Interaction between the Distribution System Operator and the Battery Storage Operator for Flexibility Procurement Services

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***Abstract*—Fast penetration of the renewable energy sources and transition toward sustainable energy supply paradigm is currently an ongoing process. It comes with many environmental benefits, but it also creates many challenges. Distribution System Operators are forced to move on from the fit-and-forget approach and take more active role in operating distribution system to face problems such as bidirectional power flows, congestion and voltage limits violation. This article, taking into consideration that regulated entities cannot interfere with market activities, proposes interaction between distribution system operator and battery storage operator for flexibility procurement and investing in battery storage units at the most critical points in the network. Firstly, using AC OPF, most critical nodes are detected and then optimal energy and power capacity of the battery storage units are determined. Value of the flexibility service is determined by observing the profit difference from an optimal market participation strategy with and without network constraints.**

***Index Terms*—battery; storage; siting; sizing; flexibility; investment**

I. Introduction

A. Motivation

The beginning of the 21st century is greatly affected by the ambitious set of measures that are to enable energy transition from the centralized fossil fuel based concept toward renewable energy sources (RES) oriented centralized paradigm. Industry and academia backed up by many world leaders are putting in a lot of effort both on developing policies and technical solutions to enable sustainable energy supply (e.g. Clean Energy Package [1]). When analyzing the state of progress, it may be seen that many initiatives are already in some extent reality. From high RES penetration, production and sale of electric vehicles (EVs) (in Norway in January 2022, 83.7% off sold vehicles were EVs [2]), to transformation of previously passive entities to more active roles. However, as a side effect, distribution system operators (DSOs) face many new challenges in ensuring safe and reliable power supply. Potential obstacles include bidirectional power flows, voltage deviations and generally congestion problems. In that manner, DSOs may no longer use only fit-and-forget approach and they are required to take a more active role [3]. This approach includes other solutions than network expansion, such as flexibility procurement and investments in energy storage units. Energy storage units present a great tool to take advantage of the periods when there is abundance of supply and lack of demand, and help by: [4], [5]:

- Increasing existing network capacity and postponing network expansion
- Enhancing power quality
- Reducing system losses
- Performing local balancing
- Providing frequency ancillary services
- Providing black start and backup energy

Having in mind that DSOs in Europe are strictly regulated and aren't allowed to interfere with the market activities, generally DSO shouldn't invest in such assets themselves. Hence, ideally the DSO would procure flexibility from the profit oriented stakeholders. On the other hand, profit-oriented stakeholders may, in addition to the usual market participation activities (e.g. arbitrage between day-ahead market (DAM) and intraday market (IDM)), help the interested DSO by providing flexibility services for a certain increase in their overall profit. But in no case at the cost of profit reduction. One of the possible approaches is that the DSO, as entity with knowledge about network constraints, places a tender for specific locations and battery storage unit (BSU) characteristics. Should no market participant accept the tender (place a bid), this then allows the DSO to invest in the BSU if the network analysis shows the need for it.

B. Literature Review

Participation of the BSUs in modern power system paradigm is already widely researched topic. Many articles discuss optimal siting and sizing of BSUs both on the transmission and the distribution level. Wogrin et al. [6] have used DC OPF to study the influence of the optimal siting, sizing and

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operation of the energy storage units (ESUs) on operational expenditure (OPEX). The results have shown a difference between energy and power based ESUs at the transmission level, with a note that in various congestion situations, a hybrid energy-power portfolio exhibits the best results. Pandzic et al. [7] used three-stage mixed integer programming and lossless DC transmission network representation to find optimal sizes and locations of BSUs, considering also the optimal operation of potential BSUs. Whereas Hassan and Dvornik [8] used bilevel programming to optimally site and size the ESUs. Upper level minimizes DSO's OPEX and capital expenditure (CAPEX) and models the distribution system using AC OPF, while lower level maximizes the social welfare and models the transmission system using DC OPF. The result indicates that the ESUs located at the distribution level may be of help both to the transmission and distribution systems if their operators are coordinated. Boonluk et al. [9] used genetic algorithm and particle swarm optimization approaches to optimally size and site BSUs in a distribution network with high share of RES to reduce voltage deviations, power losses and peak demands. They argue that their approaches improved the efficiency of the observed IEEE 33-bus distribution network. On the other hand, Zhang et al. [10] simultaneously considered optimal allocation (siting and sizing) of a BSU and a photovoltaic generation to improve system resilience. Their multi-objective optimization has three main objectives: i) the investment and operation costs, ii) the capacity accessibility for electricity demand, and iii) the capacity accessibility for non-black-start generating units. Rodriguez-Gallegos et al. [11] also observed a simultaneous optimal allocation of various units (diesel generators, PV panels and batteries) for an off-grid system with the total system cost minimization objective. Two-stage particle swarm algorithm firstly determined optimal site and size of the system and delivered optimal schedule. The result showed the financial and technical benefits of using combined diesel generators, PV panels and batteries compared to the case where some of these three were left out. Ehsan and Yang [12] determine the optimal mix, siting, and sizing of wind turbine, photovoltaic, and BES units to maximize the net present value of DSO while fully exploiting the BSU's arbitrage benefit. Their proposed solution, consisting of a scenario-based stochastic active distribution network planning model using the heuristic moment matching method, outperformed deterministic planning model.

Besides optimal siting and sizing, numerous scientific papers deal solely with optimal scheduling and bidding of the BSUs, having in mind different objectives. For instance, Karandeh et al. [13] present optimal energy scheduling algorithm using linear programming for solar power smoothing, based on the predicted day-ahead demand and PV generation output. Whereas Pandzic et al. [14] presented a bilevel model for optimal battery storage participation in day-ahead energy market as a price taker, and reserve capacity and activation market as a price maker. They argued that regardless of the relatively low battery size compared to the overall reserve market, the battery storage can significantly affect it, because the activated energy is rather low. Steriotis et al. [15] emphasize the need for power system flexibility under high RES penetration circumstances and recognize the potential of distributed energy resources to provide the necessary flexibility. They proposed a bilevel model for participation in traditional transmission level wholesale markets and newly proposed distribution level flexibility market. They argue that their model achieves super-linear gains. Meaning that the BSU owner/operator obtains significantly higher profits through the joint optimization of both the TSO and the DSO services than the sum of the individual profits from devoting the BSUs to one of the two applications.

It may be observed that both siting and sizing of the BSUs and their scheduling are widely researched topics. Plenty of articles are focusing on these topics either together or separately. As far as the author knows, what lacks is deeper research how could BSUs provide flexibility services at the distributional level. What technical and legislative obstacles such framework may present, and the most important question - what are the potential benefits for system operators and flexibility providers. Steriotis et al. [15] have gone in that direction taking into account distribution level flexibility market in their stacked revenues model, but there is still a big research gap considering distribution level flexibility and DSO - BSU operator cooperation under high RES penetration circumstances.

C. Paper Contribution and Structure

The focus of this paper is the DSO-BSU operator interaction. DSO wants to use flexibility services to ensure safe and reliable power supply in the most economically and technically adequate manner, whereas BSU operator seeks for profit increase opportunities. More precisely, we have defined a model for finding optimal locations and BSU capacities from the DSO's side and then cost-benefit analysis from the potential BSU investor. The article presents tender process proposal where firstly DSO runs AC OPF and determines sites and sizes of BSU, then the flexibility procurement values are defined by comparing BSUs optimal operation and profit considering network constraints and without network constraints.

The rest of the paper is structured as follows. Mathematical formulation of the model is given in Section II. The case study and results are presented in the Section III. The final conclusion and further research thoughts are given in the Section IV.

II. Mathematical Formulation

A. 1st stage

The goal of the 1st stage is to, from the DSO's perspective, choose optimal locations and BSU's characteristics to help secure safe and reliable supply with minimum costs taking into consideration network constraints. In that manner, Branch-flow model [16], [17] is used to model AC OPF. When the most promising candidate is found, the algorithm is run once more to determine is the problem feasible with possible location locked to only that from the most promising candidate. If the problem is feasible, we proceed to the second stage. If not, next most promising candidate's location is also added to the problem, and this is done iteratively until the problem becomes feasible.

The objective function minimizes the system losses ($loss_t^{cost}$) and BSU investment cost ($batt^{cost}$). For the system losses calculation, day-ahead market (DAM) price is used and multiplied with the energy lost (squared current multiplied with line resistance), whereas BSU investment cost include per diem cost for energy capacity (€/MWh) and power (€/MW).

$$\min_{varijable} \sum_{i=1}^{N} [\sum_{t=1}^{T} loss_{i,t}^{cost} + batt_i^{cost}] \tag{1}$$

Constraint (2) models the active power flow between nodes. $P_{ij,t}$ denotes the active power flow between the nodes $i - j$, $i_{ij,t}$ is the squared current between those nodes and R_{ij} line resistance. $p_{j,t}^{gen}$ is a variable which represents active power output from a generator located in the node j, whereas $P_{j,t}^{load}$ is a parameter depicting demand in the node j. $dch_{j,t}$ and $ch_{j,t}$ are variables representing battery discharging and charging, respectively, in the node j. The last term in the constraint - $\sum P_{jm,t}$ denotes power flows between the node j and all other neighbouring nodes.

$$\begin{aligned} p_{ij,t} = i_{ij,t} \cdot R_{ij}(p_{j,t}^{\text{gen}} + dch_{j,t} - p_{j,t}^{\text{load}} - ch_{j,t}) \\ + \sum_{m:j \longrightarrow m} P_{jm,t}, \quad \forall ij, t \end{aligned} \tag{2}$$

Constraint (3) models the reactive power flow in the analogous manner as the above presented constraint. Hence, reactance is relevant (X_{ij}). Reactive power generation and battery input through an inverter are variables, and reactive demand is a parameter.

$$\begin{aligned} q_{ij,t} = i_{ij,t} \cdot X_{ij} - (q_{j,t}^{\text{gen}} - q_{j,t}^{\text{load}} + q_{j,t}^{\text{batt}}) + \\ \sum_{m:j \longrightarrow m} Q_{jm,t}, \quad \forall ij, t \end{aligned} \tag{3}$$

Node voltages are modeled with the constraint (4), where $u_{i,t}$ represents squared voltage and the constraint models voltage drop between two nodes.

$$\begin{aligned} u_{j,t} = u_{i,t} - 2(R_{ij,e}P_{ij,t} + X_{ij,e}Q_{ij,t}) \\ + i_{ij}(R_{ij,e}^2 + X_{ij,e}^2), \quad \forall i, j, t \end{aligned} \tag{4}$$

Constraint (5) in the exact formulation should be an equality which connects current, voltage and power. Such formulation is non-convex. Hence, the formulation is relaxed in a form of the rotated second-order cone constraint [18]

$$i_{ij,t} \cdot u_{i,t} \geq p_{ij}^2 + q_{ij}^2, \quad \forall ij, t \tag{5}$$

Constraints (6), (7) and (8) state allowed ranges for active and reactive power generation, and allowed node voltages, respectively.

$$P_i^{\text{gen,min}} \cdot x_{i,t}^{gen} \leq p_{i,t}^{\text{gen}} \leq P_i^{\text{gen,max}} \cdot x_{i,t}^{gen}, \quad \forall i, t \tag{6}$$

$$Q_i^{\text{gen,min}} \leq q_{i,t}^{\text{gen}} \leq Q_i^{\text{gen,max}}, \quad \forall i, t \tag{7}$$

$$U_i^{\text{min}} \leq u_{i,t} \leq U_i^{\text{max}} \quad \forall i, t \tag{8}$$

BSU's state of energy is modeled in the constraint (9) with variable $soe_{i,t}$ representing state of energy of a BSU on the node i in the time unit t and parameter η depicting battery charging and discharging efficiency.

$$soe_{i,t} = soe_{i,t-1} - dch_{i,t} \cdot \frac{1}{\eta} + ch_{i,t} \cdot \eta \tag{9}$$

Constraint (10) limits the BSU's maximal charging power, whereas constraint (11) limits the BSU's maximal discharging power. p_i^{ch} and p_i^{dch} are variables rather than parameters, because the goal in this stage is to calculate optimal BSU's charging and discharging powers in addition to BSU's optimal location and energy capacity.

$$p_i^{\text{ch}} \cdot x_{i,t}^{\text{bin}} \geq ch_{i,t}, \quad \forall i, t \tag{10}$$

$$p_i^{\text{dch}} \cdot (1 - x_{i,t}^{\text{bin}}) \geq dch_{i,t}, \quad \forall i, t \tag{11}$$

Constraint (12) determines BSU's starting state of energy.

$$soe_{i,0} = 0, \quad \forall i \tag{12}$$

Constraint (13) limits the maximum energy capacity of the BSU. $batt_i^{cap}$ is a variable so the optimal energy capacity may be found.

$$soe_{i,t} \leq batt_i^{cap} \tag{13}$$

BSU combined with an adequate inverter may provide both active and reactive power to the system, hence constraints (14) and (15) limit apparent power that may be provided by the respective BSU (i.e. inverter). q^{batt} may be positive and negative, as reactive service may be offered in inductive and capacitive mode.

$$(p_i^{ch})^2 \geq (ch_{i,t})^2 + (q_{i,t}^{batt})^2 \tag{14}$$

$$(p_i^{dch})^2 \geq (dch_{i,t})^2 + (q_{i,t}^{batt})^2 \tag{15}$$

B. 2nd stage

The idea of the second stage is to determine the value of the flexibility that BSU operator provides to the system. We propose following simple, but rather efficient method to determine the minimal compensation from the DSO to the BSU operator. Firstly, for the BSU(s) (power, energy capacity and node location) proposed in the stage 1, optimization algorithm that maximizes profit from participating in various energy markets is run without network constraints, and then with network constraints. The difference between the BSU operator's profit in those two cases is the flexibility fee that BSU operator is entitled to. Following constraints illustrate network unaware case, whereas constraints (2) - (8) need to be added for the network aware case.

The objective function (16) minimizes the costs of participating in various markets (i.e. maximizes profit). Observed markets are DAM, intraday market (IDM) and balancing market (BM). With λ_t^* denoting hourly prices for respective markets.

$$\min_{varijable} \sum_t^T \sum_i^I [DAM_{i,t}^{\text{cost}} + IDM_{i,t}^{\text{cost}} + BM_{i,t}^{\text{cost}}] \quad (16)$$

where

$$DAM_{i,t}^{\text{cost}} = (ch_{i,t}^{\text{DA}} - dis_{i,t}^{\text{DA}}) \cdot \lambda_t^{\text{DA}}, \quad \forall i,t \quad (17)$$

$$IDM_{i,t}^{\text{cost}} = (ch_{i,t}^{\text{ID}} - dis_{i,t}^{\text{ID}}) \cdot \lambda_t^{\text{ID}}, \quad \forall i,t \quad (18)$$

$$BM_{i,t}^{\text{cost}} = dev_{i,t}^{\uparrow} \cdot \lambda^{\text{BM}\uparrow} + dev_{i,t}^{\downarrow} \cdot \lambda^{\text{BM}\downarrow}, \quad \forall i,t \quad (19)$$

subject to

Constraints (20) and (21) limit the maximal discharging and charging power in the DAM, considering a binary variable $x_{i,t}^{DA}$ which determines is the BSU in the charging or discharging mode and maximal allowed battery power outputs, with $dev_{i,t}^{*}$ representing deviation from the DAM schedule settled in the BM.

$$dis_{i,t}^{\text{DA}} - dev_{i,t}^{\uparrow} \leq \overline{\text{P}}_i^{\text{dch}} \cdot x_{i,t}^{\text{DA}} \quad \forall i,t \quad (20)$$

$$ch_{i,t}^{\text{DA}} - dev_{i,t}^{\downarrow} \leq \overline{\text{P}}_i^{\text{ch}} \cdot (1 - x_{i,t}^{\text{DA}}) \quad \forall i,t \quad (21)$$

The same principle as for the DAM is also used for the IDM, and it can be seen in the constraints (22) and (23).

$$dis_{i,t}^{\text{ID}} \leq \overline{\text{P}}_i^{\text{dch}} \cdot x_{i,t}^{\text{ID}} \quad \forall i,t \quad (22)$$

$$ch_{i,t}^{\text{ID}} \leq \overline{\text{P}}_i^{\text{ch}} \cdot (1 - x_{i,t}^{\text{ID}}) \quad \forall i,t \quad (23)$$

Observing BSU's market participation in the various markets simultaneously, constraint (24) depicts all BSU's activities.

$$g_{i,t} = ch_{i,t}^{\text{DA}} - dev_{i,t}^{\downarrow} + ch_{i,t}^{\text{ID}} - dis_{i,t}^{\text{DA}} + dev_{i,t}^{\uparrow} - dis_{i,t}^{\text{ID}} \quad \forall i,t \quad (24)$$

Constraint (25) is the connection between the BSU's net activity ($g_{i,t}$), and its charging ($c_{i,t}$) and discharging ($d_{i,t}$) processes. Hence, when using constraints described in the stage 1 for the stage 2, instead of $ch_{i,t}$ and $dch_{i,t}$; $c_{i,t}$ and $d_{i,t}$ are used.

$$g_{s,k,t} = c_{s,k,t} - d_{s,k,t} \quad \forall s,k,t \quad (25)$$

Constraints (9) - (15) are necessary in all cases but with important note that in the 2nd stage, battery capacity and power ratings are parameters (as is the location also).

III. Case Study

The proposed concept is tested on a 15 bus radial distribution system from Das et al. [19] and it is presented on the figure 1. DAM and IDM prices are taken from the Croatian Power Exchange (CROPEX [20]), whereas BM prices are calculated according to the current Croatian legislative [21]. For the computational reasons, the algorithm validation has been run on a optimization horizon of one day with typical prices which are shown in the Table I. The extension of this model will take into consideration broader price horizon as this is important factor for investment decisions. Different active and reactive loads are present from the bus 2 to 15. In the current setup, there are no generators, loads may be supplied from the active network and from potential BSUs that are also interacting with the active network.

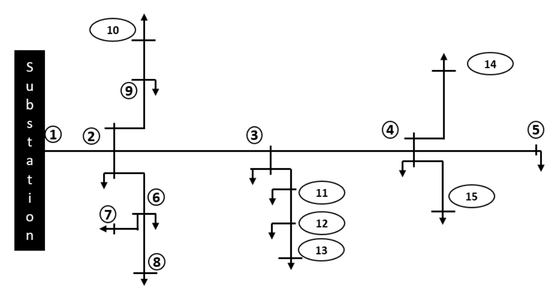

Fig. 1. Radial dsitribution network

TABLE I
PRICES IN DIFFERENT MARKETS [€/MWh]

Hour / Market	1	2	3	4	5	6	7	8
DAM	22.75	39.5	19.03	23.95	39.93	39.5	60.33	67.00
IDM	31.70	28.16	24.79	24.00	27.00	45.00	63.76	77.96
BMu	13.71	55.54	11.47	14.43	24.06	23.80	36.36	46.65
BMd	13.71	55.54	11.47	14.43	24.06	23.80	36.36	46.65
Hour / Market	9	10	11	12	13	14	15	16
DAM	75.7	72.62	69.58	67.89	65.65	63.91	63.6	63.43
IDM	81.00	88.91	105.93	80.33	90.92	80.45	56.99	64.15
BMu	53.03	102.12	93.03	40.91	92.31	89.87	89.43	89.19
BMd	53.03	102.12	93.03	40.91	92.31	89.87	89.43	89.19
Hour / Market	17	18	19	20	21	22	23	24
DAM	62.59	61.24	63.46	70.05	71.44	62.41	62.97	60.72
IDM	61.46	63.45	84.04	83.67	89.63	70.65	69.79	67.16
BMu	82.84	79.96	89.23	95.39	93.70	37.61	37.95	36.59
BMd	82.84	79.96	89.23	95.39	93.70	37.61	37.95	36.59

A. Stage 1

In the stage 1, bus 11 is determined as the most critical bus for the feasibility of the AC OPF problem. Hence, to ensure safe and reliable power supply, the potential BSU candidate is located at the bus 11 and properly sized to help the respective DSO maintain allowed power voltages and avoid problems in operating the network. For the observed network this is the expected outcome, because load 11 is in some moments far grater than the load in any other bus. Furthermore, without line expansion and BSU, it wouldn't be possible to supply load 11 from the active network. To have better understanding of the order of magnitude of the load 11, figure 2 clearly demonstrates it.

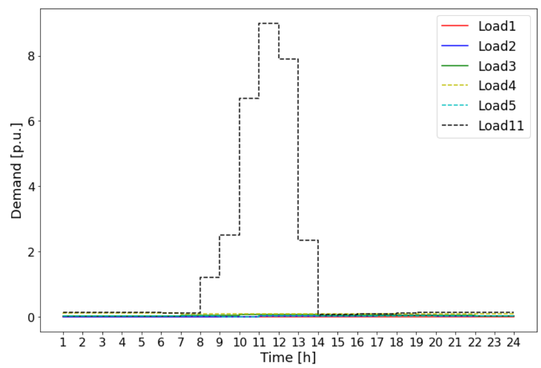

Fig. 2. Load 11 and five other loads for comparison purposes

Stage 1 proposed a BSU located at the bus 11 with the energy capacity of 18.98 MWh, charging power of 4.26 MW and discharging power of 6.65 MW. Those exact values were obtained in the second iteration of the Stage 1 when the location was locked and then energy and power capacity were determined for the BSU at the bus 11. Compared with the initial values (when all locations were allowed), BSU energy capacity was increased by 2.2%, charging power by 13.6% and discharging power by 6.40%. Hence, it may be observed that the critical point is charging power so the BSU may procure enough energy in appropriate time units.

B. Stage 2

The two main objectives of the second stage are to determine BSU's optimal operation strategy and to determine the value of the flexibility that the respective BSU is providing to the DSO. This is done by running optimal scheduling algorithm using the BSU with the characteristics obtained in the first stage with and without network constraints. In the both cases BSU operator earns money by conducting market arbitrage, but network constraints limit the operator according to the network characteristics. Figure 3 clearly shows the market arbitrage concept with many observed time units were battery is physically not charging, nor discharging. Although BSU's net activity is zero, it still generates profit by selling and buying the same amounts of energy for the same delivery times but in different markets so it can take advantage of the price difference. Of course, to do that in reality, market and generation forecasts are of the utmost importance. Taking uncertainty into consideration goes beyond the scope of this paper and it will be included in the future extensions of this model. By observing time period between hour 8 and 14, when load 11 greatly increases, it is clear how market arbitrage activities are lower in the case with network constraints compared to the case without network constraints. Resulting with greater profit in the network non-aware case, but ensured feasibility in the network aware case. For the BSU observed in this case (18.98 MWh), profit at the end of the day when network constraints are take into consideration is 2312.29 €, whereas in the network non-aware case profit is 2390.13 €. So addition of the network constraints reduces BSU's profit by about 3.3%, and this is the price of flexibility that DSO should pay BSU operator. Moreover, the calculated flexibility fee (in this case 77.84 € per day) may be used as great benchmark for DSO's cost-benefit analysis whether it makes more sense to invest in network expansion or procure flexibility.

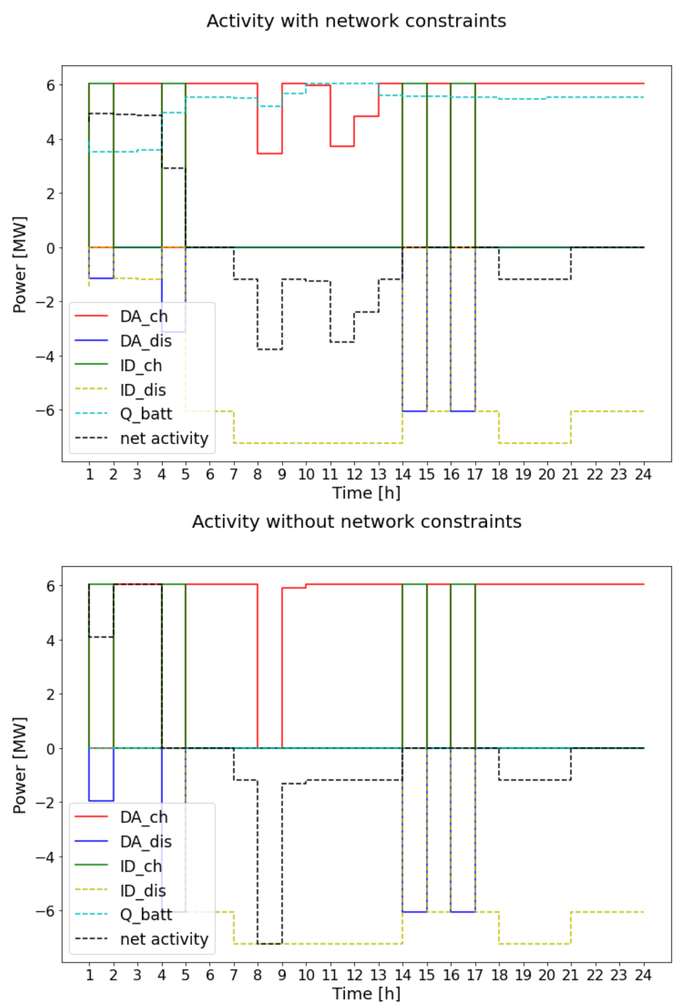

Fig. 3. BSU activity

IV. Conclusion

DSOs are facing many challenges in the ongoing transition toward sustainable electrical energy supply paradigm. Bi-directional power flows, congestion and voltage deviations are problems that DSOs need to resolve by taking much more active role than passive fit-and-forget approach. First and foremost, flexibility need at the distribution level is of enormous importance. This article has proposed an algorithm to determine ideal locations (including energy and power capacities) of potential BSUs at the most critical nodes in the observed distribution network. Moreover, investment in the proposed candidate BSUs ensures network feasibility and enables network expansion cost deferral. The method results in a concrete figure that DSO may use to choose whether it makes more sense investing in the network expansion or flexibility procurement service when conducting a cost benefit analysis. The method itself still has space for many enhancements. Further research will deal with taking into consideration of market and forecast uncertainties, taking into account much wider time horizon (as this is an investment problem) and a deep analysis of current BSUs investment and degradation costs.

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