Value of Storage in Distribution Grids—Competition or Cooperation of Stakeholders?

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***Abstract*—The implementation of storage capacities in distribution grids is seen as an important element for the integration of fluctuating feed-in caused by photovoltaic and wind generators. However, the responsibility for the operating of these assets is not defined in most market designs. Since decreasing costs are to be expected with further market penetration, next to distribution grid operators (DSO) further storage stake holders may be interested in controlling local storage devices. In this paper optimal storage profiles for different stakeholders (DSO and energy traders) are derived based on a case study with real world data. The results reveal conflicting interests—peak shaving of fluctuating feed-in (objective o the DSO to avoid reinforcements) is hampered significantly by storage usage of trading companies (objective of exploiting price spreads in the spot market). It is shown that unreasonable high costs occur with undesired economical side-effects if no control or cooperation mechanism is implemented.**

***Index Terms*—Electricity supply industry deregulation, energy management, energy storage, photovoltaic cells, power distribution, power generation, smart grids.**

I. Introduction

THE INCREASE of electricity generation out of renewable energy sources (RES-E) poses major challenges on grid operators to integrate the fluctuating generation. In Germany, especially distribution grid operators (DSO) are faced with massive reinforcement needs since 97% of the photovoltaic (PV), wind and biomass generators are connected to these voltage levels [1]. The social and political objective in Germany and many other countries is to further increase the RES-E capacities to reduce the carbon footprint and enable the phasing out of nuclear power. However, distribution grids have not been built for the large amounts of distributed generation—according to an investigation of the BDEW, a reinforcement need with additional cables of a length of 380 000 km is estimated in German's medium and low voltage grids with costs of more than 20 billion Euro (€) until 2020 [2].

The current regulation design forces grid operators to adjust investment and operation strategies on efficiency criterions. Hereby, the incentive regulation is a very common used approach to regulate grid operators. Examples for this kind of regulation are the revenue cap regulation (e.g., in Germany) or yardstick competition, e.g., implemented in the Netherlands (see [3] and [4] for an overview in the context of smart grids and current challenges for grid operators and regulation agencies). Thus, DSOs aim to find alternative solutions for the integration of RES-E compared with the conventional reinforcement with additional assets like cables, lines and/or transformers.

One "smart" solution of reinforcement is the implementation of local (distributed) storage capacities. In combination with information and communication technologies (ICT), used to measure and analyze the real situation in the grid, the storage assets can avoid local voltage and load problems. To achieve this, the surplus feed-in is stored and withdrawn in case of a lack of feed-in with a need for energy to cover consumption. By this, a lower variation of the voltage and load value can be achieved as well. This peak-shaving scenario is the main objective of the DSO for introducing storage assets. Moreover, additional positive effects for other parts of the energy supply chain may occur: the installation of storage capacities in distribution grids may avoid that a feed-in peak produced by simultaneous feed-in of PV and/or wind generators is transferred to the next upstream grid levels (e.g., the transmission grid). Further positive effects are enabled for conventional generation types due to a more levelled way of production. Finally, an increased market penetration of storage assets may lead to decreased prices and enable more installations also in islanded grids to integrate RES-E.

In the above context, it is not clear which role DSOs have with the integration of distributed storage systems and what scope of responsibilities they have. It is also unclear if other storage stakeholders, for example energy traders, may support a cost-efficient integration of RES-E or even cause additional grid problems leading to increased reinforcement needs. To investigate this topic, in this paper the optimal usage of local storage capacities for different storage stakeholders is derived based on a case study. Since the optimization objectives differ for DSO and energy trader, different profiles for the usage of the storage capacity are expected. The executed simulations are based on real measured local production and consumption data in a distribution grid area as well as on real spot market prices in Germany. We focus on the German market since this is one of the largest markets for decentralized PV and wind generation. However, the corresponding technical and economic effects are likely to occur also in a lot of other countries in the future.

As the grid is faced with a lot of PV, wind, and biomass generators leading to a bidirectional, fluctuating energy flow, the optimal usage profile of the storage asset from the perspective of the DSO is oriented on peak shaving to reduce reinforcement needs for further RES-E integration. In contrast to this, the

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optimal storage usage of an energy trader focuses on the maximal profit by buying electricity at low price periods and selling it when prices are high (arbitrage). The profiles of the energy flows resulting from these different objectives are compared to reveal complementary or supplementary operating conditions. The results enable a discussion started in this paper on the reasons and consequences of an intervention of DSOs when integrating storage assets in distribution grids.

The paper is built up as follows. In Section II the background of this work is presented by giving a short overview on related work. Furthermore, the reasons for focusing on the two chosen stakeholders (DSO and trader on the spot market) are explained. Section III contains the description of the case study. For this, the situation in the underlying distribution grid is explained as well as current (spot) market designs and the integration of RES-E in these markets. The approach for calculating the optimal storage usage for 1) peak shaving (perspective of the DSO) and 2) maximizing arbitrage (perspective of the energy trader) is presented in Section IV followed by the results in Section V. We end up with a discussion and proposals for an improved and efficient integration of distributed storage assets in Section VI and a conclusion in Section VII.

II. Related Work

The importance of storage assets for the integration of RES-E is in general undisputed since the fluctuating feed-in of PV and wind requires storage of electricity as well as an improved adjustment of consumption to the production. This is all the more important since, e.g., in Germany, within the next years the installed capacity of PV and wind generators exceeds in some time periods the consumption within the national transmission grid and, thus, the energy needs to be stored to ensure the security of supply. In certain distribution grids with a rural character, lots of RES-E is combined with a low total consumption, which shows that this effect may already exist nowadays.

The importance of storage assets as an essential contribution to reach climatic objectives with increased RES-E is discussed in [5]. Next to large-scale technologies (such as pumped hydro power and compressed air storage) also some distributed storage alternatives (such as batteries) are presented. Further overviews on current technologies for storage systems are presented in [6]–[8]. The usage of storage assets for the avoidance of grid extensions in distribution grids is discussed in [9] with a presentation of a biogas buffer balancing the feed-in of biogas and PV generation enabling a flattened feed-in profile and reduced feed-in peaks. The combination of two different types of storage technologies such as lead-acid and super-caps is presented in [10]. The goal is to exploit the advantages of both technologies reducing the wear and tear and increasing the profitability.

Distributed storage systems may cover a wide range of applications in grids. Depending on the chosen technology, the appropriate usage may focus on power (e.g., ancillary services with fast reacting battery technologies, such as Li-Ion or super caps) or on energy issues, e.g., for compensating fluctuations in the feed-in of RES-E and peak shaving. Typical technologies able to operate with the latter described situations are lead-acid and redox-flow systems. Hereby, the c-rate is a common used and technology specific parameter for batteries indicating the (discharge) power rate normalized to the total energy content [11]. Hence, the choice of the technology has to consider the objective and situation or operation, but both priorities, power and energy issues, can be considered with appropriate technologies.

The support for new technologies in the storage sector is likely to lead to reduced prices for storage assets due to economies of scale and economies of learning. This may enable a profitable implementation of storage devices not only from the view of grid operators by avoiding conventional grid extensions—but also other storage stakeholders like energy traders may participate. In this context, the storage asset is used for arbitrage purposes to exploit price spreads at the imbalance- or spotmarket. This scenario is presented in [12]. It is stated that for the Dutch energy market in the years 2000–2004 the imbalance market was the most profitable market due to largest price spreads. However, the forecasting of the imbalance market with its stochastic character is much more difficult compared with the spot market and its more regular patterns. Thus, the theoretical potentials of revenues in imbalance markets are higher, but are subject to much more risk. The study in [10]concentrates only on traded electricity—grid benefits and restrictions have not been considered.

In [13] a multi-objective approach is presented considering grid objectives as well as arbitrage purposes and an optimal sizing and siting of storage assets is derived. However, since we focus on the real world energy supply chain with separate, unbundled market roles and their different optimization objectives, the focus of the research differs significantly.

A further important application of storage assets is the RES-E integration in islanded grids. For this, the storage is used to balance fluctuations in generation and consumption. However, the usage in such scenarios is mainly determined by the technical objective for the operation, e.g., to avoid black-outs. As a consequence, in islanded operation in principle one stakeholder is responsible for the storage and, thus, conflicting potential for the operation of the storage by different stakeholders is not as relevant as for distribution grids in industrial countries with a lot of different stakeholder operating in it.

The German regulation agency states in [14] that a market mechanism should not be aligned to support grid purposes. In contrast, the grid should enable the market mechanism to exploit its potential. As it is shown in [15] this philosophy may lead to undesired economic effects from a welfare point of view since the grid reinforcement costs can exceed significantly the cost savings on the consumer and/or supplier side. Hence, it seems question able whether official parties, such as the regulation agency, recognize the reasonable cooperation of market roles as an important factor of success for the implementation of smart grids or not. With a more future perspective, [16] assumes that with more decentralized generation, there is a greater need for a more integrated view on transmission, distribution and storage.

The former mentioned optimization approaches in [12] and [13] derive the theoretical reachable maximum profits. These theoretical profits imply perfect forecast of future prices and (as in our case) of feed-in and consumption data. In real world applications, predictions are never perfect. Therefore a control methodology is needed that approximates the benefits of a theoretical optimization with perfect knowledge by using only the information that is available in real-time. Such an approach is presented in ([17]–[19]). The control methodology TRIANA consists of the three steps forecasting, planning and real time control. However, for the purposes in this work, the theoretical optimization is appropriate to show the different resulting profiles for the storage stakeholders, regardless of with what kind and accuracy of forecasting and real time control this maximum can be achieved in reality.

Summarizing, the usage of storage assets for different purposes and the compatibility of these profiles in distribution grids is a relatively new topic. We investigate such a situation with a case study, which is presented in the next section.

III. Case Study

This section contains a short description of the used data in the case study. Hereby, the focus is on a real rural 30-kV-distribution area in Emsland, Germany, which is exemplary for a lot of other distribution grid areas (i.e., the nationally harmonized feed-in support leads to comparable load profiles in other regions). In the downstream 10-kV and 1-kV voltage levels the given consumers and feed-in capacities are connected. In the past, the energy flow only went from the 30-kV voltage levels passing the transformer to supply the distribution grid area. Nowadays, at certain times with lots of PV, wind, and biomass generation, a load reversal occurs. In principle, this bidirectional energy flow is not critical for the installed assets. However, the feed-in capacities still experience significant growth rates. Since DSOs are forced by law to connect all the generators to the grid, transport the energy and reinforce the grid assets[1], a massive investment need is expected (see e.g., [2]). As described in Section I, this reinforcement is primarily done with additional cables and transformers.

To give an indication of the bidirectional energy flow, the load profile of the distribution grid area is presented in Fig. 1 for a one week period. The measured values of the 30/10-kV transformers are used to derive this load profile. Note that a positive value of the power passing the transformer indicates a surplus energy in the distribution grid area which is transported via the 30-kV grid to the next substation with a higher voltage level (110-kV). Thus, in these periods with positive flows a "net" production of the area is given, in contrast to the periods with "net" consumption indicated by negative values. The periods with negative values in Fig. 1 occur especially in the evening and night hours with absent of sun. In the course of this section, we first deepen the insights in the grid related issues followed by elaborations dealing with the trading part of the supply chain.

Fig. 1 visualizes the load reversal which occurs especially in the noon since a lot of PV generators are connected to the grid. Furthermore, since assets in grids have to be dimensioned for the maximum energy flow occurring, the figure indicates that for this area the production scenario is more critical than the consumption scenario. This is supported also by the fact that

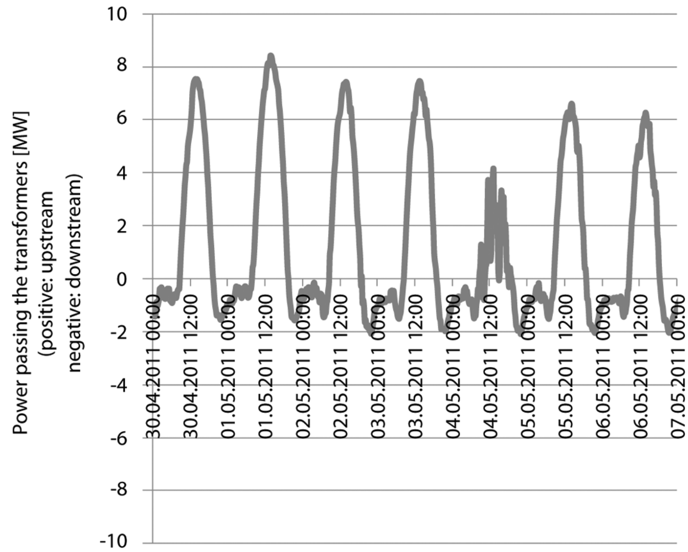

Fig. 1. Power passing the transformer for a time period of 7 days.

the maximum downstream value (consumption) over the whole year is -5.03 MW (occurred in March) and the maximum upstream value (production) is 8.43 MW. The latter value occurred on May 1st, which was a Sunday with low consumption but high sun radiation and hardly clouds in the considered area. Considering the complete time period of one year, the average value in the 15-minute intervals is -0.28 MW , indicating that despite the high, but unsteady feed-in peaks, the area is still a net consumption area. Since PV is one of the most growing generation types in Germany, this profile is likely to be seen in a lot of other distribution areas. Note that still a further increase of the feed-in in this rural area is expected. Therefore, in this area the implementation of storage capacities may be an alternative for the reinforcement with additional assets accompanied by positive effects for the rest of the supply chain as mentioned in Section I.

Next to the DSO, also energy traders may have an interest in installing storage capacities, if economically feasible. To reveal the optimal storage usage profile of such an energy trader, the German EPEX spot market prices are considered. The spot market offers short-term contracts with a fulfillment of the transactions immediately (intraday market) or with one day delay (day-ahead market). Compared with long-term contracts (e.g., Futures), the intraday and day-ahead prices are characterized by a relatively large price volatility. In our scenarios, the trader is assumed to be a "price taker," so the own consumption or feed-in will not have an effect on the price itself. This seems to be a reasonable assumption due to the negligible power (2 MW) of the battery compared with the total load in the transmission system. The objective of the energy trader is on (time) arbitrage to use time periods on the spot market with low prices for buying energy to be stored and to withdraw energy in periods with high prices.

In the considered data set with German hourly prices of 2011 we find an average price for the day ahead product (EPEX Spot Phelix Day Ahead) of 51.12 €/MWh with a standard deviation of 13.60. The intraday price (EPEX Spot Intraday) with 51.19 €/MWh shows a similar level, but is even more volatile (standard deviation of 15.49) [20].

[1]In Germany, the Erneuerbare-Energien-Gesetz (EEG) has been introduced in the year 2000 with its latest amendment in the year 2011. According to the Global Status Report of REN21 [22], similar laws (e.g., with feed-in tariffs including premium payments) have come into force in 57 countries.

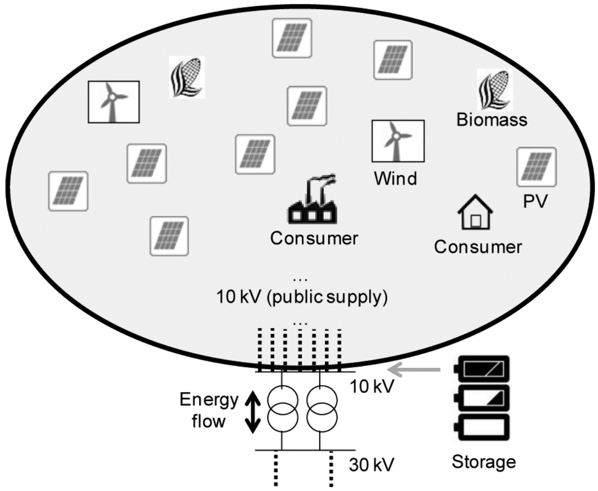

Fig. 2. Scheme of supply in the case study.

In the current German market design, the relation of feed-in of local RES-E capacities and spot market prices is given by the real time merchandising of the RES-E capacities. For this, the forecasted RES-E profiles are determined for each transmission grid area and placed as a bid in the day ahead auction by the transmission system operator at the German spot market. Thus, a negative correlation should be expected (the higher the RES-E feed-in, the lower the prices). However, the correlation of distributed feed-in and spot market prices is influenced by many other parameters, such as total load, amount of conventional generation or RES-E feed-in in other distribution areas or transmission grids. Furthermore, the RES-E operator is not necessarily incentivized to react on price signals since current feed-in laws in Germany enable an unlimited priority of RES-E with fixed feed-in tariffs. These elaborations indicate also the assignability of these developments to other countries with similar market structures of (regulated) distribution grid operators and (non-regulated) trading companies operating at an energy spot market as well as countries faced with a transition from conventional, large scale power generation to renewable, decentralized generation (such as PV).

Another aspect to be treated is the placement of the batteries. The distribution grid is faced with a lot of RES-E capacities as well as consuming devices. The storage asset should be used to avoid or delay additional reinforcements (e.g., in bigger dimensioned 30/10-kV transformers) and enable a more flattened profile passing the transformer. For the energy trader it is important to install distributed storage capacities in voltage levels with relatively low installation costs (thus, 10-kV is more appropriate than 30-kV) but relatively high capacities (thus, 10-kV is more appropriate than 1-kV). Hence, the installation of distributed storage assets on the 10-kV-side of the substation seems to be a proper choice. For the sake of clarity, the chosen situation in the case study with the assumed placement of the storage asset is presented in Fig. 2.

Note that the typical size of the distributed storage assets considered for this scenario are assumed to be in the low MW-range (power) with a capacity being able to store the energy flow of a few hours [MWh]. The technical feasibility of such installations in this range of power and capacity has been demonstrated in practice (see for example [21]). Examples for the choice of appropriate storage devices are battery systems or distributed biogas buffers, which have been discussed in more detail in the previous Section II. However, the choice for a specific storage system is not the focus of this research. We assume that the power of the storage asset equals 2 MW with a capacity of 8 MWh. As it is shown later, a storage asset of this dimension with an energy to power *(E2P)* ratio of 4 (8 MWh/2 MW) is able to cope with the PV peak and, thus, is appropriate for the objective of the DSO to avoid reinforcement. Furthermore, a storage asset characterized by these parameters is likely to be large enough to significantly reduce local grid problems (such as a reinforcement need for the transformer) but is still in a range to be realizable in regard to requirements for space and investment costs. The influence of larger capacities on the storage usage profile for trading companies is not the scope of this research and left for future work.

In the next section an approach to determine an optimized storage profile is presented. For this, we focus on the optimization for two different stakeholders: grid operator (minimize peaks) and energy trader (maximize profit by arbitrage).

IV. Approach

This section contains the derivation of the optimal storage profiles. The optimization objectives for the different market roles with the two considered stakeholders vary, such that two different kinds of simulations have to be processed. To determine their optimized storage usage profiles, we first start with the model of the battery and the constraints for an efficient operation.

A. Model of the Battery

In this section, the model of the battery is derived, which is used for all different optimization scenarios. First, we use a discretization of time, meaning that we model the observed time horizon by time intervals of fixed length. For each time interval i $(i \varepsilon \{1, \ldots, T\})$ let PR_{i} denote the given amount of electricity production/consumption in the area. Furthermore, for each time interval i two variables are introduced: T_i denoting the amount of transported electricity passing the transformer (in MWh), and B_i denoting the battery flow. The relation between these three values for time interval i is given by

$$T_i = PR_i + B_i. \tag{1}$$

Note that positive values for the transport T_i, the production PR_i and the battery B_i indicate energy flows to the upstream grid. Thus, a negative value for the production indicates a consumption of energy of the considered area. Furthermore, let P denote the given limit on the maximum amount of electricity (in MWh) that can be drawn from or put into the battery in one time interval. This value P origins from the power limitations of the battery and the used time interval length. The following constraint uses this parameter to limit the battery energy flow in time interval i:

$$-P \leq B_i \leq P. \tag{2}$$

Next to the limitation per time period, the battery also has a maximum total capacity denoted by C. We have to ensure that the state of charge of the battery S_i in every time period i is in the interval $[0, C]$.

$$0 < S_i \leq C. \tag{3}$$

Later on it is explained how S_i depends on B_i and behaves over time. In our model, the length of a time interval is chosen as 15 minutes and the data is given for a complete year $(T = 35\,040)$. To characterize the state of charge S_i, the efficiency E of the charging process has to be considered. For our model, we chose this value to be 0.8 meaning that 20% of the charged energy is characterized as loss, occurring during the charging process. This simplification is used to enable a simulation within reasonable time horizons. The chosen value corresponds with typical values for current battery technologies (see, e.g., [8]). To determine the loss occurring in a given time interval we have to split up the battery flow. Hereby, let I_i denote the inflow and O_i the outflow in the time interval i. Using these variables, the charging states S_i are determined as follows.

$$S_i = S_{i-1} - O_i + I_i \cdot E \tag{4}$$

with

$$B_i = O_i - I_i \quad I_i,\, O_i \,\varepsilon\, \mathbb{R}_0^+. \tag{5}$$

Note that in each time interval at least one of the two variables I_i or O_i has to take the value 0. This determination is required to integrate appropriately the efficiency E in (4). To complete a correct formulation, we need additional constraints to force that this is ensured. However, due to the huge amount of data we have chosen to disregard such constraints, prioritizing that the model remains only using linear constraints and non-integer decision variables. In the analyzed scenarios, the combination of the used objective and the bound on the loss due to the efficiency value E [see (6)] already lead to the desired results of having no inflow and outflow in the same time interval.

B. Model for Battery Operation

As a next step, the operation of the storage assets is restricted by a bound on the permitted loss L to avoid undesirable high operational costs as well as the rapid wear and tear due to frequent starting of the (re-)storing. More precisely, a loss-limitation factor μ is introduced which forces the total loss caused by battery usage to be smaller than μ times the flow through the transformer during the observed horizon of one year. In the case study, a value of $\mu = 0.03$ is assumed, so that the losses are limited to 3% of the total production.

$$L = \sum_{i=1}^{T} (1 - E) \cdot I_i \geq \mu \cdot \sum_{i=1}^{T} |PR_i|. \tag{6}$$

As all introduced constraints (1)– (6) are linear, these constraints can be incorporated in a Linear Program (LP). Further effects describing the characteristics over time like wear and tear, the decreasing usable capacity of the battery or self-discharging are not integrated since the focus of this research is not on describing a specific battery type with long term effects but on their way of use with short time horizons for different stakeholders. This applies also for storage parameters like the depth of discharge or the influence of the cycling numbers on the lifetime of the storage asset which may affect the storage operation and the profitability and differ significantly depending on the chosen storage technology.

C. Optimization for Grid Purposes

In this paragraph the derivation for the optimal storage profile of the grid operator are presented, followed by the optimization for the energy trader in the next paragraph. The objective of the DSO is to minimize the absolute transported peak to avoid (or at least delay) conventional grid reinforcements.

To formalize the objective for the grid operator, we need to determine the peak value of the flow, both for upstream and downstream. For this, a variable TP is introduced, which represents the absolute bound on the transported electricity [see (8)] and which has to be minimized [see (7)].

$$\min TP \tag{7}$$

$$-TP \leq T_i \leq TP. \tag{8}$$

The model (1)–(8) leads to an LP and can be modeled using AIMMS with CPLEX 12.3 for solving the linear program. The measured data for the production and consumption of the distribution grid area with the 15-minute values is used as input data for the model. Before describing the results, the optimization models for the arbitrage scenario and for a scenario of combined operation are presented in the next paragraphs.

D. Optimization for Arbitrage Purposes

In this paragraph we discuss the model for the trading stakeholder. Hereby, the objective is on maximizing the profit caused by price spreads (arbitrage). The corresponding equation is given in (9) where p_i is the spot market price in period i.

$$\max \sum_{t=1}^{T} p_i \cdot B_i. \tag{9}$$

We consider the prices for the day ahead market and the intraday market in two different scenarios leading to different transport and storage profiles and—consequently—to different correlations and peak behavior compared with the grid scenario of peak shaving. The technical constraints for the flow in and out of the battery are again given by (1)—(6). For the maximization of the profit, we neglect further possible types of costs like grid charges, electricity taxes or the levy for supporting renewable energies. This seems to be an acceptable assumption since it is still under discussion, whether the exemption for the payment of these cost types is an expedient incentive to increase the penetration of storage assets (see more detailed in the discussion of Section VI).

E. Optimization for a Combined Operation

The two objectives in the previous paragraphs focus on two extreme cases. However, it also may be of interest to investigate how much room for price optimization is left if some grid constraints are added to the model. This may be important for the profitability of the storage asset itself but also from the perspective of the (national) economical operation of storage assets to avoid a profit for a market participant inducing significantly higher costs for other stakeholders. We simulate these scenarios by using the optimization in (9) and consider (8) as a constraint, meaning that the profits should be maximized, but a predefined value of the transported peak TP may not be exceeded. The value of TP can be determined, e.g., by the grid operator. These scenarios with the derived reduced profits are shown after the "basic" scenarios in Section V.

F. Scenarios

The resulting profiles for the transport of the energy for the different optimization profiles are the main scope of the following analysis. They are chosen due to their relevance for the dimensioning of the grid assets (e.g., the 30/10-kV-transformer). For this, we analyze four different scenarios:

a) profile without storage: in this case, the transport profile equals the production/consumption profile $(T_i = PR_i)$.
b) profile with peak shaving (grid scenario): the reduction of the transported peak is the objective of the usage of the storage asset.
c) profile with the maximization of profits using price spreads (arbitrage) with day ahead prices.
d) like c), but using intraday prices.

The results of these different scenarios are presented in the next section. Afterwards and according to the model described in Section IV-E, the analysis for the combined operation for day ahead c)$*$ and intraday prices d)$*$ are presented.

V. Results

As already mentioned, we used a storage asset of 2 MW power with a capacity of 8 MWh for the analysis of the transportation profiles.Fig. 3 shows the profile for the transported electricity of the 30/10-kV-transformer for the time period from 01.04.2011–30.09.2011.

The profile for scenario a) gives a maximum peak of 8.43 MW as already mentioned in Section III. For scenario b) the influence of the operation of the storage assets is visible leading to a reduced peak. Looking at scenario c) and d) we reveal seldom peaks even exceeding the value of 8.43 MW. This figure gives a first impression on the impact of different optimization objectives on the resulting profiles of storage and transportation. In the other seasons of the year no remarkable power values are visible. The first (last) exceeding of 8.43 MW for the scenarios c) and d) is noticed on 03.05.2011 (02.09.2011, respectively) and thus, visible in the time period included in the figure.

The main results for the different scenarios are summarized in Table I. The maximum transport values are listed confirming the former elaborations; in scenario b) with peak shaving the maximum transport decreases precisely by the maximum power of the battery (2 MW) to 6.43 MW, so that the potential of the storage assets is completely exploited. This indicates that the chosen capacity of 8 MWh for the battery seems to be large enough. However, for scenario c) using the day ahead prices we find a maximum transport of 10.29 MW and for the intraday scenario 8.71 MW. The average transport value gets more negative for all storage scenarios', meaning that on average more electricity is transported downstream. This increase results from the need to cover the losses when operating the storage assets. As in all cases for using storage assets from an ecological and economical point of view, the usage should bring more benefits than the effort for the extra energy used (e.g., by lower grid costs due to reduced reinforcements which outperform the costs for the extra energy).

Note that in all scenarios the maximum allowed loss of 3% of the total absolute production/consumption is considered (see the

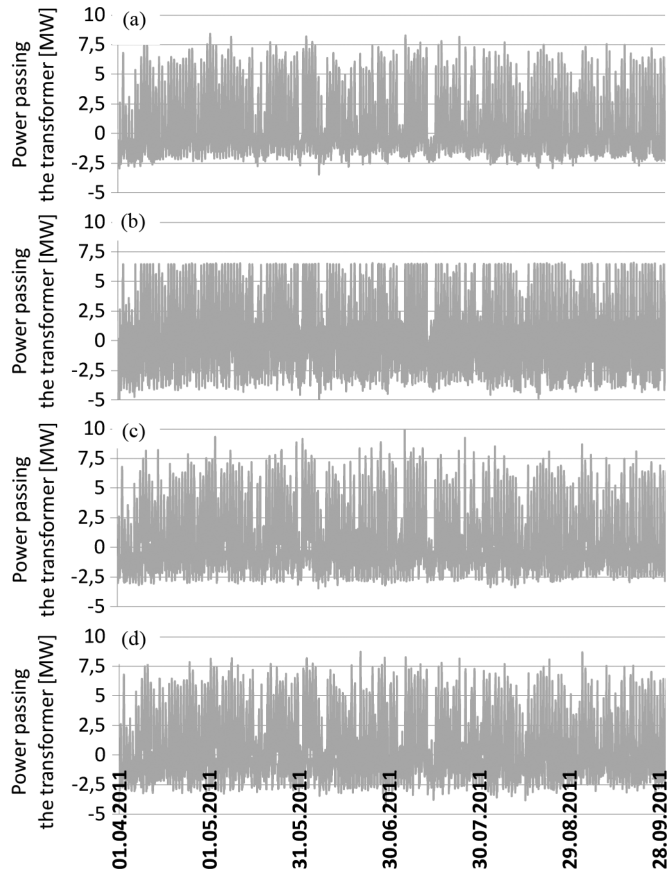

Fig. 3. Transport values for (a) the scenario without storage, (b) the scenario with peak shaving (objective of the grid operator), (c) the arbitrage scenario with prices of the day ahead market and (d) like (c), but with prices of the intraday market.

TABLE I
Main Results for the Different Scenarios

Results overview	a) scenario without storage	b) scenario peak shaving	c) scenario day ahead price	d) scenario intraday price
Maximum transport [MW]	8.43	6.43	10.29	8.71
Average transport per 15 minutes [MW]	-0.28	-0.33	-0.33	-0.33
Standard deviation for the transport profile [MW]	2.28	2.45	2.44	2.41
correlation coefficients		$r_{Tb,Tc}=0.8403$; $r_{Tb,Td}=0.8399$	$r_{Tc,Td}=0.9252$	

TABLE II
INFLUENCE OF THE STORAGE ASSET ON TP

	b) scenario peak shaving	c) scenario day ahead price	d) scenario intraday price
number of incidents for λ > 0	0	35	2
number of incidents for λ > 0 in %	0.00%	0.10%	0.01%

constraint in (6) in Section IV). The value for the standard deviation of the transport values increases indicating a risen volatile transport profile.

To evaluate the comparability of the transport profiles of the different scenarios, it is useful to calculate the correlation. More precisely, we calculate the correlation coefficients $r_{Tx,Ty}$ of the transport profiles using the 15-minute values of T_i for each pair (x, y) of scenarios $(x,\ y\ \varepsilon\ \{b,\ c,\ d\})$. The resulting coefficients are given at the bottom of Table I.

All transport profiles are highly correlated. For the correlation coefficient $r_{Tb,Tc}$ between the transport values of scenario b) peak shaving and c) arbitrage using day ahead prices, we get $r_{Tb,Tc} = 0.8403$; for the correlation of the transport values for b) peak shaving and d) intraday prices we get $r_{Tb,Td} = 0.8399$. Finally, for the comparison of the arbitrage scenarios with the transport values of scenario c) day ahead and d) intraday, we get $r_{Tc,Td} = 0.9252$. This high correlation was to be expected, since the bounded capacity of the battery allows only a restricted change in the transport profile. However, the large deviations in the maximum peak of the transported energy need an explanation.

To get more insight in the impact of the storage asset on the maximum peak occurring, we introduce a new parameter $\lambda_{i,x}$, where x represents the considered scenario $(x\ \varepsilon\ \{b,\ c,\ d\}$. This parameter is defined as the difference of the peak of the scenario $T_{i,x}$ and the peak TP_a of the scenario without using storage assets, divided by the power of the storage asset P. As described above, the value for TP_a is given with 8.43 MW and the power of the storage asset with $P = 2$ MW.

$$\lambda_i = \frac{T_{i,x} - TP_a}{P}. \tag{10}$$

If $\lambda_i > 0$, this indicates that the usage of the storage assets induces an increase of the peak compared with the scenario without storing. Thus, λ_i is used as a simple and transparent parameter to illustrate the exploitation of the storage asset and is given as percentage of P. As described before, in scenario b) the storage power is completely exploited to reduce the peak. For scenario c), an inferior result is shown—in the extreme situation, the maximum value increases by 93% of the power of the storage device compared to the scenario without storage (see also Table I). We have determined the number of time intervals with $\lambda_{\mathrm{i}} > 0$ to reveal the frequency of these situations. Note that by using 15-minute time intervals per year, in total 35 040 time intervals are given.Table II indicates that only very seldom, time intervals with $\lambda_{\mathrm{i}} > 0$ occur.

Summarizing, the maximum values for the transported power differ significantly. However, a high correlation coefficient for the transport values is found. Since the grid assets have to be dimensioned for the seldom, but high peaks, a detailed view is given below to reveal further relations.

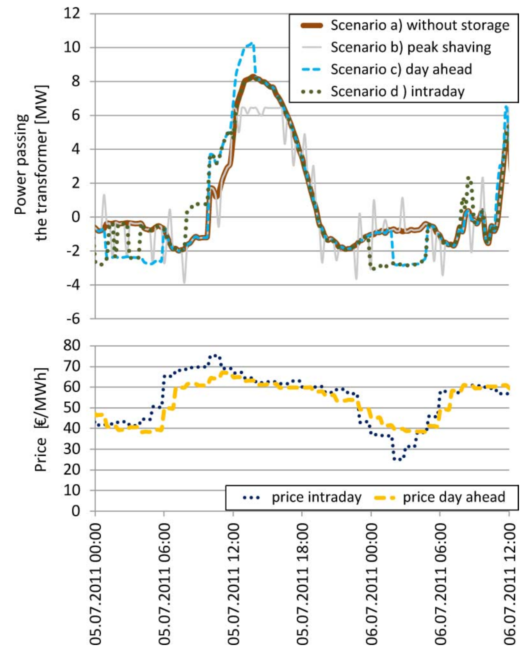

Fig. 4. Detailed analysis of the transport profile and price structures.

For an analysis of the peaks, a detailed look at the transport profiles in combination with the given price structures is useful. In Fig. 4 the transport profiles around the maximum peak over all scenarios are depicted (10.29 MW, scenario c) day ahead on June 5th) together with the day ahead and intraday prices. Note, that a deviation of the transport value for the specific scenarios compared with the curve for the transport in scenario a) (without storage) indicates a

— storing [curve is below the value for a)], since less energy passes the transformer and, instead, is used for charging the storage asset.
— restoring [curve is above the value for a)].

When comparing the curves of the transported power of the different scenarios, a few main observations can be made.

— In the profile of the peak shaving [scenario b)] we can see that the maximum value of 6.43 MW occurs after noon. The energy stored during the corresponding period is restored in times with less RES-E (e.g., in the evening hours or at night).
— In the considered time period the intraday price is at its maximum just before noon with 75 €/MWh. Thus, restoring and selling of energy is rational at these times since here maximum profits can be earned. A further restoring and selling of energy at noon, where the prices are still high, is not possible due to the given limitations of the capacity of the storage asset. Hence, if a larger capacity of the storage asset is chosen, a restoring going along with the PV peak in the hours after noon would have been detected. The storing of energy is done particularly at night (e.g., on June 5th with 41 €/MWh or on June 6th with 25 €/MWh) since the electricity is cheap in these periods and buying is rational.
— The day ahead prices reach their maximum later at noon with 67 €/MWh. Note that the described price profiles confirm the elaborations on the basic statistics of the day

ahead and intraday prices in Section III—the average values are comparable for both scenarios, but intraday prices are characterized by a higher volatility. Due to the later price peak compared to the intraday prices, the surplus energy runs together with the production peak and, hence, a high peak value occurs. The storing of needed energy takes place at night with lower prices (e.g., 38 €/MWh during the night of June 6th), too.

Note that this effect has been observed for six further days and thus, the 35 occurrences of $\lambda > 0$ mentioned in Table II are explainable. Furthermore, this detailed analysis gives an explanation of the high correlation coefficients. Since the power of the storage asset is limited with 2 MW, the transport profiles cannot differ significantly. The constraints for the allowed losses reduce the volatility further. Hence, to some extent, the correlation coefficients are deceptive and the analysis of the peak values is more practical.

The analysis in Fig. 4 indicates also that the large decentralized production in the considered area is superimposed by other impact factors on the price. Since photovoltaic experienced significant growth rates and especially in summer around noon contributes distinctly to the energy supply, also a noticeable impact on the price may be expected. With a ceteris paribus view, a large(r) amount of supply should lead to a decreased price for the energy. For the described time period in Fig. 4, this effect is not visible. The production peak occurs at around noon, but in these periods still very high prices are given. This may be caused by less contribution of decentralized energy in other regions or by high consumption, little energy supply by conventional power plants (e.g., caused by low water levels for the cooling of power plants) or a combination of these influencing factors. As a consequence, investigating the influence of local RES-E production profiles on national market prices is an interesting task left for the future with growing RES-E shares. With regard to the current situation, we can conclude that steering signals by market prices are not appropriate (even counterproductive) to solve local problems in distribution grids.

In a final step, the impact of a "cooperated" operation of the storage asset is evaluated as described in Section IV-E. The cooperation of an energy trader and a grid operator may result in a usage of distributed storage assets for more than one purpose leading to more efficient use. This is in contrast to a situation, where a trader exploits the economic value of peak prices but may force the grid operator to reinforce grid assets to enable the resulting profiles.[2]

As described in Section IV, we model this situation by optimizing the profit with (9) and integrate the constraint of (8). In the concrete case, we fixed $TP = 6.43$ MW, meaning that the storage potential is used for grid purposes to reduce the peak as much as possible.

The results for the calculations are given in Table III. The maximum transport in a time interval is depicted to reveal the resulting effect (e.g., a decrease of the peak by 38% in the day ahead scenario), but the results in the table show that adding the grid objective has only am in or effect on the annual reduction

[2]Note, that the costs for these reinforcements are covered by the DSO, but considering the regulation of grid operators, (at least most of) these costs are to be passed with delay to the consumers connected to the grid (see, e.g., [4]).

TABLE III
IMPACT OF GRID CONSTRAINTS FOR THE PROFIT OPTIMIZATION

	scenario: c) → c)* day ahead price with grid constraint	scenario: d) → d)* intraday price with grid contraint
maximum transport [MW]	10.29 → 6.43	8.41 → 6.43
annual reduction of profits [€]	3,707	2,916
annual reduction of profits [%]	1.86%	1.28%
correlation coefficient to the 'basic' scenario without grid constraints	0.9956	0.9970

of the profits. Furthermore, the high correlation coefficients to the basic scenario are shown with values above 0.99 for both scenarios c)$*$ and d)$*$ compared with the scenarios without considering grid constraints (scenario c) and d), respectively).

According to Table III, the annual reduction in profits can be compared with the reinforcement costs of the grid operator (e.g., due to limited capacity of the 30/10-kV transformer) to enable the operation of the high peak in the price driven scenarios. The investments in this reinforcement are likely to be much higher by a few orders of magnitude and, thus, do not justify this investment from an overall economic point of view. However, current market design still supports this situation since DSOs do not have the opportunity to intervene in the schedule of storage assets operated by energy traders. Currently, this is still a very seldom scenario, but with increased market penetration of the electricity generation out of renewable energy sources (RES-E), concepts to allow a more overall efficient usage of storage assets should be introduced.

VI. Political Implications

The presented results enable the discussion for an appropriate integration of the distributed storage assets with a corresponding market design, which is presented in this section.

The achieved results show that an "uncontrolled" operation of distributed storage assets by energy traders has an influence on local grid problems—it does not reduce the need for reinforcements to integrated RES-E but it even may intensify this need. Nevertheless, there is a promising potential for a cooperation of the stakeholders energy trader and DSO, since an intervention of the DSO may be needed seldom and therefore leads only to an acceptable reduction of profits, but has large effects on the investment costs for the DSO. Based on the described results, we propose two main solutions for an efficient integration of storage assets. We concentrate in our discussion on the situation in Germany, but the conclusions are likely to be transferable to a lot of other industrial countries, since similar problems in distribution grids with an increased share of RES-E and similar price profiles may occur.

First of all, the operation of storage assets by DSOs should not be hindered in general by law since market mechanisms do not solve local grid problems. Instead, even an increase in transported peaks and thus, in the need for reinforcements is shown in this work. Currently, it is still in the debate if grid operators may be allowed to buy and sell energy to operate the storage asset since the unbundled market design intends separate market roles for trading, generating, selling and distributing the energy. On the one hand, the selling of energy by DSOs is already implemented in the current design since DSOs have to cover grid losses by calling for tenders for the supply of energy in a non-discriminatory manner. On the other hand, the trading of energy is not the objective of the grid operator when operating the storage assets. Thus, if the storage asset is implemented to avoid the conventional reinforcement and if this solution is more efficient with lower costs compared with conventional alternatives, it should not be hindered by the market design.

Secondly, if the storage stakeholder is a trading company, the incentive for considering grid restrictions may be implemented by the DSO itself. As described in Section IV it is still in debate how the investment in local storage assets should be incentivized. We assumed an exemption of grid fees and taxes for the arbitrage scenario. This incentive for the trading companies operating a storage asset should only be enabled if the DSO is allowed to intervene in the (re-)storing profile to avoid seldom, but high peaks. As shown in Section V, a reasonable decrease in profits occurs going along with a significant decrease of the production peak. This proposal for the creation of incentives for investing in local storage assets contradicts with the ideas of the German regulation agency—in [14], it is stated that the agency assumes storage assets to be "usual" appliances connected to the grid. Hence, the agency sees no reason for reduced or exempted grid fees. This position reveals the unclear situation for the incentivizing of investments in storages assets. As shown in our results and within this discussion, we only agree with this statement in case of uncontrolled operation of the storage asset. In the case of considering grid constraints with the possible result of avoided or delayed reinforcements, the exemption of grid fees seems to be an appropriate incentive for the storage stakeholder with positive effects on low grid costs. In practice and future, "smarter" energy markets, this cooperation could be achieved, e.g., by forecasting, planning and real-time control of energy management of the grid operator and the trader as presented in [17]–[19] and discussed shortly in Section II. However, a detailed proposal for a cooperation mechanism in the energy supply chain is to be derived in future work.

In general, storage assets are likely to play an important role in future energy supply chains. Next to peak shaving and arbitrage also providing ancillary services and short-term balancing (i.e., in regard to frequency deviations) are interesting level playing fields in the future, if economically feasible. This applies also for the introduction of storage assets in islanded grids when integrating fluctuating RES-E. However, as discussed in Section II, less conflicting issues for the different storage stakeholders is expected.

To exploit the potential of storage assets in grids in industrial countries with lots of stakeholders, changes in the market design are required. These adaptions should enable storage operation for different parts of the supply chain including a rational prioritization. Surely, other countries differ in regard to specific market structures, legal frameworks as well as the development of (renewable) generation and the structure of the load. Nevertheless, we expect that also in these countries at least some developments resulting from similar climatic objectives will occur in the near future.

VII. Conclusion

In this paper the influence of different market participants on profiles of distributed storage assets is investigated. For this, a situation is analyzed with real world data for the consumption and production of a distribution grid area in Germany [scenario a)]. This area is faced with a lot of renewable energy generation (especially photovoltaic). For the considered area, the operation of a locally installed storage capacity in this grid is simulated with differing optimization objectives. In scenario b) the storage is used to minimize the peak transported upstream to the 30-kV grid. For the other two scenarios, the storage asset is assumed to be operated by a trading company, aiming to maximize the profits by using prices spreads (arbitrage). For this, German day ahead prices are used [scenario c)] as well as intraday prices [scenario d)].

The analysis shows significant differences between the scenarios, especially with regard to the transported peak focusing on the 30/10-kV transformer. Whilst in the scenario b) of peak shaving the storage is fully exploited to decrease the transported peak, the arbitrage scenarios reveal in the worst case that the maximum peak is increased significantly. In the scenario c), the maximum peak even increased with $+93\%$ of the power of the storage device, so that extra grid reinforcement is needed. Although the effect of an increase of peaks occurs very seldom, the grid has to take these peaks into account. Thus, undesired situations occur from an economical point of view, since the costs for the grid reinforcements (passed to the consumers) significantly exceed the arbitrage profits for these seldom time periods. Following these observations, we present a proposal to cope with this problem by 1) enabling DSO to integrate storage assets for own purposes and 2) incentivize trading companies for an integration of storage assets by reduced or exempted grid fees when the grid operator is allowed to use the storage for grid congestions in seldom, but critical situations.

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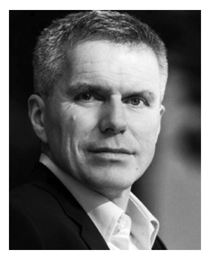

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