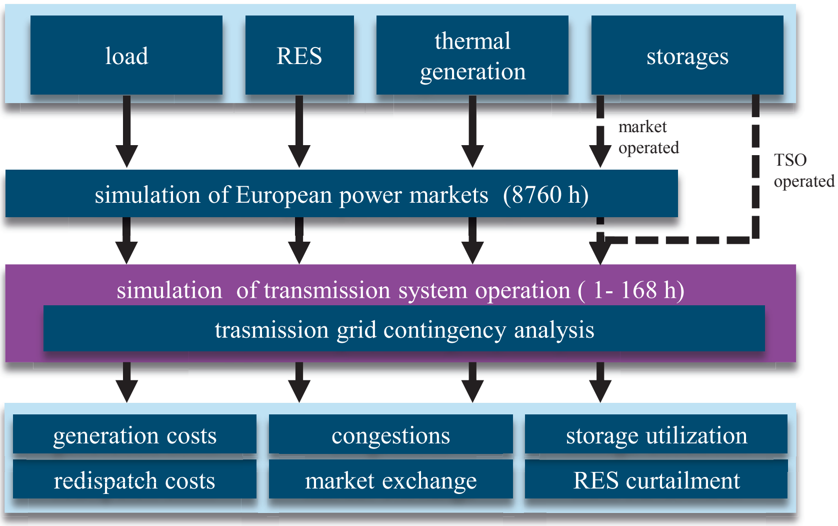

Figure 1 Evaluation methodology for market and TSO based storage utilization

Therefore, this paper analyses the impact of storages in the transmission grid and identifies potential of grid based usage of storages to secure transmission grid operation.

2. Research Methodology

In order to evaluate the effects of storages solely administrated by TSOs in mid and long term, the resulting consequences and costs to restore a (n-1) secure grid will be compared in a two-step approach. The several levels of simulation are depicted in Figure 1.

Initially, the European electricity market is simulated for the period of one year considering 8760 consecutive hours [2]. The input parameters for the market simulation are divided into thermal power plants, storage units and feed-in of renewable energy resource as well as load and reserve. At this the storages depend on the applied scenario.

Economically feasible due to the required capacity sizes are nowadays compressed air storage, pumped storage power stations, batteries and hydrogen storages. Because of the largest distribution and the highest efficiency mainly pumped storage power plants will be taken into account in this paper.

The simulation is conducted once with market operated storages and once without the evaluated storages and results each in an hourly unit commitment. Afterwards, based on the market based dispatch, a contingency analysis and a simulation of transmission system operation are carried out on a network model of the transmission grid on a variable timescale.

Comparison of the simulated transmission system operation for a single point in time and for a time range enables the evaluation whether the redispatch participation of storages is beneficial for the overall system operation. Furthermore, the storage dispatch and basin levels estimated in the simulation of power markets are assumed for market operated storages on the one hand and the assumption of no market dispatch and medium basin levels for storage operation by a TSO is made on the other hand. The assessment of interdependencies in between these scenarios allows the estimation whether or not there is an advantage of storages solely administrated by a TSO.

In the following the simulation of transmission system operation that enables these analyses will be presented in greater detail.

3. Simulation of transmission system operation

The simulation of measures taken by the TSOs during system operation is based on the assumption of an ideal TSO selecting and implementing optimal remedial measures. Therefore the upcoming network utilization consisting of nodal load and in-feeds is assumed to be known a priori.

Since for a future scenario voltage problems are assumed to be of minor importance due to the growing deployment of reactive power compensations units and FACTS, current limits are expected to be the primary operational limit in transmission system operation. This operational limit has to be complied with in normal operation and during contingencies as defined in [3]. The compliance has to be ensured by network based measures like tapping of phase shifting transformers and market related measures like redispatch. To ensure cost efficient network operation the amount of costly redispatch measures should be kept to a minimum.

There are a number of optimization formulations available that are capable of simulating the impact of congestions on energy generation. The main challenges in the development of such an optimal power flow (OPF) problem is the consideration of contingency situations as security constraints and the applicability to large networks models. Suitable approaches for these challenges are developed e.g. in [4] and [5] but none of them considers inter-temporal dependencies that are crucial for the consideration of storages.

To tackle this challenge, an optimization problem is formulated as a security constrained optimal power flow (SCOPF). In a first step, the SCOPF calculates a solution for the loadflow equations in normal operating conditions n and for all relevant contingencies $c \in C$.

$$\vec{\underline{S}_s} = 3 \cdot diag(\vec{\underline{U}}_s) \cdot \underline{Y}_s^* \cdot \vec{\underline{U}}_s^{\,*} \qquad s \in S, S = \{n, C\} \qquad (1)$$

Within this equation, $\vec{\underline{S}}$ is the vector of nodal apparent power, $\vec{\underline{U}}$ is the vector of nodal voltages and $\underline{Y}$ the node admittance matrix. The currents over all branches b can be estimated using the quadripole equation [6].

$$\vec{\underline{I}}_{b,s}(\vec{\underline{U}}_s) = \begin{pmatrix} \underline{I}_{1,b,s} \\ \underline{I}_{2,b,s} \end{pmatrix} = \begin{pmatrix} \underline{Y}_{11,b} & \underline{Y}_{12,b} \\ \underline{Y}_{21,b} & \underline{Y}_{22,b} \end{pmatrix} \cdot \begin{pmatrix} \underline{U}_{1,b,s} \\ \underline{U}_{2,b,s} \end{pmatrix} \qquad \begin{matrix} b \in B \\ s \in S \end{matrix} \qquad (2)$$

$\underline{I}_{1,b}$ and $\underline{I}_{2,b}$ are the currents at the beginning and end of branch b, $\underline{U}_{1,b}$ and $\underline{U}_{2,b}$ are the voltages at both sides of the branch. The index s indicates the loadflow situation. The currents have to maintain below the maximum permissible current $I_{max,b}$ at all times.

$$\begin{pmatrix} |\underline{I}_{1,b,s}| \\ |\underline{I}_{2,b,s}| \end{pmatrix} < I_{max,b} \qquad \begin{matrix} \forall\, b \in B \\ \forall\, s \in S \end{matrix} \qquad (3)$$

To ensure the compliance with these constraints, network and market related measures can be utilized. In the optimization the modeling of these measures means that the derivative of the nodal voltage vector with respect to the effect of the remedial measure can be calculated. For redispatch measures, the derivative is estimated by an inversion of the jacobian matrix $\underline{J}_s$, that is used for solving the loadflow equations within the Newton-Raphson algorithm [6]. For transformers, an equivalent in-feed is estimated based on the partial derivative of the transformer quadripole with respect to the complex transmission ratio of the transformer $\underline{t}$ and the nodal voltages $\vec{\underline{U}}_s$. The equivalent in-feeds on both sides of the transformer are then treated equivalent to changes of power injections during redispatch.

A significant speed-up of the optimization problem can be achieved by reducing the number of jacobian matrix inversions and approximating the derivatives by a current injection method based on approaches from [4] and [7].

To consider storages and their time interdependencies in the simulation of transmission system operation, the formulation is extended to cope with multiple points in time:

$$S = \{S_1, \ldots, S_T\} = \{\{n_1, C_1\}, \ldots, \{n_T, C_T\}\} \quad (4)$$

Where T is the number of simultaneously optimized points. The time coupling formulation enables the consideration of storage constraints, e.g. the reservoirs of hydropower generation units. The storage level can be assessed as network flow model.

$$V_{r,t+1} = V_{r,t} + q_{r,t}^{nat} + \sum_{j\in R, j\neq r} \left(q_{j,r,t} - q_{r,j,t}\right) \qquad \begin{matrix} \forall\, r \in R \\ \forall\, t \in \{1, \ldots, T\} \end{matrix} \quad (5)$$

The natural flow to the basin $q_{r,t}^{nat}$ in combination with the sum over the differences between water flowing to the basin $q_{j,r,t}$ and from the basin $q_{r,j,t}$ represents the change of basin levels in each period t through the dispatch of turbines and pumps. The storage level $V_{r,t}$ of basin r at time t is estimated based on the market dispatch of hydropower plants and prior redispatch measures.

The minimum and maximum water levels of the basin have to be adhered to at all times. In addition, the water levels of the basin are supposed to be unchanged at the beginning and the end of each optimization time period. These restrictions allow a parallelization of multiple timeframe calculations and could be replaced by a rolling implementation.

$$\begin{matrix} V_{r,min} \le V_{r,t} \le V_{r,max} \\ V_{r,0} = V_{r,0,ext} \\ V_{r,T} = V_{r,T,ext} \end{matrix} \qquad \begin{matrix} \forall\, r \in R \\ \forall\, t \in \{1, \ldots, T-1\} \end{matrix} \quad (6)$$

The basin levels $V_{r,t,ext}$ are external targets prescribed by a market simulation.

Due to regulatory reasons, the TSOs are supposed to minimize the market impact of redispatch measures. This minimization is not necessarily a minimization of redispatch costs, but a multi objective optimization taking into account redispatch volume and cost.

$$f_{obj} = \min \sum_{t}^{T} \sum_{m\in M} c_{m,t} \cdot \Delta P_{m,t} + c_{vol} \cdot \left|\Delta P_{m,t}\right| \quad (7)$$

Where M is the set of all redispatch measures, c_m are the specific costs per power of measure m at time t and c_{vol} is a penalty component that reflects the requirement of a minimal amount of redispatch volume. In addition, if the optimization problem tends to be infeasible, an additional term to minimize branch overloading can be introduced in addition to the current constraints.

The results, composed of generation costs, redispatch costs, congestions, market exchange, storage utilization and RES curtailment, will provide quantitative findings, whether storages could be seen as grid equipment or only as market participant, as today.

4. Exemplary Results

4.1. Scenario context

In order to conduct the analysis, the scenario boundaries have to be defined. For the simulations of the year 2020 the scenario of the research project "Roadmap Speicher" (RMS) is used, which is based on the Leitstudie 2011 and adapts recent developments, e.g. released in the National Action Plans for Renewable Energy [8, 9].

To meet actual developments, only projects for new power plants which are already in-built are considered. Existing generation units are taken into account if their expected life time according to BNetzA is not exceeded in 2020. Figure 2 depicts the installed capacities in Germany according to scenario B of the German network development plan 2012 [10]. The considered capacities of renewable energy sources (RES) are based on Leitstudie 2011, National Action Plans for Renewable Energy and current expansion of wind and solar power, mainly photovoltaic. Based on these capacities the nodal feed-in is generated with use of historic weather information [11]. The expected demand bases on the Leitstudie 2011 and the development till 2022 which is shown in network development plan, scenario B. Likewise, the demand is modeled as hourly and nodal load.

To evaluate the impact of storages, it is also essential to map other existing flexibility parameters like demand side management (DSM). Therefore, this is taken into account due to controlled load leveling prior to the market simulation considering time dependencies and technological potentials.

The fuel price path and the CO_2-certificate prices are set in line with the Leitstudie 2011 and incorporate a small increase in demand of fossil fuels in future years.

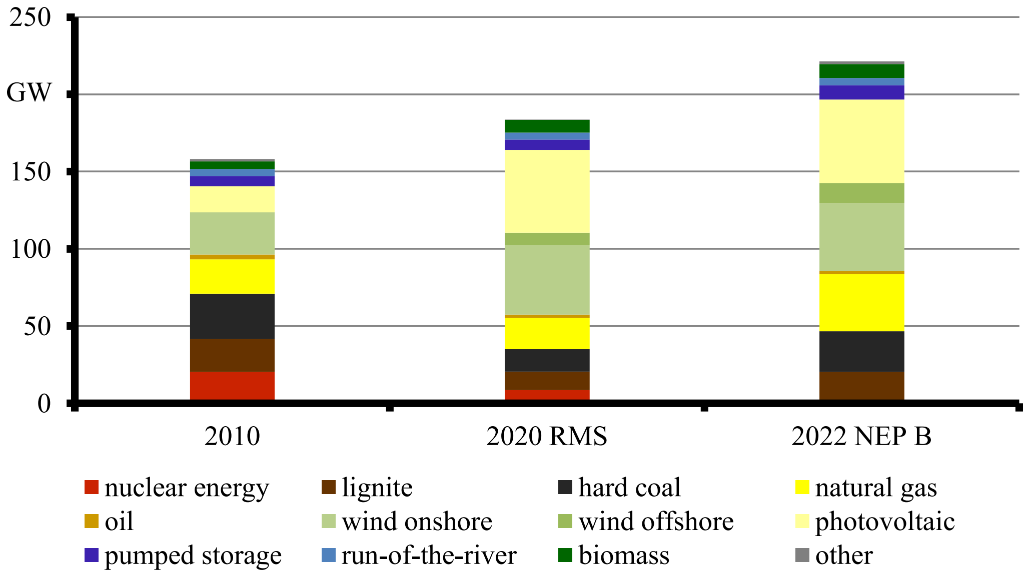

Figure 2 Installed capacities in Germany

Based on the results of the market simulation congestions in the transmission grid are evaluated and the measures taken by the TSOs during system operation are simulated for Germany. Consequently a model of the transmission system is necessary. Therefore IAEW developed a model of the European transmission grid based on publicly available data. This model was benchmarked intensively for year 2010 [12]. The assumption on the conducted network reinforcements are derived from the German network development plan 2013 [13]. Divergent from the network development plan, the commissioning of HVDC lines in Germany is assumed to be postponed until 2022.

To identify potentials of grid based usage of storages to secure transmission grid operation, two scenarios considering different developments of storages are simulated in the market for 2020. First, only pumped storage hydro power plants in operation in 2013 are considered in the scenario “TSO operated”. Second, all expected storages corresponding to the German network development plan 2013 are included in the scenario “market & TSO operated” [13]. In both scenarios the commitment for the considered storages is evaluated. Based on these results the usage of all storages in the grid operation is simulated.

Through this, the impact of additional storages only applied by TSO can be identified.

4.2. Market based dispatch

In this section the results of the market simulations for both scenarios are presented. For this, the change in generation is shown in Figure 3 for exemplary countries. The figure illustrates the differences in generation between “market & TSO operated” and “TSO operated”, that means the influence by additional storages in the market. The results demonstrate an increase of nuclear of 0.12 TWh and lignite of 0.25 TWh in Germany. Simultaneously the dispatch of pump storages is increased, what can be seen in the increase of turbining of 0.31 TWh and the increase of pumping of 0.44 TWh. Due to the development of new pump storages in Germany the commitment of storages in Austria decreases. Furthermore the generation of gas power plants with combined heat and power or gas turbines can be decreased in Germany and Austria as well as in the Netherlands and Poland and the generation of hard coal is increased.

Overall a higher generation of base load power plants and a reduced generation of peak load power plants can be achieved due to the dispatch of the expansion of pumped storage hydro power plants and additional compressed air storages in Germany. But the influence on the generation is insignificant.

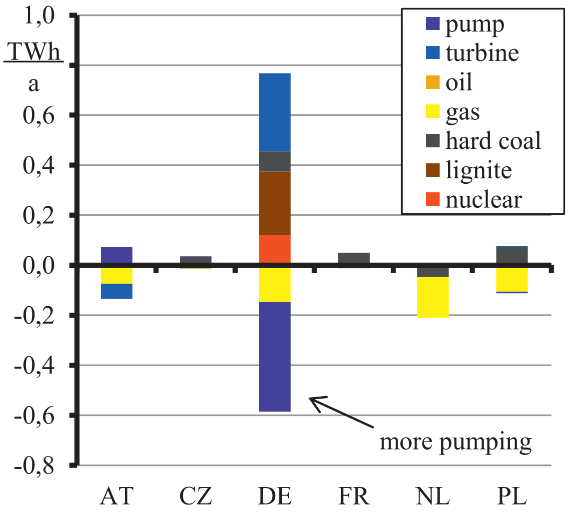

Figure 3 Change of generation
(difference “market & TSO operated” to “TSO operated”)

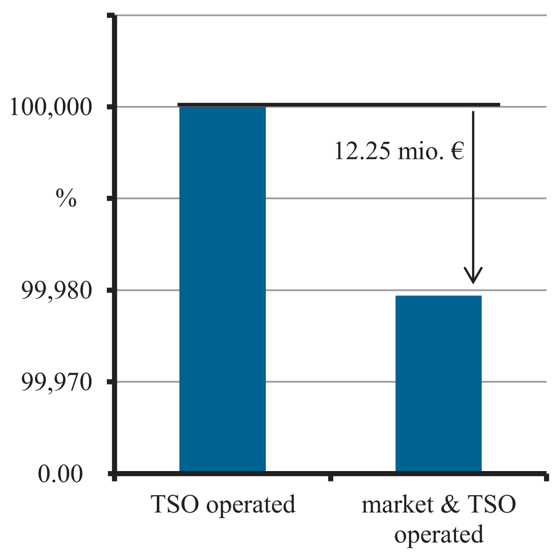

Figure 4 Differences in generation costs

The displacement of gas generation by base load lignite power plants also leads to a slight increase of CO2 emissions by 0.02 % in whole Europe and 0.16 % in Germany in case of “market & TSO operated” storages.

These effects can also be seen in the change of generation costs (see Figure 4). Due to the insignificant impact on unit commitment by the additional storages the decrease of costs amount to approximately 0.02 % over all European market areas, while the generation costs in Germany increase negligible due to the higher generation. In sum the reduction of generation costs in whole Europe amount to 12.25 mio. €. Furthermore no curtailment of feed-in of wind power could be determined in both scenarios.

Following, based on the simulated unit commitment the overloadings in the transmission grid and the necessary measures during system operation are evaluated for both scenarios. At this, all developed storages are considered as possible component for the TSO.

4.3. Network based dispatch

To evaluate the effect of market and TSO based storage dispatch, a simulation of transmission system operation is carried out for two exemplary weeks with high network utilization. The considered network model for the year 2020 assumes a delay in the construction of HVDC lines within Germany and therefore shows a significant amount of congestions.

In a first step the effect of market based storage dispatch on the amount of congestions is evaluated. The construction of new market operated storages causes a slight increase of the amount of congestions by 1.5 %. In a second step, a full simulation of transmission system operation is performed for the two different scenarios of storage operation and two different planning horizons. To guarantee the possibility of predetermined dispatch, for each planning horizon fixed basin levels have to be ensured at the beginning and at the end of the optimization. In case of the "market & TSO operated" scenario these basin levels are taken from the market simulation, for the "TSO operated" scenario without prescribed basin levels for additional storages, the basin levels of the existing storages are set to the half of the maximum to guarantee the maximum degree of freedom.

As can be seen in Figure 5, the comparison of both scenarios over the different planning horizons shows contrasting impacts on the costs. The 'hourly' simulation in the "market & TSO operated" scenario indicates a slightly increased effort in remedial measures to the "TSO operated" scenario. Whereas, the increased usage of hydro power plants in the longer planning horizons reduces the costs for redispatch measurements. Due to the fact, that a significant amount of thermal power adjustments is substituted, the consumption of primary energy is reduced. Furthermore, it can be noticed that the costs of the "market & TSO operated" scenario are lower than the "TSO operated" scenario. From the network perspective, that can be ascribed to reasonable allocated storages and predetermined dispatch, which endorse a secure and cost effective network operation.

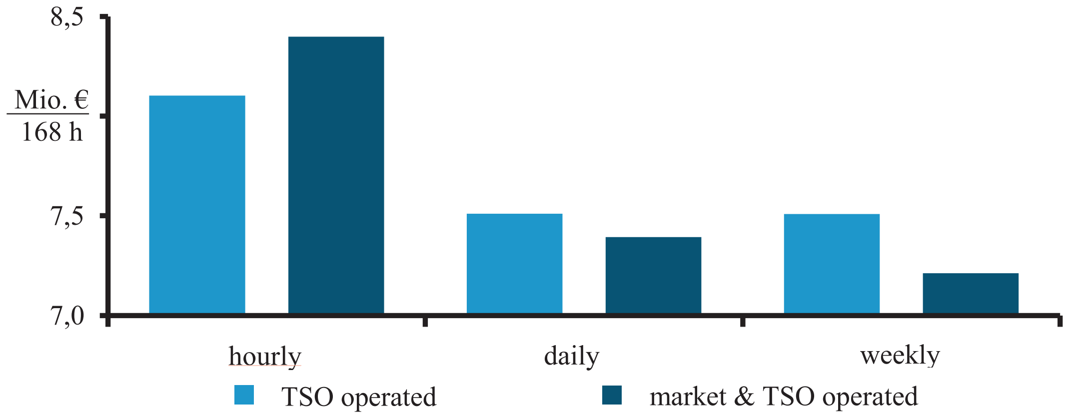

Figure 5 Exemplary redispatch costs of one week

Compared to the overall redispatch, the "TSO operated" scenario requires 3 % less redispatch energy and causes 2 % less redispatch costs for a weekly planning horizon. This is induced due to the opportunity of shifting redispatch from times with large amount of congestions and therefore high redispatch costs per congestions to situations with a less stressed grid situation. The operation mode can be compared to normal peak shaving operation, but taking into account nodal redispatch costs instead of market area wide energy costs

The benefits of storages solely administrated by TSO can be assessed by evaluating the difference in redispatch power between the two scenarios for distinct situations. Therefore, Figure 6 shows the difference between the required redispatch power in the "TSO operated" and "market & TSO operated" scenarios for all calculated network situations ordered by the difference of redispatch power. In two thirds of the situation it is less redispatch required in the "TSO operated" scenario. The benefit of TSO operation in these cases is barely affected by the planning horizon. If this operation scheme requires more redispatch power, the amount is significantly affected by the planning horizon. If a daily renewal of fixed basin levels is required, the overall benefit of storage operation by the TSO in terms of avoided redispatch is reduced to 34 % of the week planning horizon benefit.

In general the redispatch costs savings in the "TSO operated" scenario, even in an optimistic assessment, do not significantly exceed the generation cost savings in the market operated case.

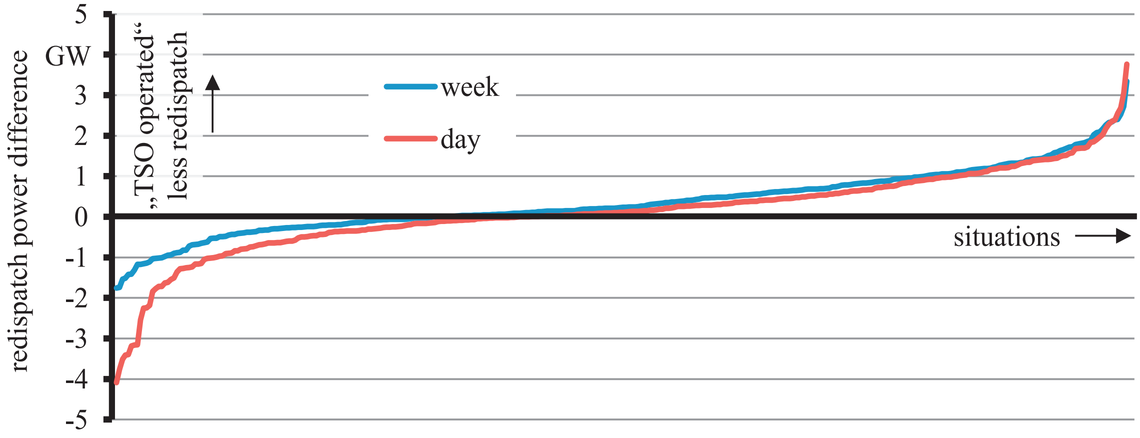

Figure 6 Influence of planning horizon on difference of redispatch power between scenarios

5. Summary

The growing share of power generation from renewable energy sources causes new challenges in transmission grid operation. Storages could be used to tackle the problem of a growing amount of congestions by participating in redispatch. Therefore, this research paper presents a method for evaluation of storage operation in energy markets and transmission grid operation. The method is applied in a case study for the year 2020 on the European energy markets and the German transmission grid operation.

The expansion of storages in Germany leads to slight changes in energy generation and a small reduction of the overall generation costs. The participation of storages in redispatch causes reduced amounts of redispatch energy and costs. The benefit of storages solely operated by a TSO is traceable, especially for long planning horizons, but does not decisively exceed the generation cost savings caused by market operated storages.

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