# COMPENSATION OF SHORT-TERM POWER FLUCTUATIONS AT THE TRANSMISSION GRID LEVEL BY CENTRALIZED AND DISTRIBUTED SHORT-TERM STORAGE TECHNOLOGIES ON THE EXAMPLE OF AUSTRIA

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## Abstract

This paper examines the role of centralized and distributed short-term storage technologies in Austria at the transmission grid level to maximize renewable power generation utilization. A linear optimization problem is evolved for the expansion planning of storage technologies and the operational planning of the entire electrical energy system's plant park to enhance the renewable generation/load balance respectively to minimize the fossil electricity production. In this paper, existing pumped-storage power plants take the role of centralized storage technologies. Batteries and distributed pumped-storage operate as distributed short-term storage technologies. The model's objective function minimizes the total system costs, the sum of operational costs, and the expanded technologies' annuity costs. Results show that the potential of centralized storage technologies is, in general, sufficient for balancing the short-term power fluctuations when renewables dominate the overall generation characteristic. An installation of distributed storage technologies does not improve the transmission grid level's regenerative load coverage ratio.

## 1 Introduction

By setting national and international climate targets, many European countries have committed themselves to a renewable energy supply path. Those targets also include the electrical energy sector. As part of its national climate and energy strategy "#mission2030" [4], Austria has set the goal of covering 100% of its total electricity consumption (on a federal balance basis) with renewable energy sources. The expansion of renewable power generation centers is production-oriented. That means that profitable renewable power plant parks' locations are not necessarily located near the existing high-capacity grid sections. They are also not necessarily placed close to consumption centers. Furthermore, wind and photovoltaics have highly volatile generation characteristics that are only partially controllable, difficult to forecast, and do not necessarily correlate with the electrical load profile. Considering those elements, the electrical operating grid limits are often reached when a high share of weather-dependent and volatile renewable power generation is fed into the grid. Grid upgrades or curtailment of power generation are the remedial measures to avoid overloading of grid components. Another remedy can be a temporal decoupling of power production and power consumption by storing surplus electricity.

This paper's goal is to examine whether the potential of centralized pumped-storage power plants in Austria is sufficient for balancing the domestic short-term power fluctuations at the transmission grid level if a high share of renewable power generation is utilized. Compared to the centralized pumped-storage power plants, the potential of distributed storage technologies (batteries and distributed pumped-storage) for balancing the short-term power fluctuations is investigated.

The following section presents the developed methodology for examining centralized and distributed short-term storage technologies in Austria. Here, the focus lies in presenting the implemented optimization model with all relevant components of the electrical energy system's model.

## 2 Methodology

The storage technologies' role in increasing the regenerative generation/load balance is determined based on an expansion and operational planning of the electrical energy system's plant park. The developed linear optimization model is applied to different scenarios of the investigated power system. First of all, the effects of a massive expansion of renewable energy sources on existing generation capacities and pumped-storage power plants are determined. The operational planning of existing generation capacities is reassessed in further optimization calculations by including other storage technologies in the investigated topology. Thereby, the expansion planning of new storage technologies is determined.

### 2.1 Model description

For this paper's investigations, a linear optimization model developed within a doctoral thesis [1] is deployed. The thesis' model is implemented in GAMS. The original modeled energy system's topology comprises the electrical, gas, and heating system. For the investigations, just the electrical energy system from [1] is considered. Thus the Austrian transmission grid represents the investigated system's boundary. The modeled electrical energy system's topology consists of power plants, such as thermal power plants and (pumped-) storage power plants, distributed storage technologies, heat pumps, exogenous sustainable power generation and consumption components, import/export components, the flexibility option of electricity curtailment, and a complex transmission gird. The most crucial model's constraint is the coverage of the electrical demand for each time step, and therefore a completely balanced generation/load situation. The optimization model's objective function is the coverage of the exogenous residual load while maintaining minimal system costs. The sum of variable generation costs and annuity costs of expanded storage technologies is minimized for the entire observation period. A two-stage calculation process is realized to include the long-term and short-term requirements for balancing the electrical energy system dominated by renewables. More details concerning the two calculation processes are given in [1]. The exogenous electricity production is based on a potential scenario of a massively expanded renewable electricity production for 2030.

### 2.2 Objective function

The simplified mathematical formulation of the objective function is given by,

$$min \left\{ \sum_{mk} \sum_{i} C_{var}(mk, t_i) + \sum_{nk} \sum_{es} C_{inv}(nk, es) \right\}. \quad (1)$$

The expression $\sum_{mk}\sum_{i} C_{var}(mk, t_i)$ represents the sum of variable costs of active model components $mk$ over all sampling instances $i$ and the expression $\sum_{nk} C_{inv}(nk)$ represents the sum of annuity costs of expanded model components $nk$. To realize a high share of sustainable power generation, a priority is given to a renewable load coverage if technically possible. Therefore the variable costs of renewable production units are not included in the objective function. Hence, the variable generation costs' term is mostly dominated by the generation costs of fossil-fired power plants, energy losses' costs of storage technologies, costs for the cross-border power exchange, and electricity curtailment costs.

### 2.3 Transmission grid

Due to the optimization problem's linear description, the direct current (DC) load flow calculation method is applied to determine the lines' loading, i.e., branch's loading. Hence, the lines' loading is kept within the allowable limits by constraints that include the DC load flow approach. The main part of the DC load flow calculation is the determination of the branch power $P_{el}^{ZW}$, which for each time step $t_i$ and each branch $zw$ is calculated as,

$$P_{el}^{ZW}(t_i, zw) = \sum_{\substack{k=1 \\ k \neq k_{Slack}}}^{n_k} LF(zw, k) \cdot P_{el}^{KN}(t_i, k), \quad (2)$$

where $P_{el}^{KN}(t_i, k)$ is the resulting node power of the relevant node $k$ and $\boldsymbol{LF}$ is the DC load flow matrix of the type $zw \times k$. The nodal power includes all grid node's $k$ in- and outflow power flows. The in- and outflow power flows are partly predefined and partly controllable by controllable model components. The calculated branch power $P_{el}^{ZW}(t_i, zw)$ is subject to two constraints, and must be kept within predefined limits. The limits correspond to a branch power associated with the (n-1)-criterion and therefore is set to 65% of the maximum thermal utilization limit of the equivalent branch of the transmission grid,

$$-0.65 \cdot \overline{P}_{el}^{ZW}(zw) \leq P_{el}^{ZW}(t_i, zw) \leq 0.65 \cdot \overline{P}_{el}^{ZW}(zw). \quad (3)$$

The modeled transmission grid corresponds to a grid scenario 2030 from the thesis mentioned above [1] that considers all relevant expansion projects for 2030 of the Austrian transmission grid operator Austrian Power Grid AG (APG), summarized in the APG Master Plan 2030 [3]. The modeled grid's boundary is drawn at the neighboring countries' interconnectors to confine the model's complexity. However, to still consider the neighboring countries' load flow influence on the domestic load flow situation, the cross-border load flow is modeled by predefined and controllable import/export-components. All parallel

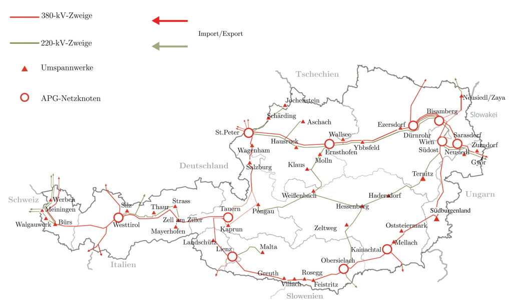



Fig. 1: The modeled transmission grid (adapted after [3])

lines and parallel transformers are reduced to an equivalent branch and converted to one voltage level to reach an acceptable problem size. The final network features 64 nods and 86 branches.

### 2.4 Controllable model components

For large-scale optimization problems, it is recommended [2] to model, if possible, all representative technical operation characteristics of different energy technologies like power output $P$, electrical energy output or primary energy $E$ by using just one variable, i.e., by derivates of this one variable. The time dependent energy variable $E(t_i)$ is suitable for that [2]. The energy variable $E(t_i)$ can represent for each time step

$t_i$, on the one hand, the accumulated power output or electrical energy production. On the other hand, it can be applied to model accumulated power input or electrical energy consumption. The difference between those two power/energy flows is controlled by a sign plus or minus in the corresponding node- or balance-constraints. That also means that $E(t_i)$ is defined as a monotonically increasing or decreasing function. This modeling approach ensures that the energy-related constraints build up sparse matrices within the optimization problem's constraint matrix, relevant to the resulting problem's size and calculation time. The electrical power output $P(t_i)$ for each time step $t_i$ is estimated according to the equation (4) by calculating the difference of the two consecutive energy values $E(t_i) - E(t_{i-1})$ related to the considered time resolution $\Delta t = t_i - t_{i-1}$. The electrical power output is limited within the optimization model by a minimum power $\underline{P}$ and maximum power $\overline{P}$,

$$\underline{P} \leq \frac{E(t_i) - E(t_{i-1})}{\Delta t} \leq \overline{P}. \quad (4)$$

The minimum power limit $\underline{P}$ is set for most of model components to the zero value. The maximum power $\overline{P}$ represents the installed plant's capacity and thus a parameter which is node-dependent and plant's type-dependent. The power output rate of change between two consecutive time steps can, in the same way, be calculated by the difference of two consecutive power output values related to the considered time resolution. The total energy production equals to the expression, $E(t_{i=n}) - E(t_{i=1})$, where $t_{i=n}$ and $t_{i=1}$ represent the last and first time step of the model horizon. The primary energy of most model components is queried by $E(t_i)/\eta$. Just in the case of (pumped-) storage power plants and other storage technologies, the energy variable $E(t_i)$ represents the storage's primary energy. Thus the power-related constraints include the efficiency of the conversion process.

*2.4.1 Power plants:* Thermal power plants and (pumped-) storage power plants count as controllable components of the investigated electrical energy system. The above-presented approach models both technologies. The operation of a (pumped-) storage power plant is additionally limited by the installed storage capacity ($\underline{E}, \overline{E}$) and dependent on the the natural inflow $E^{nat}(t_i)$. A perfectly forecasted natural inflow is considered in the implemented model. The spillage variable can additionally change the actual storage level. The spillage variable $E^{spill}(t_i)$ is used to control the spillage of the surplus water over the dam of the reservoir when its water level exceeds the maximum storage capacity and its maximum discharge flow rate is lower than the natural inflow. The corresponding storage capacity constraint for a (pumped-) storage power plant is defined as,

$$E^{nat}(t_i) - E(t_i) - E^{spill}(t_i) \geq \underline{E}, \quad (5)$$

$$E^{nat}(t_i) - E(t_i) - E^{spill}(t_i) \leq \overline{E}. \quad (6)$$

In the case of a pumped-storage power plant, the operating state pumping increases additionaly the actual storage capacity. Thus, the pumped-storage hydropower plant's operation responds additionally to constraints concerning the pumping-process. Furthermore the equations (5) and (6) are extended with the energy variable of the pumping process. The model structure of pumped-storage power plants resembles the storage technology component presented in the following subsection. A detailed description of modeled thermal and (pumped-) storage power plants is given in [1].

As aforementioned, the investigated electrical energy system is reduced to the level of the high-voltage grid. This means that existing power plants cannot precisely be placed to their connecting grid nodes. Thus, they are assigned to the grid nodes of the superordinate gird level. Fifty-three (pumped-) storage power plants, nine fossil-fired thermal power plants without heat extraction, nine with combined power and heat extraction (CHP), thirteen biomass-fired thermal power plants without heat extraction, and thirteen with CHP are located in the modeled high-voltage grid. The most important technical limits of the modeled controllable power plant park for this paper's investigations are presented in tables 1 and 2.

Table 1 Limits of the representative storage hydropower park

| | Pumped-storage | Storage |
|---|---|---|
| $\overline{P}_{el}$ [GW] | 6.4$^{\text{Turbines}}$ / 5.8$^{\text{Pumps}}$ | 10.1 |
| $\overline{E}$ [GWh] | 340.27 | 3791.0 |

Table 2 Limits of the representative thermal power park

| | CHP | Fossil-fired plants | Biomass-fired plants |
|---|---|---|---|
| $\overline{P}_{el}$ [GW] | without | 1.52 | 0.25 |
| | with | 5.72 | 0.58 |

*2.4.2 Storage technologies:* Storage technologies influence the underlying generation/load profile in both directions. Here, they are applied to realize a temporal decoupling of power production and power consumption by storing surplus electricity. The motivation lies in increasing the regenerative load coverage by keeping the lowest cost expenses required for their installation and operation. Centralized and distributed pumped-storage power plants and distributed batteries are the investigated storage technologies. All three storage types are modeled according to the aforementioned modeling approach by two energy-related variables. The energy-related variables represent for each time step $t_i$ the storage's accumulated injected $E_+(t_i)$ and withdrawal $E_-(, t_i)$ energy, i.e., the charging- and the discharging-process. Both variables are modeled as monotonically increasing functions. Their sum represents for each time step $t_i$ the actual storage capacity which is limited by the a minimum allowable and installed storage capacity:

$$E_+(t_i) - E_-(t_i) \geq 0, \quad E_+(t_i) - E_-(t_i) \leq \overline{E}. \quad (7)$$

The rates of change between two time steps of both variables corresponded to the withdrawal and injection power and are limited by following constraints:

$$E_+(t_i) - E_+(t_{i-1}) \geq 0, \quad E_-(t_i) - E_-(t_{i-1}) \geq 0, \quad (8)$$

$$[E_-(t_i) - E_-(t_{i-1})] \cdot \eta \le \overline{P}_- \cdot \Delta t, \quad (9)$$

$$[E_+(t_i) - E_+(t_{i-1})] \cdot \frac{1}{\eta} \le \overline{P}_+ \cdot \Delta t. \quad (10)$$

Depending on the calculated scenario and the type of the planning horizon (short- or long-term), the technical storage limits $\overline{P}_-$, $\overline{P}_+$, $\overline{E}$ are defined as known parameters or unknown variables, i.e., they are determined within the optimization calculation. Hence the centralized pumped-storage technologies represent the existing plants of the investigated electrical energy system. The technical limits for the entire pumped-storage power park are summarized in table 1. The limits of distributed batteries and distributed pumped-storage systems are calculated within the optimization scenarios. The energy conversion process efficiency for pumped-storage power plants is set according to [1] to 89.4% and for batteries to 94.5%. The batteries' installed power depends in most cases directly on the installed storage capacity. Therefore a fixed capacity to power ratio (C/P) is considered and set as predefined to the value 2 h.

*2.4.3 Other controllable measures:* Three other model component types, i.e., controllable measures, can also be considered to change the power system's generation/load balance. These are the possibility of curtailing predefined power generation, heat pumps, and cross-border power exchange. Their operation is modeled in alignment with the presented modeling approach. More details concerning those components can be found in [1].

### *2.5 Exogenous sustainable generation and consumption*

The carried out calculations base on a regenerative generation mix derived from a sustainable production and consumption scenario 2030 for Austria. A more detailed presentation of the considered sustainable production scenarios is given in [1]. Hydropower, wind power, photovoltaics, and biomass are the considered renewable generation forms. Among them, the run-of-river hydropower, wind power, and photovoltaic are modeled as predefined generation sources. A perfect feed-in forecast characterizes them. The electricity consumption is modeled as another predefined characteristic. In this paper, the transmission grid's consumer loads represent aggregated load groups assigned to individual 110 kV-grid groups, which are connected to the transmission grid shown in figure 1. The annual electricity consumption for 2030 is calculated using annual growth rates based on the 2014 annual electricity consumption. Details are presented in [1]. The annual predefined renewable power generation and consumption are summarized in table 3. The electrical energy system's residual load is the

Table 3 Predefined renewable generation and consumption

| | Wind | Run-of-river | Photovoltaic | Consumption |
|---|---|---|---|---|
| $E_{el}$ [TWh/a] | 17.06 | 42.48 | 6.39 | 76.63 |

remaining load to be covered after subtracting the predefined power generation from the consumption. Hence, the resulting predefined residual load is the basis for the preformed operational and expansion planning of storage technologies and other controllable components. Figure 2 shows the daily

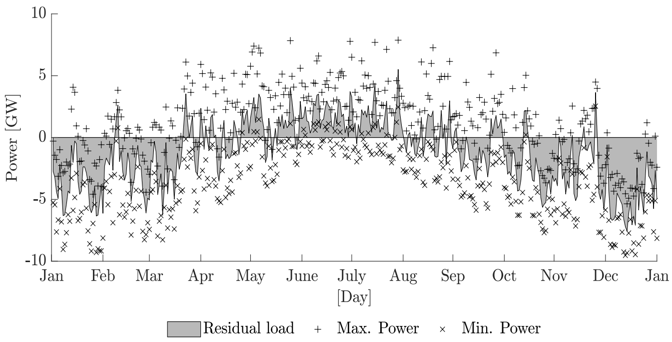



Fig. 2: Residual load's daily mean value

mean of the predefined residual load curve aggregated across all grid nodes for the entire observation period of one year. The shown residual load curve is flattened due to the aggregation of the individual residual load curves and the temporal averaging. Therefore the corresponding daily extreme values are additionally mapped in the representation. This paper's investigations concentrate on the short-term power fluctuations, which mostly occur during transitional periods, i.e., spring and autumn. The following subsection will show to which extent the short-term surplus electricity can be shifted by existing pumped-storage power plants and other storage technologies to cover the residual load's deficit phases and increase the regenerative generation/load ratio.

## 3 Results

Table 4 sums up the most relevant yearly optimization results that describe the role of investigated storage technologies at the transmission grid level. Those are the storage's number of full cycles, the non-usable regenerative surplus power, expressed by the electricity curtailment and controllable power export, and the fossil load coverage share. The first column, scenario A, represents the electrical energy system's initial state's results. Existing pumped-storage technologies are the only storage technology in the initial state's investigated topology. The expansion of distributed batteries and distributed pumped-storage systems are investigated in two other calculation runs, described respectively as scenarios B and C. The resulting State-of-Charge-curve (SoC-curve) of the calculated scenarios and the turbines' and pumps' power curve of Scenario A are shown in figure 3.

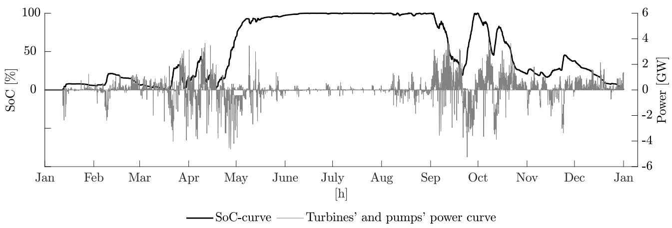
Figure 3 a) shows that existing pumped-storage power plants cannot store all of the surplus power during the long-lasting phases of surplus power. The stored capacity is kept during summer. The total surplus power in summer exceeds the existing pumped-storage power plants' capacity almost by a factor of 10. Pumped-storage power plants balance the residual load curve mainly during the transitional periods and partly in winter. This operation results in a relatively small full-cycle number of 4.8.

Performed calculations show that distributed short-term storage expenses are currently too high when they are added to the investigated topology as another support option to balance the residual load curve. To be specific, both storage technologies are expended only when a high reduction of the installation costs is assumed. It has to be stated that this statement only refers to the investigated role of distributed short-term storage technologies. The total installed battery capacity is $2.8\,\mathrm{GW}$ in scenario B. The total installed distributed pumped-storage capacity in Scenario C equals to $1.23\,\mathrm{GW}$ and $62.3\,\mathrm{GWh}$.

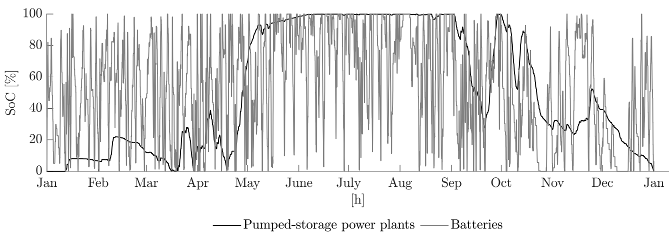
Table 4 Optimization results

| Number of full-cycles | A | B | C |
|---|---|---|---|
| Pumped-storage power plants | 4.8 | 4.2 | 4.1 |
| batteries | | 116 | |
| Distributed pumped-storage | | | 20 |
| | A | B | C |
| Non-usable surplus power | $7.47\,\mathrm{TWh}$ | $7.21\,\mathrm{TWh}$ | $6.68\,\mathrm{TWh}$ |
| Fossil load coverage share | $8.49\%$ | $8.23\%$ | $7.78\%$ |

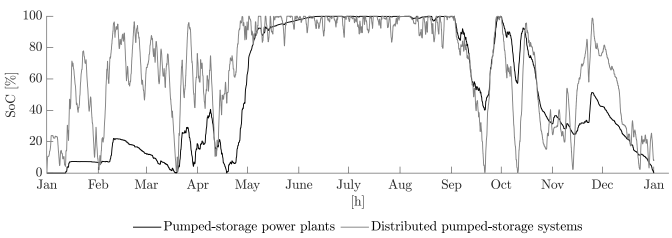
The marginal changes of the fossil load coverage share and




(a) Scenario A




(b) Scenario B




(c) Scenario C

Fig. 3: Storage operation of investigated scenarios

the non-usable surplus power between scenarios A and B show that an expansion of distributed batteries does not significantly increase the compensation of the residual load curve's surplus and deficit. The reason lies partly in a low batteries' C/P ratio. Another reason is the lack of short-term fluctuations between generation and consumption during summer. Batteries are competing technologies to existing pumped-storage systems in balancing short-term fluctuations due to their higher efficiency. They take over a considerable part of the renewable generation/load balance that otherwise would have been realized by the existing pumped-storage power plants, as presented in figure 3 a) and b), and table 4.

Due to resulting grid bottlenecks, the existing alpine regions' pumped-storage power plants cannot store the surplus of the "wind-strong" grid nodes in eastern Austria. Distributed pumped-storage systems can bridge this gap if they are installed near "new" generation centers of wind and run-of-river power plants. The significantly higher distributed pumped-storage's C/P ratio than that of the batteries has a higher effect on integrating renewable surplus power into the electrical energy system, as shown in table 4. However, even if distributed pumped-storage systems significantly reduce the curtailed surplus power, the share of fossil load coverage cannot be significantly reduced. The lack of pronounced short-term fluctuations between generation and consumption in summer is also the main reason for that. Because of the proximity to sustainable generation centers, distributed pumped-storage technologies have a higher utilization ratio than existing pumped-storage power plants.

## 4 Conclusion

Results show that the existing centralized pumped-storage power plants are essential for balancing short-term regenerative power fluctuations in the transmission grid. However, in the long continuous phases of surplus power in summer and power deficits in winter, the residual load oscillates too far from the zero line. It prevents a more pronounced use of short-term compensation options. Therefore, a further expansion of batteries and distributed pumped-storage technologies are not economically feasible to enhance regenerative generation/load compensation at a higher system level. Only storing regenerative surplus electricity in a seasonal storage facility can significantly reduce the fossil load coverage ratio.

## 5 Acknowledgements

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