Technical and economic analysis of curative actions in distribution networks utilizing battery energy storage systems

Ingo Liere-Netheler | Frank Schuldte | Karsten von Maydell | Carsten Agert

Abstract
Renewable energy generation curtailment increases due to more frequently occurring congestions in power system operation. Post-contingency curative congestion management actions can reduce the necessity of renewable energy curtailment by enabling a more efficient utilization of transmission capacities. In this research, the potential of curative actions to substitute renewable energy curtailment is studied considering technical and economic criteria. Therefore, a novel pricing methodology for the market-based provision of curative actions is introduced. The method is based on the security constraint optimal power flow technique. Simulations are carried out on a modified version of the IEEE 14-bus network and a real-world 110 kV distribution network. Battery energy storage systems are implemented as an exemplary technology to provide curative actions. The developed method achieves a positive system impact by reducing operational costs and maximizing renewable energy integration. Also, novel business models for merchant-owned battery energy storage systems are unveiled. The provision of curative actions further proves to be competitive to established battery storage applications. Additionally, results of different grid expansion scenarios of the 110 kV network reveal the need to coordinate power system planning and operation more extensively in the future.

1 | INTRODUCTION

Power systems are increasingly being operated near their capacity limits. This is caused by the progressive integration of distributed generation (DG) based on renewable energy sources and delayed completion of grid expansion projects. In order to cope with these challenges and ensure a secure system operation, grid operators must use operational congestion management measures. These can be divided into direct and indirect methods [1]. Indirect methods include energy pricing approaches. Research has been done on developing local energy management algorithms in order to reduce renewable energy curtailment [2] and support power system operation [3] by establishing dynamic energy prices. Battery energy storage systems (BESS) can also be utilized in local markets with the aim of reducing curtailment [4]. Especially in deregulated energy systems, local markets face acceptance problems and regulatory issues [5], which is why the focus in the remainder of this paper will be on direct methods. These include, for example, optimal switching [6], generator rescheduling [7] and load shedding [8].

Due to the ambition of operating power systems n-1 secure, direct congestion management measures can be further divided into pre-fault (preventive) and post-fault (corrective/curative) actions. Curative actions have to be activated as quickly as possible in order to avoid damage of network equipment and cascading outages. Preventive measures are usually costly because contingencies occur only with a low probability and therefore, transmission capacities remain unutilized in the undisturbed base case [9].

As the annual amount of preventive DG curtailment has increased significantly in recent years worldwide, for example, up to 6.5 TWh in Germany in 2019 [10], methods and concepts with the aim of reducing renewable curtailment have been studied extensively. Approaches for curtailment reduction reported in the literature include charging management of electric vehicles [11], load shifting [12], utilization of gas networks as energy sinks [13] and compressed air energy storages as

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flexibility providers [14]. Besides these approaches which require energy shifting potentials, especially post-contingency curative actions are assumed to have a large potential for curtailment reduction [9, 15-17]. The theoretical potential to substitute preventive DG curtailment by curative actions has been extensively investigated by the authors of this work in [15]. However, neither a quantification of available curative actions nor their economic assessment have been carried out yet.

Amongst others, BESS constitute a fast-controllable technology with the potential for curative power provision. The concept of exploiting BESS for post-contingency activation is called grid booster concept [16]. Two complementary BESS are used. One BESS before the congestion is charged and another BESS behind the congestion is discharged in order to keep the energy balanced. A major drawback of the existing concept in deregulated power systems is the fact that the BESS is owned by the grid operator. Hence, only grid supporting applications are possible since the grid operator is legally not allowed to participate in any market environment such as stock exchange markets or markets for frequency containment reserve (FCR). While market designs for system services have been studied widely, for example, FCR markets [18], approaches for market-based provision of curative actions are not available yet. Accordingly, the remainder of this paper focuses on the development of a pricing method which enables a market-based provision of curative actions by merchant-owned BESS. Pricing of system services is usually divided into a capacity price for reservation and an energy price for actual activation of the service [19]. Since two complementary BESS are considered for curative actions in this work, charging energy and discharging energy are balanced and therefore, only capacity prices need to be considered.

Implementation of curative actions into power system operation is addressed by the security constraint optimal power flow (SCOFP) technique in the existing literature [9, 20-25]. Objectives are reduction of generation costs [20, 22, 23], redispatch costs [21], instability risk [23] and amount of preventive and curative adjustments [9, 22, 24, 25].

An analytical method in order to determine prices for curative power provision as grid supporting services is not presented in the aforementioned studies.

Additionally, the perspective of BESS operators has already been discussed for different market-based applications, such as FCR [26-28], peak shaving [29-31] and combinations of multiple applications [32-34]. Hence, many studies analyse BESS profitability for different grid-oriented applications. However, the profitability of a market-based provision of curative actions from BESS has not been addressed in the literature yet.

Consequently, this paper closes the gap between power system optimization and profitability of system service provision by merchant-owned assets. A combined technical and economic assessment of the market-based provision of curative actions by BESS is carried out. The main contributions of this work thus include:

- A novel analytical pricing methodology for curative actions based on the conventional SCOFP formulation is introduced, which quantifies the economic value of curative actions in the form of nodal prices.

- A combined assessment of curative actions regarding the power system impact and the profitability for merchant-owned assets is established.

- The impact of grid expansion as a long-term congestion management measure on the developed method is evaluated based on different grid expansion scenarios. In this way, the impact of long-term planning of power systems on the proposed operational method is quantified.

- Methods for the economic assessment of market-based provision of curative actions by BESS are considered within the developed framework and curative power provision is economically compared to FCR provision as an alternative BESS application.

Table 1 gives an overview on the advantages of the proposed methods over other SCOFP-based approaches from literature. To the best of our knowledge, no other SCOFP-based study considers profitability of curative BESS and only few consider market-based provision of system services. On the contrary, studies dealing with BESS profitability [26-34] do not perform detailed power system optimization.

The remainder of the paper is structured as follows. Section 2 presents the simulation framework, including the implemented SCOFP formulation considering preventive and curative actions. The developed pricing methodology builds upon the SCOFP formulation and is presented thereafter, followed by methods for the economic assessment of BESS. Section 3 outlines simulation results from two case studies. Section 4 concludes the most relevant findings of the paper.

2 SIMULATION FRAMEWORK

The overall simulation framework is based on power system simulations in the commercial software DigSILENT PowerFactory. Power flow and contingency simulations are used in order to assess the security state of the system. The n-1 criterion is assessed deterministically in this work. Therefore, the probability of contingency occurrence is not explicitly considered in the methods used. This implies a conservative security assessment. By using the application programming interface (API), the simulation results are transferred to a python script. If congestions occur, a preventive SCOFP (PSCOFP) is solved and used to calculate nodal prices for curative actions with the novel pricing method. Then, curative actions can be acquired and implemented into the operational management of the power system with a corrective SCOFP (CSCOFP). The identified preventive and curative actions are implemented into the power system model and grid security is examined again. This loop is repeated until the identified preventive and curative actions solve all congestions. If no congestions are apparent, the solution is assessed economically and the next step is simulated.

A schematic overview of the simulation framework is given by Figure 1. The SCOFP is described in more detail in Section 2.1. The pricing methodology for curative actions is
TABLE 1 Classification of methods presented here into the existing literature

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Power system optimization objective</th>
<th>Market-based system services</th>
<th>BESS economic assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>[9]</td>
<td>Preventive and curative costs</td>
<td>Considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>[20]</td>
<td>Generation costs</td>
<td>Not considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>[21]</td>
<td>Redispach costs</td>
<td>Considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>[22]</td>
<td>Generation costs, curative adjustments</td>
<td>Not considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>[23]</td>
<td>Generation costs, instability risk</td>
<td>Not considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>[24]</td>
<td>BESS adjustments</td>
<td>Not considered</td>
<td>Not considered</td>
</tr>
<tr>
<td>This paper</td>
<td>Preventive costs, curative adjustments</td>
<td>Novel pricing method</td>
<td>NPV, BCR</td>
</tr>
</tbody>
</table>

![Figure 1](https://example.com/image1.png)

FIGURE 1 Schematic overview of simulation framework

presented in Section 2.2 and the economic indicators for BESS assessment are discussed in Section 2.3.

2.1 SCOPF formulation

The activation of preventive and curative congestion management actions is derived using the SCOPF technique. The SCOPF includes operational limits in the undisturbed grid state and different contingency events. The SCOPF technique has firstly been presented in [35] and was extended by the consideration of the short-term equilibrium state reached after contingency occurrence and before curative actions are activated in [36], which enables the conventional formulation of the SCOPF problem as follows:

$$
\min_{x^0, u^{prev}, u^{cur}} f^0(x^0, u^{prev}, u^{cur}),
$$

s.t. $g^0(x^0, u^{prev}) = 0$, (1b)

$$
\beta^0(x^0, u^{prev}) < \xi^{max},
$$

(1c)

$$
\beta^k(x^k, u^{prev}) = 0,
$$

(1d)

$$
\beta^k(x^k, u^{prev}) < \beta^{DAYL}, \beta^{MAX}, \xi^{max},
$$

(1e)

$$
\beta^k(x^k, u^{prev}, u^{cur}) = 0,
$$

(1f)

$$
\beta^k(x^k, u^{prev}, u^{cur}) < \xi^{max},
$$

(1g)

$$|u^{cur} - u^{prev}| \leq \Delta u^{max}.
$$

(1h)

Here, $x$ is the vector of state variables, $u^{prev}$ and $u^{cur}$ denote preventive and curative control variables, respectively. In the scope of this work, preventive control variables contain all DG units which can be curtailed. Curative control variables contain BESS that provide curative power to the grid operator. The superscript 0 refers to variables in the base case, $k$ includes short-term contingency variables before curative actions are activated and $k$ describes long-term contingency variables considering curative actions. The conventional SCOPF formulation contains the balance of real and reactive power in the base case (1b) and in short-term (1d) as well as long-term (1f) contingency conditions in the form of a set of equality constraint functions $g$. Also, operational limits, such as thermal limits of grid components, in all of these states are considered (1c), (1e) and (1g) by inequality constraint functions $\beta$. Here, the vector $\xi^{max}$ contains operational limits of all grid components. Additionally, the amount of curative adjustments is limited compared to the preventive state of control variables (1h).

Without the consideration of curative measures ($\Delta u^{max} = 0$), the optimization problem is also referred to as a PSCOPF and with curative actions ($\Delta u^{max} > 0$) the problem is called CSCOPF [22]. The post-fault short-term overloadability of grid components is modelled by the ratio of temporal (TATL) and permanent (PATL) admissible transmission loading in constraint (1e). The TATL is dependent on the time of contingency...
identification, the activation time of curative actions and several other parameters and can thus not be defined universally. In accordance with [37], the ratio of PATL and TATL is assumed to be 1.3 throughout this work, corresponding to an overload-ability of 30% in the short-term equilibrium state before curative actions operate.

The objective function (1a) used is as follows:

$$f^0 \left( x^0, \delta^\text{prev}, \delta^\text{cur} \right) = \sum_{i=1}^{N_{\text{prev}}} \epsilon \left( \delta^\text{prev,i} \right) + \sum_{j=1}^{N_{\text{cur}}} \left| \delta^\text{cur,j} \right|.$$  

(2)

Here, $N_{\text{prev}}$ and $N_{\text{cur}}$ describe the number of preventive ($\delta^\text{prev}$) and curative ($\delta^\text{cur}$) control variables, respectively. For the preventive actions, the cost function $\epsilon$ is minimized, whereas for curative measures, the amount of power adjustments is minimized. This is done in order to force the optimization algorithm to prioritize the utilization of available curative actions. These are rarely activated due to the low probability of contingency occurrence and can substitute cost intensive preventive actions [9]. The cost function for preventive DG curtailment is taken from [15] and is as follows:

$$\epsilon \left( \delta^\text{prev,i} \right) = \delta^\text{prev,i} \cdot 330 \cdot \frac{\text{€}}{\text{MWh}} \cdot \Delta t + 300 \text{€}.$$  

(3)

The curtailment costs of an exemplary DG unit $i$ consist of a variable part depending on the amount of power reduction $\delta^\text{prev,i}$ and the duration of curtailment requests $\Delta t$, which is assumed to be one hour throughout the remainder of the paper, and a fixed part. The fixed part is integrated in order to realize a trade-off between the amount of curtailment and the number of curtailment requests and therefore, the complexity of grid operation. A detailed derivation of the parameters is provided in [15].

Due to the decoupling of power flow and contingency simulations for initial grid states and the optimization problem (see Figure 1), the equality constraints (power flow equations) are implicitly fulfilled and do not have to be considered within the optimization problem. Additionally, the load flow equations are linearized in the recent grid state. Hence, the inequality constraints of the SCOPF (1c), (1e) and (1g) can be approximated as linear equations. The SCOPF formulation is thus converted into a linear optimization problem [38] and solved by a branch-and-cut algorithm. This simulation approach is beneficial due to the reduced complexity of the SCOPF. The approach is thus computationally efficient and usable to derive contingency management actions fast within close-to-real-time grid operation.

2.2 Pricing of curative actions

The pricing method for curative actions uses the results from the PSCOPF in the operational planning phase as input (see Figure 1). The method consists of four steps and calculates capacity prices for each grid node based on the expected amount of necessary preventive actions from the PSCOPF. The prices, which are the output of the method can further be used by the power system operator in order to acquire curative power provision by merchant-owned assets in the form of bilateral agreements. A schematic visualization of the pricing methodology is given by Figure 2.

In the first step, the resulting amount of preventive congestion management measures without any curative actions ($\Delta \delta_{\text{MAX}} = 0$) is determined exploiting the PSCOPF. Here, DG curtailment is implemented as an exemplary preventive measure. Hence, the costs of preventive measures are determined in the second step and further used to assess the value of curative actions. The price of balancing energy is considered as the value of curtailed energy. However, it is also possible to implement alternative energy prices, such as stock exchange prices. In case of multiple simultaneous congestions, the total amount of curtailment has to be allocated to the occurring congestions in the third step. Hence, for each congested grid component an allocation factor is calculated as follows:

$$\alpha_m = \frac{\Delta \delta_{\text{PATTL}} - \Delta \delta_{\text{TATL}}}{\sum_{m=1}^{N_{\text{congestions}}} (\Delta \delta_{\text{PATTL}} - \Delta \delta_{\text{TATL}})}.$$  

(5)

The allocation factor $\alpha_m$ for congestion $m$ thus results from the relative share of congestion $m$ in the total amount of congestions $N_{\text{congestions}}$ in the considered network. $\Delta \delta_{\text{PATTL}}$ and $\Delta \delta_{\text{TATL}}$ are the amounts of power reduction at congestion $m$ necessary to comply with the PATL and TATL, respectively. A violation of the TATL inevitably requires preventive measures (see Equation (1c)). Hence, curative actions are financially compensated only for the difference of PATL and TATL. If the TATL is not violated in contingency conditions, a congestion can be completely solved by curative actions and thus, the term $\Delta \delta_{\text{TATL}}$ is set to 0. Based on this allocation factor, the costs...
assigned to each congestion are calculated as follows:

$$c_m = a_m \cdot \Phi_{SCOPF},$$

(4)

Here, $c_m$ are the costs assigned to congestion $m$ resulting from the allocation factor $a_m$ and the total costs of preventive measures $\Phi_{SCOPF}$.

In the last step, the price offers for curative power provision at each grid node are determined by dividing the costs of congestions by the necessary nodal power adjustments to solve these congestions as follows:

$$p_i = \frac{\sum_{m=1}^{N_{congestion}} c_m}{P_{i,m}},$$

(5)

Here, $p_i$ is the capacity price offered for curative power provision in node $i$, $c_m$ describes the costs allocated to congestion $m$, $N_{congestion}$ is the number of congestions and $P_{i,m}$ is the necessary nodal power injection in node $i$ to solve congestion $m$, which is defined as follows:

$$P_{i,m} = \frac{\Delta P^{\text{PAVIL.}}_{i,m} - \Delta P^{\text{PAVIL.}}_{sens,m}}{\Phi_{sens,m}}.$$

(6)

The term $\Phi_{sens,m}$ is the sensitivity of real power injections in node $i$ on the real power flow in congestion $m$. The sensitivity values are calculated with the method presented in [38], which is based on the linearized relationship between nodal power injection adjustments and nodal voltage changes as follows:

$$\left[ \begin{array}{c} \Delta \theta \\ \Delta V \end{array} \right] = f^{-1} \cdot \left[ \begin{array}{c} \Delta P_i \\ \Delta Q_i \end{array} \right].$$

(7)

Here, $\Delta \theta$ and $\Delta V$ are the vectors of nodal phase and amplitude changes, respectively. $f$ is the Jacobian matrix of the power system and $\Delta P_i$ and $\Delta Q_i$ are nodal real and reactive power changes. Furthermore, power flow changes in grid components can be written in terms of nodal voltage changes as follows:

$$\left[ \begin{array}{c} \Delta P_m \\ \Delta Q_m \end{array} \right] = f^m \cdot \left[ \begin{array}{c} \Delta \theta \\ \Delta V \end{array} \right].$$

(8)

The matrix $f^m$ contains the partial derivatives of power flows after nodal voltage magnitudes and phases. Vectors $\Delta P_m$ and $\Delta Q_m$ describe changes in power flows in grid components induced by nodal voltage changes. Power flow sensitivities can then be derived by combining (7) and (8). Higher sensitivities reduce the term $P_{i,m}$ and subsequently, imply higher nodal price offers for curative power provision and vice versa.

2.3 Economic assessment of BESS

The operation of BESS providing curative actions is specified by the GSCOPF. However, the GSCOPF optimizes power system operation without considering the economic feasibility of BESS operation. In order to also consider the perspective of providers of curative actions, the profitability of BESS is evaluated separately in this work. Amongst others, net present value (NPV) and benefit-cost ratio (BCR) are typical economic indicators for the profitability of BESS projects in the literature [26–28, 32, 33, 39, 40] and are therefore also used here. These are defined as follows:

$$\text{NPV} = -C_0 - \sum_{t=1}^{T} \frac{B_t - C_t}{(1 + r)^t},$$

(8)

$$\text{BCR} = \frac{\sum_{t=1}^{T} \frac{B_t}{(1 + r)^t}}{C_0}.$$  

(9)

Income and costs in time period $t$ are $B_t$ and $C_t$ respectively. Typically, years are used as the considered time period and thus, $T$ is the battery lifetime in years. The discount rate $r$ is used to discount costs and income of a certain year. The term $C_0$ describes the initial investment costs of the battery project. A positive NPV value indicates a profitable BESS project whereas a project with a negative NPV would not be considered as reasonable since the financial benefit would then be lower than the costs of the project. For the BCR, the threshold for profitable projects is a value of 1. In general, investors aim at maximizing both the NPV and the BCR since larger values of both economic indicators increase the profitability. Table 2 shows parameter assumptions for NPV and BCR determination used in the methods.

![Table 2: Parameters for NPV and BCR calculation](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs (€/MWh)</td>
<td>400,000</td>
</tr>
<tr>
<td>C-rate (power-to-energy ratio)</td>
<td>4</td>
</tr>
<tr>
<td>Discount rate (%)</td>
<td>5</td>
</tr>
<tr>
<td>Calendrical Battery Lifetime [Years]</td>
<td>15</td>
</tr>
<tr>
<td>Annual operational costs (% of initial investment)</td>
<td>2</td>
</tr>
</tbody>
</table>

Besides the economic assessment of BESS based on NPV and BCR, also a further constraint is implemented into the BESS model in order to avoid simultaneous provision of charging and discharging capacity. This can be ensured by integrating binary state variables [41, 42]. The constraint used is as follows:

$$P_{\text{BESS}} = P_t \cdot \delta_c - P_d \cdot \delta_d,$$

(10a)

$$\delta_c + \delta_d \leq 1 \land \delta_c, \delta_d \in \{0, 1\}.$$  

(10b)

Here, $P_{\text{BESS}}$ is the amount of power provided by the BESS for curative actions and $P_t$ and $P_d$ are the maximum possible charging and discharging capacities, respectively. Charging
is considered as positive power provision whereas discharging is defined as a provision of negative curative power. $\delta_j$ and $\delta_j'$ are binary state variables. The sum of these variables must be less than or equal to 1 in any point in time. Hence, the BFESS can either provide no curative capacity, only charging capacity or only discharging capacity and simultaneous charging and discharging is not possible.

## 3 | SIMULATION RESULTS

The proposed methods have been tested on a modified version of the IEEE 14-bus test system and a real-world 110 kV high voltage (HV) network. Simulations have been performed on a personal computer with Intel (R) Core (TM) i5-4590 CPU (3.30 GHz) and 8 GB of memory. For each simulation setup, the solution of the PSCOPF without any curative actions is provided as a reference scenario.

### 3.1 | Case study: IEEE 14-bus system

The modifications of the IEEE 14-bus test system are implemented in order to force insecure operational grid states that require congestion management measures. This is done by integrating additional DG units into the original version of the 14-bus system. The total system load is 259 MW and the conventional generation is 272 MW. The resulting generation peak including the additional DG units is 1.097 GW. The modified system with the amount of additional DG power infeed is depicted in Figure 3.

### 3.1.1 | Resulting nodal prices for curative power provision

Two critical contingency events are identified which lead to the congestion of one transmission line in each case. The loading of these components in the respective contingency event and the resulting flexibility demand are depicted in Table 3. Here, the flexibility demand describes the amount of power flow reduction, which is necessary to comply with the PATL and TAIL of the transmission lines, respectively.

Transmission line 1–2 is overloaded by 158.3% and thus, also the TAIL of 130% is exceeded. Consequently, preventive actions are necessary to ensure a maximum overloading of the transmission lines in the respective contingency event below 130%. The congestion of transmission line 4–5 could completely be solved by curative actions, since the TAIL is not exceeded. Therefore, the flexibility demand $\Delta P_{\text{TAIL}}$ is negative and thus, set to 0 for the price determination of curative actions.

The PSCOPF solution contains preventive DG curtailment of 210 MW. The costs for balancing energy are considered as 30 €/MWh and the duration of the grid state is 1 h. Accordingly, the amount of curtailed energy is 210 MWh and causes costs for balancing energy of 6300 €. These costs are allocated to the congestions based on their allocation factor (see (3), (4)) determined from the values shown in Table 3. Finally, for each grid node, the amount of necessary power injections to solve the congestions is determined exploiting the power flow sensitivities (see (6)). Finally, the nodal price offers for curative power provision are calculated using the developed pricing methodology (see (5)). Exemplarily, the resulting prices for curative actions provided at grid node 4 for different amounts of power provision are visualized in Figure 4. Both the marginal prices and the absolute income are depicted in dependence of the curative power provision. Here, the marginal income represents the slope of the absolute income curve.

In order to solve the congestion of transmission line 4–5, a positive curative power provision (additional load) of 58.4 MW in node 4 would be necessary. This is shown by the left highlighted point ($P_1$) in Figure 4. For all power provisions below this point ($P < P_1$), the marginal price is 29.01 €/MW and the

---

**TABLE 3** Severity of congestions and resulting flexibility demand

<table>
<thead>
<tr>
<th>Congestion</th>
<th>Loading (%)</th>
<th>$\Delta P_{\text{PATL}}$ [MW]</th>
<th>$\Delta P_{\text{TAIL}}$ [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L01-02</td>
<td>158.3</td>
<td>134</td>
<td>66</td>
</tr>
<tr>
<td>L04-05</td>
<td>116.6</td>
<td>42</td>
<td>-31</td>
</tr>
</tbody>
</table>

**FIGURE 4** Absolute and marginal income dependent on the amount of curative power provision in grid node 4
absolute income thus increases linearly. An additional load in node 4 with a higher curative power provision (P_2) does not have an added value for this congestion since it is completely resolved. Therefore, the marginal price decreases for larger curative power provision to 21.59€/MW and thus, the absolute values increase with a smaller slope. The right highlighted point (P_2) describes the maximum potential of positive curative power provision in node 4 in order to terminate the second occurring congestion in this operational state. Since the congestion of transmission line 1–2 cannot totally be solved by curative actions (ΔP_{\text{STATE}} > 0), only the difference between ΔP_{\text{STATE}} and ΔP_{\text{CATAL}} is financially compensated. Beyond this power injection of 127.5 MW, no additional benefit can be realized for any congestion. Accordingly, the marginal price is 0 €/MW and the absolute income remains constant. Subsequently, a higher curative power provision does not increase the possible income of a merchant-owned BESS and would not be reasonable in this specific grid state and scenario.

### Table 4: Operational costs of PSCOPF and CSCOPF solutions

<table>
<thead>
<tr>
<th>Solution</th>
<th>Curtailment Costs (€)</th>
<th>Costs of curative power provision (€)</th>
<th>∑</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSCOPF</td>
<td>6300</td>
<td>0</td>
<td>6300</td>
</tr>
<tr>
<td>CSCOPF</td>
<td>4200</td>
<td>2019</td>
<td>6219</td>
</tr>
</tbody>
</table>

#### 3.1.2 Operational costs of PSCOPF and CSCOPF solution

In order to assess the capability of the proposed pricing method to optimize power system operation, the PSCOPF solution is compared to the CSCOPF solution with an exemplary 75 MW/18.75 MWh BESS installed at grid node 4. The PSCOPF and CSCOPF problem are solved using the branch-and-cut algorithm in python. The costs of preventive DG curtailment and curative power provision for the PSCOPF and the CSCOPF solutions are compared in Table 4.

The additional curative power provision by the BESS reduces the costs for preventive DG curtailment from 6300 € in the PSCOPF solution to 4200 € in the CSCOPF solution. Additionally, the battery is compensated with 2019 €. Consequently, the total operational costs can be slightly reduced from 6300 € in the preventive solution to 6219 € in the CSCOPF solution. Furthermore, the amount of preventive DG curtailment can be reduced by 33% in comparison to the PSCOPF solution. Hence, the results indicate the potential of the proposed pricing methodology to provide lower cost solutions compared to the PSCOPF and maximize the integration of renewable energy generation into the power system at the same time.

However, to assess the practicability especially in terms of an economically reasonable BESS operation, a more practical case study should be investigated for a longer time period than just one exemplary grid state. For this reason, the application of the presented methods to the model of a real 110 kV HV distribution system located in the North-West of Germany is considered in the next section and time series simulations are executed for the time horizon of 1 year.

### Table 5: Power system key parameters of case study in different scenarios

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NE</td>
</tr>
<tr>
<td>Peak load (MW)</td>
<td>881.35</td>
</tr>
<tr>
<td>Peak DG infed (MW)</td>
<td>2650</td>
</tr>
<tr>
<td>Number of grid nodes</td>
<td>100</td>
</tr>
<tr>
<td>Total line length (km)</td>
<td>822</td>
</tr>
<tr>
<td>BESS capacity (MW/MWh)</td>
<td>57.14.25</td>
</tr>
</tbody>
</table>

#### 3.2 Case study: 100-Bus 110 kV system

The model of the 110 kV HV distribution network is provided by the grid operator Avacon Netz. In order to estimate the future demand for congestion management in this grid, a scenario for the increase in DG penetration for the target year 2030 has been presented in [43] and is used in this case study. Time series simulations for the target year 2030 with a resolution of 1 h are applied. Measurements of real and reactive power at the interconnection points to the subtransmission medium voltage level are available from the reference year 2016 as input data. These are disaggregated into load and generation by the method presented in [44] and scaled up to the installed capacities in 2030. The resulting network is characterized by an annual peak load of 881.35 MW and a maximum DG infed of 2650 MW.

In order to display uncertainties in the necessity and timely realization of grid expansion measures until the target year 2030, three different scenarios representing distinct grid expansion stages are derived for this case study. These include the scenario no expansion (NE), delayed expansion (DE) and complete expansion (CE). The scenarios represent different transmission capacities in the considered 110 kV network. Furthermore, in each scenario different BESS are integrated into the system for the provision of curative actions. The power system parameters for this case study including the differences in grid capacities and BESS capacities between the three scenarios are shown in Table 5.

#### 3.2.1 Comparison of PSCOPF and CSCOPF solutions

**Impact on power system operation**

Again, the branch-and-cut algorithm in python is used to solve the PSCOPF and CSCOPF problems. The PSCOPF solution is used as a reference scenario to assess the effectiveness of the proposed pricing method for curative actions. The operational costs in the three investigated scenarios are visualized in Figure 5. A price of 35 €/MWh is assumed for loss energy.
Moreover, the proposed pricing methodology determines the battery remuneration in the CSCOPF solution. According to Figure 5, the operational costs are highly dependent on the grid expansion scenario. The annual costs of the PCSOPF solution are 29.82 M€ in scenario NE, 14.85 M€ in scenario DE and 26.45 M€ in scenario CE. In scenarios NE and DE, the total operational costs are mainly driven by the share of balancing energy costs. Due to the extensive grid expansion measures in scenario CE, the demand for preventive DG curtailment is reduced significantly and the costs for grid losses are predominant. In all scenarios, operational costs are lower in the CSCOPF solution compared to the PCSOPF solution (28.74 M€ in scenario NE, 14.79 M€ in scenario DE and 25.43 M€ in scenario CE). Accordingly, the combined additional costs for compensation of curative actions and for the increase in grid losses are lower than the reduction of costs for preventive DG curtailment. Additionally, the provision of curative power in the CSCOPF solution reduces the preventive amount of DG curtailment significantly from 1026 GWh to 893 GWh (18%) in scenario NE, from 423 GWh to 245 GWh (42%) in scenario DE and from 64 GWh to 49 GWh (23%) in scenario CE. Hence, not only the operational costs are reduced but also the integration of renewable energy generation into the power system is increased.

This is further clarified by the annual rates of energy curtailment in Table 6. For the sake of comparability, the results are compared to the studies of [45] and [46], which both analyze the resulting curtailment demand in a reference scenario without BESS utilization and in a scenario with BESS being deployed. As can be seen from Table 6, the curtailment rates of the PCSOPF without curative actions are 11.98%, 4.95% and 0.75% in scenarios NE, DE and CE. These values refer to the total annual energy production of DG systems considered. The reduction of DG curtailment through using the CSCOPF instead of the PCSOPF is higher compared to the results presented in [45] (11.92% reduction) in all scenarios. The reduction achieved in [46] of 37.80% is larger compared to scenarios NE and CE and smaller compared to scenario CE. Overall, the CSCOPF solution achieves considerable reduction in DG curtailment in all scenarios.

Scenario CE shows the lowest operational costs but on the other hand causes the largest investment into new transmission lines compared to the other scenarios. This aspect should also be evaluated in further studies but is out of the scope of this paper, that focuses on operational analyses rather than power system planning issues.

Altogether, the developed pricing method incites the reduction of DG curtailment by using cheaper curative congestion management measures in each grid expansion scenario.

**Increase of reactive power demand**

The boxplot in Figure 6 shows the distribution of the reactive power demand within the simulated year for all grid states with occurring congestions.

In each scenario, the grid is characterized by an inductive rather than a capacitive reactive power demand. This is due to the mainly inductive behaviour of overhead transmission lines and transformers included in the grid model. According to Figure 6, the PCSOPF solution is accompanied by a slightly larger reactive power demand in scenarios NE and DE. Moreover, the impact of curative actions in scenario CE is negligible due to the reduced battery size. Furthermore, the difference between the scenarios is significantly larger than the difference between the PCSOPF and CSCOPF solution within the respective scenarios. This can be explained by the significant differences in the implemented curtailment measures. The large amount of grid expansion in scenario CE enables a higher utilization of assets and therefore, increases the reactive power demand. Overall, the increase in the reactive power demand of
TABLE 7 NPV and BCR values in the three scenarios compared to the studies of [26,27] and [39–40]

<table>
<thead>
<tr>
<th>Scenario/literature contribution (battery size)</th>
<th>NPV (M€)</th>
<th>BCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE (57 MW/14.25 MWh)</td>
<td>47.93</td>
<td>4.48</td>
</tr>
<tr>
<td>DE (73 MW/18.25 MWh)</td>
<td>52.13</td>
<td>3.96</td>
</tr>
<tr>
<td>GE (17 MW/4.25 MWh)</td>
<td>1.50</td>
<td>1.37</td>
</tr>
<tr>
<td>Frequency regulation (50 MW/12.50 MWh) [26]</td>
<td>24.56*</td>
<td>1.22</td>
</tr>
<tr>
<td>Frequency regulation (55 MW/21.5 MWh) [27]</td>
<td>31.97</td>
<td>n.a.</td>
</tr>
<tr>
<td>Frequency regulation + arbitrage trading</td>
<td>2.05*</td>
<td>n.a.</td>
</tr>
<tr>
<td>(10 MW/10 MWh) [39]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grid investment deferral + frequency regulation</td>
<td>4.94*</td>
<td>3.75</td>
</tr>
<tr>
<td>(6 MW/14.5 MWh) [40]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Values in the original publication are given in US$ and have been converted to € with an assumed exchange rate of 1 US$ = 0.84 €.

the power system due to the commitment of post-contingency curative actions turns out to be significantly lower compared to the increase caused by grid expansion measures.

3.2.2 Profitability of curative power provision

Resulting NPV and BCR values

The profitability of the BESS in the three scenarios is assessed based on the realized NPV and BCR values derived from the annual simulations, which are given by Table 7. In order to increase the comparability of the results, also the NPV and BCR values of different literature studies with alternative BESS applications are depicted in Table 7 if available.

The highest NPV in the considered literature studies is achieved in [27] with 31.97 M€. Here, the BESS size and C-rate are similar to scenario NE in this work. However, the achieved NPV of the BESS providing frequency regulation is considerably lower than the NPV values in scenarios NE (47.93 M€) and DE (52.13 M€) in this work. Moreover, the highest BCR in the literature studies is realized in [40] with a value of 3.75. This is also exceeded by the values in scenarios NE (4.48) and DE (3.96). The realized NPV (1.5 M€) in scenario CE of this work is the lowest compared to all literature studies whereas the BCR value (1.57) is the second lowest.

Altogether, the profitability of providing curative power with BESS is competitive and can even be larger compared to other applications, such as FCR or arbitrage trading. However, it is associated with larger uncertainties in the long term due to the expansion stage of the power system and the resulting demand for operational congestion management.

Compatibility with alternative BESS applications

The CSCOPE simulations carried out in this case study assumed a complete availability of BESS for the provision of curative actions. However, the real-time operation of BESS is usually optimized towards the most profitable application, as for example, presented in [47]. Consequently, technical potentials for the provision of curative actions by BESS can be unavailable at certain times if other applications offer higher profits. In order to quantify the availability of merchant-owned BESS for curative actions, the provision of FCR is analysed as an exemplary alternative BESS application, since FCR is recently a common application for BESS in the German power system [48].

The FCR price has decreased drastically within the last few years, especially in 2019 and 2020 [48]. Therefore, differing from the reference year 2016 for all other used data in this work, the FCR prices for daily products from July 2019 to June 2020 are used in this work.

The comparison of curative prices and FCR prices is visualized in Figure 7 for an hourly market horizon and each scenario. Note that the relative price for curative power provision is not constant but rather dependent on the amount of power provision, as demonstrated for the IEEE 14-node case study in Figure 4. In each graph, the price for curative power provision (PCUR) and the FCR price (PFCR) are shown on the x-axis and y-axis, respectively. The dots represent hours of the simulated year. Moreover, Figure 7 only contains hours with a demand for curative actions due to occurring congestions. Blue dots represent time points with higher FCR prices and green dots with higher curative prices. Both areas are divided by the linear grey curve representing identical FCR and curative prices.

According to Figure 7, curative prices are higher than the FCR prices most of the time in all graphs. The curative prices are subject to larger fluctuations, whereas the FCR prices are more constant. The maximum hourly price for curative actions (258 €/MW in scenario NE, 270 €/MW in scenario DE and 209 €/MW in scenario CE) is significantly higher than the maximum FCR price (66 €/MW).

Altogether, the provision of curative actions proofs to be competitive to the provision of FCR, which is currently a popular form of marketing merchant-owned BESS. Prices for curative actions have large temporary peaks and are subject
3.3 Computational performance of SCOPF

The methods are developed in order to be implemented into close-to-real-time applications in operational grid management. Therefore, efficient computation is required. Table 8 shows the average computation time of the branch-and-cut algorithm implemented in the SCOPF formulation per time step in each case study. In order to increase the comparability with alternative methods, also the best results from one central SCOPF algorithm presented in [22] and one distributed algorithm in [49] are depicted.

The distributed approach from [49] achieves the smallest computation time of 0.006 s per call. However, it has to be noted that the algorithm is a distributed algorithm without overall system knowledge and therefore not applicable for grid control centre integration. Also, the algorithm is not tested on a larger scale power system. Compared to the alternative central algorithm from [22], the approach presented here achieves considerable reduction in computation time. Also, the algorithm shows to be robust in terms of the size of the considered power system since the difference between the 14-node case study and the considerably larger 100-node system is low.

Altogether, it can be concluded that the proposed SCOPF implementation is applicable for implementation into close-to-real-time applications in operational management. In general, distributed algorithms are superior regarding computation time but do not consider the overall system. In order to further improve the computational efficiency of the proposed SCOPF and enable close-to-real-time applications also in very large-scale networks, the method could also be transformed into a partly distributed algorithm by dividing the considered power systems into different zones based on the existing power flow sensitivity model.

<table>
<thead>
<tr>
<th>Case study</th>
<th>Average solver time (s)</th>
<th>Number of buses</th>
<th>Type of algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 14-node</td>
<td>0.107</td>
<td>14</td>
<td>Central</td>
</tr>
<tr>
<td>100-bus 110 kV</td>
<td>0.144</td>
<td>100</td>
<td>Central</td>
</tr>
<tr>
<td>[22]</td>
<td>2.3</td>
<td>96</td>
<td>Central</td>
</tr>
<tr>
<td>[49]</td>
<td>0.006</td>
<td>26</td>
<td>Distributed</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

The implementation of novel curative actions on the distribution grid level with the aim of reducing preventive DG curtailment is discussed. A novel approach for the market-based acquisition of curative power provided by merchant-owned BESS is presented. The proposed pricing methodology is based on the conventional PSCOPF technique and the curative actions are integrated into grid operation by a SCOPF approach.

Based on extensive simulations in the IEEE 14-node case study and the 100-node real-world HV distribution network, the methods proved to reduce operational costs of power systems, increase DG integration and offer novel business models for merchant-owned BESS. The reduction of preventive curtailment in the IEEE 14-node case study by implementing curative actions is 33%, while costs of power system operation could slightly be reduced by 1.3%. In the 100-bus case study, operational costs could be reduced by up to 4% while preventive DG curtailment was reduced by up to 42%. At the same time, BESS NPVs of up to 52.13 M€ could be accomplished. Additionally, results of different grid expansion scenarios revealed large interdependencies between long-term planning and the operational management of power systems. This is reflected by large differences in the reference PSCOPF simulations between the scenarios. The demand for preventive DG curtailment is 1026 GWh in scenario NE, 423 GWh in scenario DE and 64 GWh in scenario CE. Altogether, curative actions prove to be a sufficient tool in order to reduce preventive DG curtailment. Results show that the increase in grid losses and reactive power demand of the network caused by the implementation of curative actions are negligible. Furthermore, the market-based provision of curative actions is economically reasonable also for merchant-owned assets, such as BESS. Therefore, the market-based provision of curative should be established for future applications since it is beneficial both for power system operators and for merchant operators. Due to the large interdependencies between the demand for operational congestion management and long-term power system expansion, both domains should be tightly synchronized in the future.

The methods proposed in this work can further be developed in future studies by considering a probabilistic assessment of n−1 security, uncertainty in DG operation, novel market structure enabling trading of curative actions between multiple power system operators and merchant owners and implementation into power system planning in order to support long-term investment decisions.

NOMENCLATURE

- API: application programming interface
- BCR: benefit-cost ratio
- BESS: battery energy storage system
- CSCOPE: corrective security constrained optimal power flow
- DG: distributed generation
- FCR: frequency containment reserve
- HV: high voltage
- NPV: net present value
- PATL: permanent admissible transmission loading
- PSCOPF: preventive security constrained optimal power flow
- SCOPF: security constrained optimal power flow
- TATL: temporary admissible transmission loading
Indices

\( i \) index to the set of preventive control variables
\( j \) index to the set of curative control variables
\( k \) index of contingencies after activation of curative actions
\( k^c \) index of contingencies before activation of curative actions
\( l \) index to the set of grid nodes
\( m \) index to the set of occurring congestions
\( t \) index to the set of time points in the lifetime of BESS

Parameters

\( f_{\text{max}} \) vector of operational limits (MW)
\( N_{\text{congestions}} \) number of occurring congestions per time step
\( N_{\text{cont}} \) number of curative control variables
\( N_{\text{prev}} \) number of preventive control variables
\( P_{\text{restr}} \) permanent admissible transmission loading (MW)
\( P_{\text{ext}} \) temporary admissible transmission loading (MW)
\( r \) discount rate (%)
\( T \) battery lifetime (years)
\( \Delta u^{\text{max}} \) vector of maximum adjustments of control variables between base case and contingency events

Functions

\( c \) cost function of preventive congestion management actions
\( f^0 \) objective function of the SCOPF formulation
\( g^k \) equality constraints in the base case
\( g^k \) equality constraints in contingency event \( k \) after activation of curative actions
\( g^k \) equality constraints in contingency event \( k \) before activation of curative actions
\( h^0 \) inequality constraints in the base case
\( h^k \) inequality constraints in contingency event \( k \) after activation of curative actions
\( h^k \) inequality constraints in contingency event \( k \) before activation of curative actions

Variables

\( BCR \) benefit–cost ratio of BESS projects
\( B_i \) income of BESS projects in time period \( t \) (€)
\( c_m \) costs allocated to congestion \( m \) (€)
\( C_i \) costs of BESS projects in time period \( t \) (€)
\( NPV \) net present value of BESS projects (€)
\( P_{\text{BESS}} \) curative power provided by BESS (MW)
\( P_i \) maximum charging capacity of BESS (MW)
\( P_i \) maximum discharging capacity of BESS (MW)
\( p_i \) price of curative power provision at grid node \( l \) (€/MW).
\( P_{\text{m}} \) necessary power adjustments in node \( l \) to solve congestion \( m \) (MW)
\( \mu^{\text{cont}} \) vector of curative control variables
\( \mu^{\text{prev}} \) vector of preventive control variables
\( x^0 \) vector of state variables in the base case
\( x^k \) vector of post-contingency state variables after activation of curative actions
\( x^k \) vector of post-contingency state variables before activation of curative actions

\( \delta_1 \) binary state variable for BESS charging
\( \delta_2 \) binary state variable for BESS discharging

ACKNOWLEDGEMENTS

The authors would like to thank all project partners of the research project ‘enera’. In particular, the authors thank Avacon Netz GmbH for providing their grid model. Furthermore, the authors thank EWE NETZ GmbH for the provision of the aggregated load time series and the German Meteorological Service (DWD) for providing meteorological data through the COSMO-DE model. Open access funding enabled and organized by Projekt DEAL.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Avacon Netz GmbH and EWE NETZ GmbH. Restrictions apply to the availability of these data.

CONFLICT OF INTEREST

We have no conflicts of interest to disclose.

REFERENCES


41. Shen, Z., Wei, W., Wu, D., Ding, T., Mei, S.: Modeling arbitrage of an energy storage unit without binary variables. CSEE J. Power Syst. 7(1), 156–161 (2021)


