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Anwendungen

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Coordinated operation of pumped hydro energy storage with reversible pump turbine and co-located battery energy storage system

Koordinierter Betrieb eines Pumpspeicherkraftwerkes mit reversibler Pumpturbine und einem Batteriespeicher an einem geteilten Standort

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Abstract: This publication examines the coordinated operation of pumped hydro energy storage and battery energy storage systems to improve profitability. While pumped hydro energy storages offer high storage capacity but have slower response times, battery energy storage systems have lower capacity but faster response times. A hybrid system combining both can thus harness synergies. A mixed-integer linear programming model was developed to depict the coordinated use of both systems in the German market. The proposed approach is also applicable to other regional markets where energy and balancing services are traded in a similar manner. In this model, the pumped hydro energy storage operates in the spot market and provides automatic Frequency Restoration Reserve, while the battery energy storage systems supplies Frequency Containment Reserve. The model takes into account the costs caused by degradation effects in both storage types. The results show a 10.05 % increase in revenue through coordination compared to the independent operation of both storage systems. This added value can be achieved through more efficient use of the power capacity, particularly that of the battery energy storage systems, in coordinated operation.

Keywords: pumped hydro energy storage; battery energy storage system; reversible pump turbine; electricity market; optimization; mixed-integer-linear-programming

Zusammenfassung: Dieser Beitrag untersucht die Koordination eines Pumpspeicherkraftwerkes mit einem Batteriespeicher zur Ertragsoptimierung. Pumpspeicherkraftwerke bieten eine hohe Speicherkapazität, jedoch begrenzte Reaktionszeiten. Batteriespeicher hingegen verfügen über niedrigere Kapazität, aber weisen dafür schnellere Reaktionszeiten auf. Ein hybrides System aus beiden Speichern kann somit Synergien erzeugen. Ein Mixed-Integer-Linear-Programming-Modell wurde entwickelt, welches den koordinierten Einsatz beider Systeme abbildet. Der vorgestellte Ansatz ist ebenfalls auf andere regionale Märkte übertragbar, in denen Energie und Regelleistung in vergleichbarer Weise gehandelt werden. Das Pumpspeicherkraftwerk agiert im Spot-Markt und bietet zusätzlich noch Sekundärregelleistung an. Der Batteriespeicher dient zur Bereitstellung von Primärregelleistung. Das Modell berücksichtigt zudem die durch Verschleiß und Alterungseffekte resultierenden Kosten. Die Ergebnisse zeigen eine Ertragssteigerung von 10,05 % durch die Koordination im Vergleich zum eigenständigen Betrieb beider Speichersysteme. Dieser Mehrwert kann durch eine effizientere Nutzung der Leistungskapazitäten, insbesondere des Batteriespeichers, realisiert werden.

Schlagwörter: Pumpspeicherkraftwerk; Batteriespeicher; Reversible Pumpturbine; Strommarkt; Optimierung; Mixed-Integer-Linear-Programming

1 Introduction

Pumped hydro energy storages (PHESs) are an established and mature technology, representing the largest share of electrical energy storage worldwide [1]. While they offer

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large storage capacity in the range of 100 MW to 1 GW [2], their startup time is slow. It is fast enough to provide automatic Frequency Restoration Reserve (aFRR), which requires balancing power activation within 5 min. However, it is too slow to start up and supply Frequency Containment Reserve (FCR) from standstill, where activation must occur within 30 s [3]. While most of the unused potential of hydropower lies in developing countries, the expansion of this renewable energy form has stalled in industrialized countries [4], such as Germany, due to exhausted potentials as well as ecological and financial risks [2]. In contrast, the costs for battery energy storage systems (BESSs) have significantly decreased in recent years [5], making them an attractive technology for large-scale stationary storages. Furthermore, BESSs offer shorter response time through their power electronics, making them suitable for applications where PHESs would be too slow. Utility-scale BESS are found in the range of 1–50 MW [6]. The German energy market consists of various submarkets with different products and requirements, for which different storage systems are suitable. A hybrid storage system combining different technologies, therefore, offers the opportunity to exploit synergies and improve marketing possibilities [7]. There are already some studies about the coordinated operation of PHES and BESS in the literature [8], [9]. Examine the battery hybridization of PHES to reduce wear and [10] analyses the benefits of such coordination for FCR in the Nordic gird area and [7] for the German grid area. However, to the authors' best knowledge, in scientific literature is a lack of comprehensive works on coordinated operation of PHES and BESS for the provision of multiple ancillary services like FCR and aFRR while taking the degradation of both storage systems into account. In this study, the coordinated operation of PHES and BESS is considered as such a hybrid energy storage system. The PHES consists of a reversible pump turbine, and the BESS is assumed to be a lithium-ion battery. The overall system is depicted in Figure 1. This work is an improved version of a previously published case study [11] and improves the mathematical modeling, has an updated ageing model and considers different sizes of the BESS. The main goal of this study is to model and optimize the coordinated operation of both storages and the utilization of their respective capacity resources to maximize the generated revenues. For this purpose, a model is developed taking into account the specific characteristics, constraints, and operating states of PHES and BESS. The real location of a PHES in Herdecke, which also houses a BESS, serves as the template for the modeling [12], [13]. Market participation in the wholesale market, as well as the provision of balancing services, are integrated into the model. The PHES operates in the spot market and provides aFRR, while the BESS provides FCR and manages its charging level through the spot market. A coordination scheme for the operation of both storage systems is developed, considering the costs associated with the wear of mechanical components in the PHES and the aging of the battery cells. The optimization aims to maximize the revenue generated by the system and is implemented using the Python programming language [14] and the modeling package Pyomo [15]. The solver Gurobi [16] is used to solve the resulting optimization problem. This optimization covers a one-year period, utilizing historical market data from January 1, 2023, to December 31, 2023, which is integrated into the model. The optimization is carried out iteratively [17]. By dividing the optimization period into smaller time intervals of one day and performing iterative optimization, the total computation time can be significantly reduced, and the partial solutions can be combined into an overall solution.

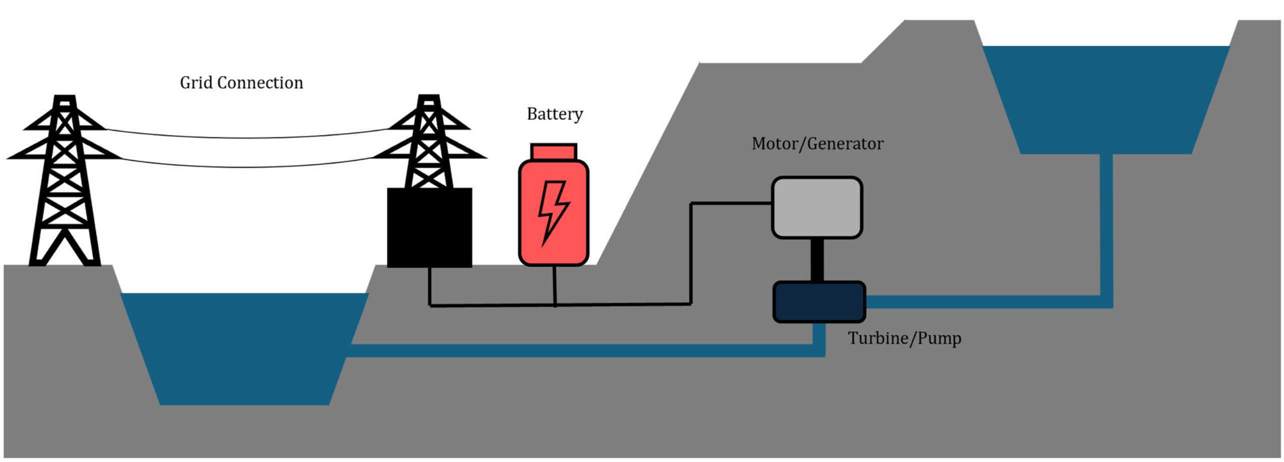

Figure 1: Structure of the PHES with reversible pump turbine and electrical machine connected to the battery energy storage system [11].

2 Modeling

The combined system and its provided services are modeled using mixed-integer linear programming (MILP), where variables can be represented as both continuous and integer values in a linear model. This modeling approach was chosen, because linear models with limited levels of detail are common for modeling and optimizing flexible energy systems [18]. The model is an improved version of a previous PHES and BESS model [11]. It introduces an ageing model, based on counting the increase of full equivalent cycles (FECs) which replaces a state of health based model. The overall modeling approach builds on a preceding model of a PHES with ternary machine set coordinated with a BESS [19] and approaches from the literature [7], [20]. The resulting optimization problem is solved through maximizing a defined objective function, which determines the optimal operating schedule of the system resulting in the highest revenue for the analyzed time period. The optimization is constructed with five-minute time steps.

2.1 Pumped hydro storage system providing automatic frequency restoration reserve

As part of the PHES modeling, the lower reservoir of the plant is considered sufficiently large in comparison to the upper storage reservoir, so it can be neglected. Therefore, for the modeling of the PHES, only the filling level of the upper reservoir is relevant, and the lower reservoir is not modelled. The filling level of the upper reservoir L in % at a given time step is determined by Equation (1). Here, V^{N} in m^3 represents the nominal storage volume of the PHES, Q_{Pump} in m^3/s represents the inflow during pumping operation, Q_{Turb} in m^3/s represents the outflow during turbine operation, and Δt in s is the length of a time step. The initial and final filling levels of the reservoir are assumed to be half full.

$$L(t) = L(t-1) + \frac{[Q_{\mathrm{Pump}}(t) - Q_{\mathrm{Turb}}(t)] \cdot \Delta t}{V^{\mathrm{N}}} \tag{1}$$

Due to the design of the reversible pump turbine, the power output of the PHES cannot be regulated in pumping operation. This means that the pump turbine can only operate at a fixed operating point during pumping. The inflow in pumping mode results from the binary on/off state u_{Pump} and the nominal flow rate $Q^{\mathrm{N}}_{\mathrm{Pump}}$ in m^3/s.

$$Q_{\mathrm{Pump}}(t) = Q^{\mathrm{N}}_{\mathrm{Pump}} \cdot u_{\mathrm{Pump}}(t) \tag{2}$$

The relationship between the flow rate and the power produced during turbine operation is considered linear in this study. The flow rate is determined by the power output P_{Turb} in MW and a constant conversion factor d_{Turb} in $\mathrm{m}^3/(\mathrm{MWs})$.

$$Q_{\mathrm{Turb}}(t) = P_{\mathrm{Turb}}(t) \cdot d_{\mathrm{Turb}} \tag{3}$$

The relationship between power and flow rate of the pump turbine is shown in Figure 2. The conversion factor is determined by the values of the maximum and minimum flow rates $Q^{\max}_{\mathrm{Turb}}$, $Q^{\min}_{\mathrm{Turb}}$ in m^3/s as well as the maximum and minimum power output $P^{\max}_{\mathrm{Turb}}$, $P^{\min}_{\mathrm{Turb}}$ in MW through linear interpolation.

$$d_{\mathrm{Turb}} = \frac{Q^{\max}_{\mathrm{Turb}} \cdot Q^{\min}_{\mathrm{Turb}}}{P^{\max}_{\mathrm{Turb}} \cdot P^{\min}_{\mathrm{Turb}}} \tag{4}$$

To adress the two marketing options for the PHES The controllable power output in turbine operation is divided into two areas. Due to the fixed operation point, the PHES can not provide balancing services during pumping operation. The output $P^{\mathrm{plan}}_{\mathrm{Turb}}$ in MW is used for pre-planned calls by spot marketing, while $P^{\mathrm{flex}}_{\mathrm{Turb}}$ MW is the flexible power used for the provision of aFRR. The turbine output during operation must be kept within its specific output limits, with u_{Turb} representing the on/off state of turbine operation and $P^{\min}_{\mathrm{Turb}}$, $P^{\max}_{\mathrm{Turb}}$ in MW the minimal/maximal power output.

$$P_{\mathrm{Turb}}(t) = P^{\mathrm{plan}}_{\mathrm{Turb}}(t) + P^{\mathrm{flex}}_{\mathrm{Turb}}(t) \tag{5}$$

$$u_{\mathrm{Turb}}(t) * P^{\min}_{\mathrm{Turb}} \le P_{\mathrm{Turb}}(t) \le u_{\mathrm{Turb}}(t) \cdot P^{\max}_{\mathrm{Turb}} \tag{6}$$

Caused by the fixed operating point in pump mode, the current pumping power results from the on/off state of the pump operation u_{Pump}. This limitation to a binary pumping mode is due to the characteristic of the reversible pump

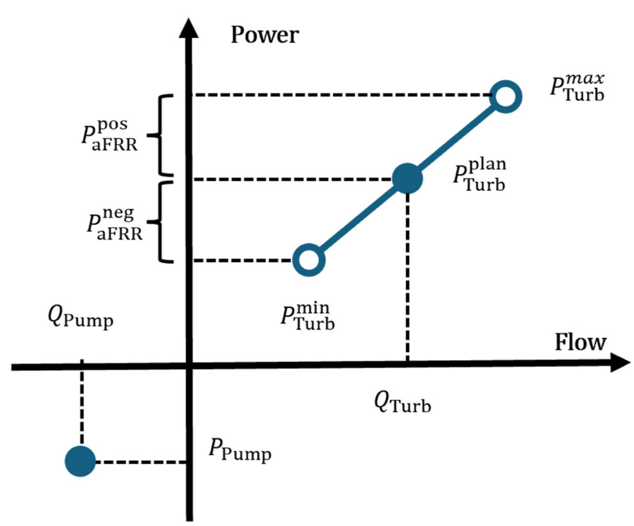

Figure 2: Relationship between power and flow rate of the reversible pump turbine during turbine operation and the fixed operation point during pumping mode (adapted from [20]).

turbine located in the PHES in Herdecke and not valid for all PHESs. Other types of PHESs without a binary pumping mode can be depicted by editing the following two equations in this modeling approach. The generated power P_{Pump} in MW therefore corresponds to the nominal power $P^{\text{N}}_{\text{Pump}}$ in MW or the pumping mode is in its off state.

$$P_{\text{Pump}}(t) = u_{\text{Pump}}(t) \cdot P^{\text{N}}_{\text{Pump}} \tag{7}$$

The reversible pump turbine can either be switched off, is active in turbine mode or is active in pump mode due to its structure. These resulting conditions for the operation are represented by the following Equation (8) in the model.

$$u_{\text{Turb}}(t) + u_{\text{Pump}}(t) \le 1 \tag{8}$$

The start/stop processes in a time step t are characterized by the variables for start v_{Turb}, v_{Pump} and stop w_{Turb}, w_{Pump}. These variables are determined through the on/off states.

$$u_i(t) - u_i(t-1) = v_i(t) - w_i(t-1), \quad \forall\ i\ \in\ \{\text{Turb}, \text{Pump}\} \tag{9}$$

The available power capacity for the provision of aFRR, both positive $C^{\text{Pos}}_{\text{aFRR}}$ in MW and negative $C^{\text{Neg}}_{\text{aFRR}}$ in MW, are determined by the distances between the planned power and the power output limits of the turbine. These distances determine the power capacities which can be offered for the provision of aFRR. It is important to note that the power capacity marketed on the balancing service markets must remain constant over a period of 4 h, in accordance with the product structure of the aFRR market.

$$C^{\text{Pos}}_{\text{aFRR}}(t) \le u_{\text{Turb}}(t) \cdot P^{\max}_{\text{Turb}}(t) - P^{\text{plan}}_{\text{Turb}}(t) \tag{10}$$

$$C^{\text{Neg}}_{\text{aFRR}}(t) \le P^{\text{plan}}_{\text{Turb}}(t) - u_{\text{Turb}}(t) \cdot P^{\min}_{\text{Turb}}(t) \tag{11}$$

The effective provision of aFRR, specified as $P^{\text{Pos}}_{\text{aFRR}}$, $P^{\text{Neg}}_{\text{aFRR}}$ in MW, corresponds to the call signals $S^{\text{Pos}}_{\text{aFRR}}$, $S^{\text{Neg}}_{\text{aFRR}}$ in MW, as long as they do not exceed the offered power capacity. If the call exceeds this capacity, only the amount of power that is in range with the offered capacity will be provided.

$$P^{j}_{\text{aFRR}}(t) \le \min(S^{j}_{\text{aFRR}}(t), C^{j}_{\text{aFRR}}(t)), \quad \forall\ \text{j}\ \in\ \{\text{Pos}, \text{Neg}\} \tag{12}$$

The parameters of the PHES were taken from the real plant in Herdecke, which has a comparable structure to this modeling approach [12]. Missing values of for the parameters were estimated based on the values used for other PHES models in the literature [20]. The values for the start-up costs of a PHES were also taken from the literature and scaled to the modelled capacity of the pump turbine. Verbundforschungsvorhaben Merit Order der Energiespeicherung im Jahr 2030. The corresponding values for the used parameters are listed in Table 1.

Table 1: Parameters and their corresponding values in the PHES model.

Parameter	Value	Parameter	Value
$P^{\max}_{\text{Turb}}$	162 MW	$Q^{\text{N}}_{\text{Pump}}$	101.7 m^3/s
$P^{\min}_{\text{Turb}}$	58.8 MW	$V^{\text{N}}_{\text{PHES}}$	1,530,000 m^3
$Q^{\max}_{\text{Turb}}$	110 m^3/s	c_{Turb}	541.1 €
$Q^{\min}_{\text{Turb}}$	47.3 m^3/s	c_{Pump}	1,374.6 €
$P^{\text{N}}_{\text{Pump}}$	153.6 MW	–	–

2.2 Battery energy storage system providing frequency containment reserve

The state of charge of the battery, expressed as SoC in %, for a specific time step is calculated similarly as the filling level of the reservoir of the PHES. This value depends on the power, the state of charge of the previous time step, the storage capacity E^{N} in MWh and Δt. The power of the battery storage system is divided into power input $P^{\text{Pos}}_{\text{BESS}}$ in MW and power output $P^{\text{Neg}}_{\text{BESS}}$ in MW, as the efficiency η of the system must be taken into account differently depending on the direction of the energy flow.

$$\text{SoC}(t) = \text{SoC}(t-1) + \frac{\left[P^{\text{Neg}}_{\text{BESS}}(t-1) \cdot \eta - P^{\text{Pos}}_{\text{BESS}}(t-1)/\eta\right] \cdot \Delta t}{E^{\text{N}}} \tag{13}$$

The two power variables are equipped with respective on/off states u_{Pos}, u_{Neg}. They can assume values in the range between zero and the nominal power of the BESS $P^{\text{N}}_{\text{BESS}}$ in MW, but, like the operational states of the PHES, they must not be active at the same time step.

$$0 \le P_k(t) \le P^{\text{N}}_{\text{BESS}} \cdot u_k(t),\ \forall\ k \in \{\text{Pos}, \text{Neg}\} \tag{14}$$

$$u_{\text{Pos}}(t) + u_{\text{Neg}}(t) \le 1 \tag{15}$$

The cyclic lifetime FEC^{N}, which is specified by the expected number of FECs, makes it possible to quantify the aging costs of the BESS [21]. By relating the power of the BESS to the energy capacity, the increase in FECs ΔFEC can be determined for each individual time step.

$$\Delta\text{FEC}(t) = \frac{\left[P^{\text{Pos}}_{\text{BESS}}(t) + P^{\text{Neg}}_{\text{BESS}}(t)\right] \cdot \Delta t}{2 \cdot E^{\text{N}}_{\text{BESS}}} \tag{16}$$

The initial costs of the battery storage c_{BESS} in €/MWh, together with the cyclic lifetime, enable the calculation of the aging costs c_{FEC} in € of the BESS per FEC [21].

$$c_{\text{FEC}} = \frac{c_{\text{BESS}} \cdot E_{\text{BESS}}^{\text{N}}}{\text{FEC}^{\text{N}}} \tag{17}$$

In the marketing of the power capacity for FCR of the battery C_{FCR} in MW, it is ensured that the offered power capacity does not exceed the nominal power of the battery storage at any time. In addition, during operation of the storage system, Equations (18) and (19) ensures that the regulatory boundaries for the SoC are met [22]. This ensures that the BESS can consistently deliver its offered power, both in positive and negative directions, for a duration of 15 min at any given time.

$$\text{SoC}(t) \leq \frac{(E_{\text{BESS}}^{\text{N}} - C_{\text{FCR}}(t)) \cdot 0.25}{E_{\text{BESS}}^{\text{N}}} \tag{18}$$

$$\text{SoC}(t) \geq \frac{C_{\text{FCR}}(t) \cdot 0.25}{E_{\text{BESS}}^{\text{N}}} \tag{19}$$

The actually provided FCR P_{FCR} in MW results from the deviation of the grid frequency Δf in Hz from its set point value of 50 Hz according to the regulation [23], including a dead band for deviations in the range of ± 0.01 Hz, as shown in Equation (20).

$$P_{\text{FCR}}(t) = \begin{cases} C_{\text{FCR}}(t), \ \forall \ \Delta f > 0.2 \text{ Hz} \\ C_{\text{FCR}}(t) \cdot \dfrac{\Delta f(t)}{0.2 \text{ Hz}}, \\ \forall \ 0.01 \text{ Hz} \leq |\Delta f| \leq 0.2 \text{ Hz} \\ 0, \ \forall \ |\Delta f| \leq 0.01 \text{ Hz} \\ -C_{\text{FCR}}(t), \ \forall \ \Delta f < -\ 0.2 \text{ Hz} \end{cases} \tag{20}$$

The parameters for the BESS were chosen according to the real storage system in Herdecke [13], whereby missing values were replaced by corresponding data from the literature [24]. A list of all used parameters and their values can be found in Table 2.

2.3 Operation of both storage systems

In the standalone operation, each storage system has its own power balance. The PHES only provides the power for aFRR and its share of the power, marketed on the spot markets $P_{\text{PHES}}^{\text{Spot}}$ in MW, while the BESS only provides power for FCR and its spot power share $P_{\text{BESS}}^{\text{Spot}}$ in MW. The Equations (21) and (22) thereby ensure, that there is now energy flow between both systems.

$$P_{\text{PHES}}^{\text{Spot}}(t) + P_{\text{aFRR}}^{\text{Pos}}(t) - P_{\text{aFRR}}^{\text{Neg}}(t) = P_{\text{Turb}}^{\text{plan}}(t) + P_{\text{Turb}}^{\text{flex}}(t) - P_{\text{Pump}}(t) \tag{21}$$

$$P_{\text{BESS}}^{\text{Spot}} + P_{\text{FCR}}(t) = P_{\text{BESS}}^{\text{Pos}}(t) - P^{\text{Neg0}_{\text{BESS}}(t)} \tag{22}$$

To implement the coordinated operation of both storage systems, they are connected via one single power balance (Equation (23)). This balance makes it possible to cover the actual power demands of FCR and aFRR with the flexible power output of the PHES and the power output of the BESS combined.

$$P_{\text{PHES}}^{\text{Spot}}(t) + P_{\text{BESS}}^{\text{Spot}} + P_{\text{FCR}}(t) + P_{\text{aFRR}}^{\text{Pos}}(t) - P_{\text{aFRR}}^{\text{Neg}}(t) = P_{\text{Turb}}^{\text{plan}}(t) + P_{\text{Turb}}^{\text{flex}}(t) - P_{\text{Pump}}(t) + P_{\text{BESS}}^{\text{Pos}}(t) - P_{\text{BESS}}^{\text{Neg}}(t) \tag{23}$$

2.4 Objective function

The objective function used, which represents the total revenue R_{total} in € generated in the operation of the system, is shown in Equation (24). The first line of this function illustrates the realized revenue from the trading in the spot market, which is made up of the energy sold/bought and the market price c_{Spot} in €/MWh. The revenue from the provision of FCR in the second line is the result of the offered power capacity and the corresponding capacity price c_{FCR} in €/MW. The revenue from the provision of aFRR is similar to that of FCR, although additional revenue is generated by the actually provided energy. Therefore, in addition to capacity prices $c_{\text{C,aFRR}}^{\text{Pos}}$, $c_{\text{C,aFRR}}^{\text{Neg}}$ in €/MW, the objective function also includes energy prices $c_{\text{E,aFRR}}^{\text{Pos}}$, $c_{\text{E,aFRR}}^{\text{Neg}}$ in €/MWh for positive and negative aFRR, as shown in the third and fourth line. The costs caused by wear and tear of the PHES result from the number of starts and the specific start costs for pump c_{Pump} in € and turbine operation c_{Turb} in €. The costs caused by the aging of the battery can be calculated from the increase in FECs and the corresponding aging costs. The spot price, FCR and aFRR data were taken from public available sources [25]–[27].

$$\begin{aligned} \text{Max } R_{\text{total}} = & \sum_t \left[P_{\text{PHES}}^{\text{Spot}}(t) + P_{\text{BESS}}^{\text{Spot}}\right] \cdot \Delta t \cdot c_{\text{Spot}}(t) \\ & + \sum_t C_{\text{FCR}}(t) \cdot c_{\text{FCR}}(t) + \sum_t C_{\text{aFRR}}^{\text{Pos}}(t) \cdot c_{\text{C,aFRR}}^{\text{Pos}}(t) \\ & + C_{\text{aFRR}}^{\text{Neg}}(t) \cdot c_{\text{C,aFRR}}^{\text{Neg}}(t) + P_{\text{aFRR}}^{\text{Pos}}(t) \cdot \Delta t \cdot c_{\text{E,aFRR}}^{\text{Pos}}(t) \\ & + P_{\text{aFRR}}^{\text{Neg}}(t) \cdot \Delta t \cdot c_{\text{E,aFRR}}^{\text{Neg}}(t) - \sum_t \upsilon_{\text{Turb}}(t) \cdot c_{\text{Turb}} \\ & + \upsilon_{\text{Pump}}(t) \cdot c_{\text{Pump}} - \sum_t \Delta\text{FEC}(t) \cdot c_{\text{FEC}} \end{aligned} \tag{24}$$

Table 2: Parameters and their corresponding values in the BESS model.

Parameter	Value	Parameter	Value
$P_{\text{BESS}}^{\text{N}}$	7 MW	c_{BESS}	276,000 €/%
$E_{\text{BESS}}^{\text{N}}$	7 MWh	FEC^{N}	3,500
η	92.7 %	–	–

3 Results

Through the optimization, an operation plan resulting with the highest possible revenue was generated for both storage systems over the considered period. However, it should be noted that this plan was created under the assumption of a perfect price forecast for the different markets. In reality, the actual generated revenue achieved will deviate from the simulated, as a perfect prediction of market prices is not possible. The total revenue and the individual revenue sources of the simulated year are shown in Table 3. By coordinating both storage systems, a significant increase in total revenue by 10.05 % was achieved in this case study. This increase in revenue is reflected in every revenue source, while at the same time the costs due to wear and tear of the PHES and the aging of the BESS were reduced through coordinated operation. The resulting operation plans of both storage systems in uncoordinated operation are shown in Figure 3 for the first 5 days of the considered period. While the standalone PHES provides balancing services during turbine operation, with both positive and negative aFRR being called up, the BESS continuously supplies FCR and varies its output in the range ±2 MW. The served calls for balance power are therefore well below the maximum nominal power capacity of the battery storage system. Occasionally there are higher power spikes, which indicate the SoC management of the BESS through the spot market. The result of the first five days for the coordinated system is illustrated in Figure 4. The operation of the PHES shows hardly any changes compared to standalone operation. This is due to the relatively high power capacity of the PHES in relation to the BESS, which means that the influence of coordination on the operation of the PHES is small. Clearer differences can be seen in the use of the BESS in the coordinated operation. There are several time periods in which the output of the battery is zero, and thus the FCR calls are covered by the PHES. In addition, significant more power peaks can be identified that indicate a more intensive use of the power capacities

Table 3: Comparison of revenues between the two operational strategies for the simulated year.

Revenue source	Standalone	Coordinated	Change
Total	40.635 Mio €	44.718 Mio €	+10.05 %
Spot	32.341 Mio €	34.298 Mio €	+6.05 %
FCR	0.741 Mio €	0.750 Mio €	+1.16 %
aFRR	9.133 Mio €	11.235 Mio €	+23.01 %
Degradation	−1.581 Mio €	−1.565 Mio €	−0.99 %

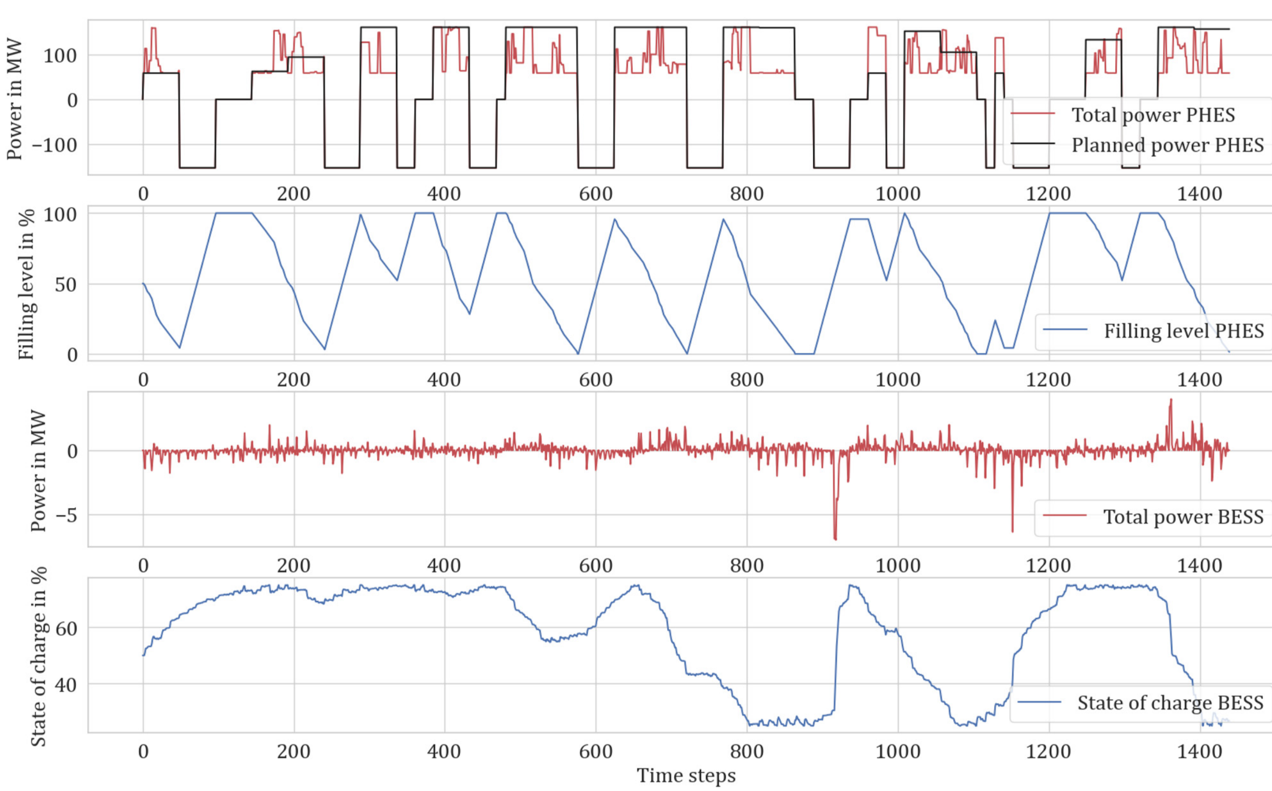

Figure 3: Optimization result for both storage systems in standalone operation for the first five days of the investigated period.

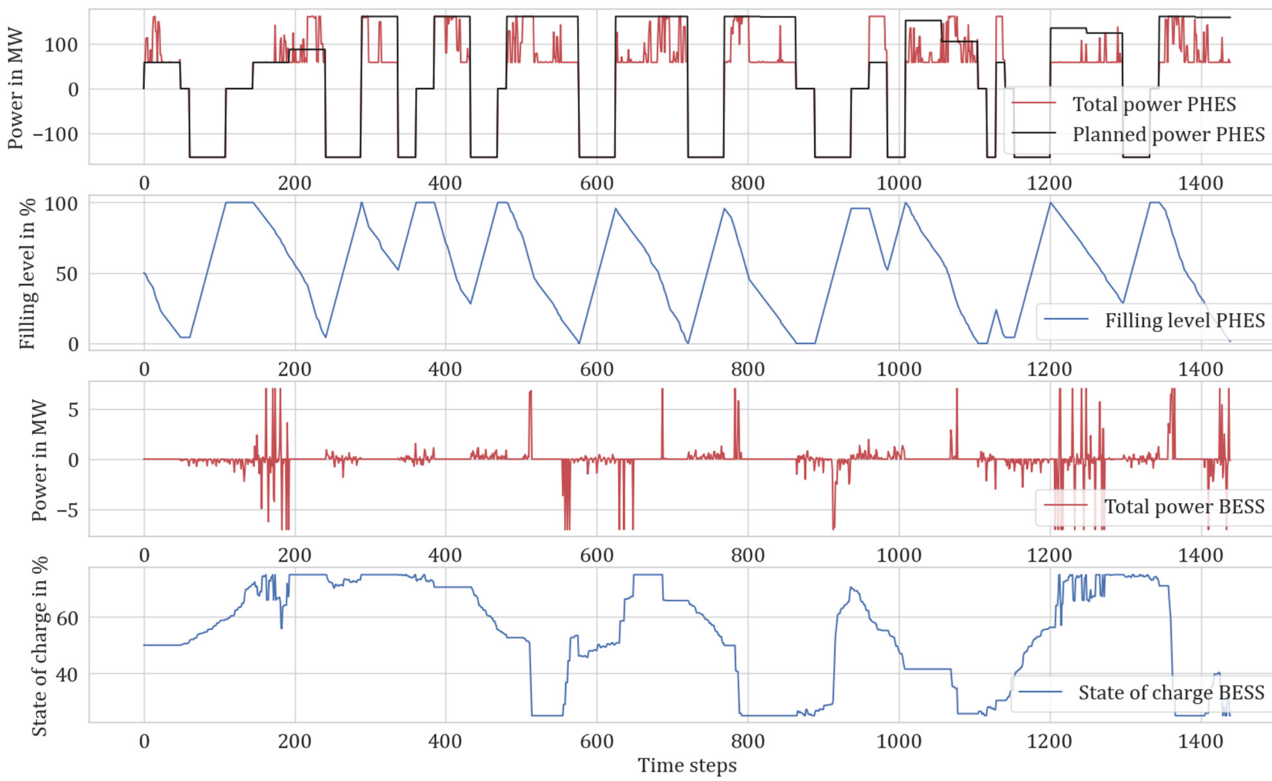

Figure 4: Optimization result for both storage systems in coordinated operation for the first five days of the investigated period.

of the BESS. Therefore, the increased profitability results from improved market participation and efficiency, which is achieved through coordinated operation planning, while taking the degradation of both storage systems into account. Compared to the previous study with a state of health based ageing model for the BESS [11], the FECs based model leads to lower impact of the operation strategy on the degradation of both storage systems. To evaluate the impact of BESS size on the added value derived from coordinated operation, the optimization process was repeated for varying power and energy capacities of the BESS. The corresponding results are presented in Table 4. The findings indicate that increasing the BESS size does not result in significant gains in revenue change. In fact, the added value from coordinated operation of the two storage systems slightly decreases. It is important to note that the additional investment costs for expanding BESS capacity were not considered in this analysis. Therefore, it can be concluded that BESS size plays a limited role in enhancing operational performance, while the primary benefit is achieved through the coordinated operation of the two storage systems itself. This finding will serve as a motivation for future research on the coordinated operation of flexible energy systems.

Table 4: Comparison of revenues between the two operational strategies for different BESS sizes for the simulated year.

BESS size	Standalone	Coordinated	Change
7 MW/MWh	40.635 Mio €	44.718 Mio €	+10.05 %
14 MW/MWh	41.292 Mio €	45.284 Mio €	+9.67 %
21 MW/MWh	42.007 Mio €	46.127 Mio €	+9.81 %
28 MW/MWh	42.575 Mio €	46.688 Mio €	+9.66 %

4 Discussion and outlook

In this study, the effectiveness of the coordinated operation of a PHES with a co-located BESS was investigated and compared with standalone operation. The Optimization is based on mathematical models for PHES and BESS, which are based on MILP and were explained in detail in this article. The results of the optimization show that the coordinated operation of both storage systems lead to a significantly higher revenue of 10.05 %, which is a considerable added value. Increasing the size of the BESS does not lead to an improvement in revenue change. This result is attributed to the fact that the additional profitability is mainly due to the flexibility gained from the coordinated operation of the two storage systems. The ratio between the capacities of the two storage systems has a comparatively smaller influence on the profitability. This study provides important insights into the technical and economic potential of coordinated operation of PHES and BESS, and lays a foundation for future research in this field. For further research, the consideration of prediction errors and the development of robust marketing strategies would be useful, which would allow the assumption of a perfect prediction of market prices to be dropped. In addition, the modeling could be extended by a more detailed consideration of complex technical aspects such as the turbine characteristic curve and a more precise aging model of the BESS. This could be done by including non-linear mechanisms using linear approximation or by converting the model to a mixed-integer nonlinear programming (MINLP) problem. Determining the optimal energy and power capacity of the BESS for the given PHES also represents an interesting research question.

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