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# Using storage devices for compensating uncertainties caused by non-dispatchable generators

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**Abstract**—This paper presents a study on combining a grid-connected stochastic generator with an energy storage device. The storage device is used to balance the power fluctuations of the non-dispatchable generator in order to feed power into the network according to an hourly pre-determined constant profile. The negative effects of inaccurate forecasts are thus reduced by turning the stochastic generation into a deterministic network infeed. Important parameters for achieving this goal are the energy capacity of the energy storage and the error magnitude of the forecast used to define the infeed profile.

A general method for simulations based on a measurement series is presented, together with a method for the simulation of forecasts with different forecast errors. The methodology is then applied in a case study to investigate the feasibility of using an storage device for hourly balancing. The emphasis is on the relation between infeed accuracy, forecast error and energy capacity of the storage.

## I. INTRODUCTION

The stochastic behavior of electric power generated from renewable sources such as wind or sun has stimulated research on the issue of combining such generators with an energy storage device (ESD). Many publications focus on the use of ESDs in small isolated systems containing generators converting renewable sources, often also in combination with diesel engines [1]–[3]. Usually, the ESD serves as buffer between the stochastic production and the load demand, hence improving the reliability of supply and increasing the value of the renewable source.

Grid connected generators converting renewable power sources, on the other hand, are allowed – or even obliged, depending on different countries’ governmental policies – to feed any production at any time into the existing grid. The imbalance between their stochastic production and the load demand is compensated by the grid and fast responding generators. Thus, it does not seem necessary to combine the generators with an ESD, as the network and other generators have the same function as the ESD does have in an isolated network.

However, the increasing number of grid-connected non-dispatchable generators results in cumulated infeed power fluctuations, which are difficult to predict. Depending on the generation technology, already smaller forecast errors can have significant effects, leading to two major disadvantages: on the one hand, grid operators, who must place their bids in a day-ahead market, often incur comparatively high penalties

because they cannot meet their projected production pattern due to inaccurate forecasts [4]. On the other hand, several generators have to run as backup on idle or on reduced power to be able to quickly compensate possibly induced fluctuations. Usually hydro storage and gas-fired power stations are used for this purpose; running a thermal power plant at reduced power however implies lower efficiency and hence a relatively higher amount of CO<sub>2</sub> per MWh, reducing the positive impact of renewable-based generators in terms of emissions. It would thus be favorable to alleviate or even eliminate the fluctuations of the intermittent source before they are transferred to the network.

Therefore, this paper presents a study on combining a grid-connected stochastic generator with an ESD, to compensate fluctuations in the network infeed. In contrast to isolated systems, the ESD is not used to follow a load but to balance the generator’s output to feed into the network with a pre-defined, deterministic hourly constant generation profile (see Fig. 1). This profile is defined a given amount of hours in advance, based on a forecast for the stochastic generator’s output and on the power and energy capacities of the ESD. Corresponding to the settlement policies of most power exchanges, the profile is kept constant during each hour, whereas other time-intervals are also conceivable. Earlier work [5] showed however that constant levels spanning several hours require hardly feasible energy capacities.

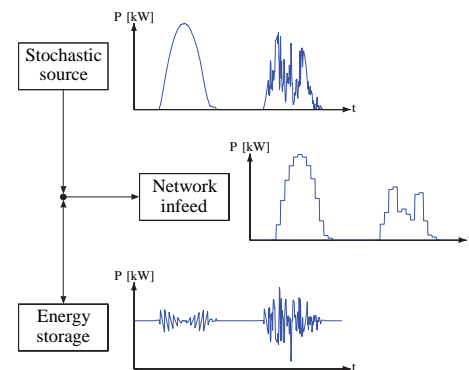


Fig. 1. Symbolic representation, showing the stochastic generation, the balancing operation of the storage and the leveled network infeed profile.

A deterministic generation profile offers two major advan-

tages compared with a stochastic profile:

- Independent of the market structure, the stochastic generator can be reliably incorporated into the production portfolio planning, allowing the use of former backup generators for other purposes.
- In a day-ahead market structure, the ability to determine the exact near-future production allows to accordingly sell and buy on the spot market with reduced risk of incurring balancing penalties.

The ability of generator and ESD to effectively fulfill the predefined infeed profile depends both on the actual forecast error as well as on the characteristics of the ESD and will be measured according to both reliability criteria as well as system losses and incurring balance penalties. The results will be used to identify the relation between the size of the forecast error and the capacities of the storage device.

The first part of the paper presents generally applicable methods and procedures both for the simulation and for the analysis of the results. The second part consists of a case study using a measured time series of 5 min values of 3 years from a 500 *kWp* photovoltaic installation<sup>1</sup>.

## II. MODELING APPROACH AND ALGORITHM

This section starts with a brief overview of the simulation procedure and then addresses the algorithm's key elements.

The model is depicted in Fig. 1 and consists of three parts: the stochastic source, the energy storage device and the targeted network infeed profile. The targeted profile should be met as accurately as possible and can also be regarded as the load, which the generator together with the ESD has to supply. In contrast to an isolated system however, surplus energy (i.e. energy that exceeds both the capacity of the ESD and the targeted profile) can be fed into the grid. The resulting trade-off between storage capacity and surplus energy will be discussed later in the case study, section IV.

The simulation algorithm is based on a time-series (either simulated or measured values), representing the source. The algorithm sequence is shown in Fig. 2 [6]. After an initialization phase, the loop starts with a check, whether a new forecast period begins ( $t = t_{fc}$ ). If so, the algorithm calculates the forecast for the next period, to be used for the definition of the new network infeed profile. This profile is set constant over the duration of an hour. For the case study, which is based on 5 min measurement values, this means that every hourly value is the average of 12 measurements. The loop then continues with operating the ESD, based on the real measurement data, to fulfill the planned infeed profile as accurately as possible. The meaning of accuracy in this context will be discussed in section III. A cycle of the loop ends by updating the storage level as well as by progressing one step in the time series. If the end of the time series is reached, the algorithm terminates.

The main elements of the algorithm will be discussed in more detail in the following subsections.

<sup>1</sup>The generation data have been kindly provided by HTA Burgdorf, Switzerland; <http://www.pvtest.ch>.

### A. Initialization

In the initialization phase, the data set is loaded and the simulation parameters are set. These are the forecast error, which will be discussed in the next section, and the storage device's power rating  $P_{st}$ , energy capacity  $E_{st}$  as well as charge efficiency  $\eta_{ch}$  and discharge efficiency  $\eta_{dch}$ . The ESD is modeled as non-ideal, which is why every *kWh* that is stored, will be reduced to  $\eta_{ch} \cdot \eta_{dch}$  *kWh* by the time it is actually fed into the network. Thus it is not possible to feed the total amount of generated energy into the grid; a certain share is lost for conversion inside the storage. To take this into account, the so-called usage factor  $\beta_{usage}$  was defined, relating the generation of the source  $\mathbf{P}_{source}$  to the generation that is planned to be infeed  $\mathbf{P}_{planned}$ .

$$\sum_{t=1}^T \mathbf{P}_{planned}(t) = \beta_{usage} \cdot \sum_{t=1}^T \mathbf{P}_{source}(t) \quad (1)$$

The usage factor satisfies  $0 \leq \beta_{usage} \leq 1$  and is an efficiency factor concerning all the energy, which has to be temporarily stored. It should not be mistaken as an overall efficiency factor, as most of the generated energy is fed directly into the network without being stored at all; the ESD is only used to balance the hourly deviations.

If both the forecast would be perfect and the storage device would be lossless, all the energy from the stochastic source could be fed into the network. However, the more the ESD is charged and discharged, the more energy is lost for conversions. If  $\beta_{usage}$  is close to 1, the ESD will hardly be used and small amounts of energy will be lost for conversions. A high  $\beta_{usage}$ , implying a comparatively high infeed level, most probably results in little surplus energy and many incidents where the profile cannot be met, even with the assistance of

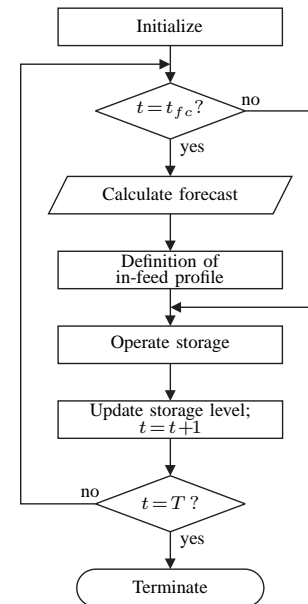


Fig. 2. Schematic representation of the simulation algorithm; forecast interval of 24h, starting at midnight.

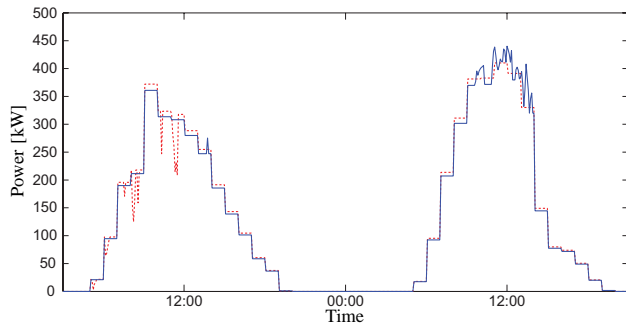


Fig. 3. Infeed profile for  $\beta_{usage} = 0.99$  (---) and  $\beta_{usage} = 0.96$  (—), showing the decrease and increase of insufficient and surplus power, respectively.

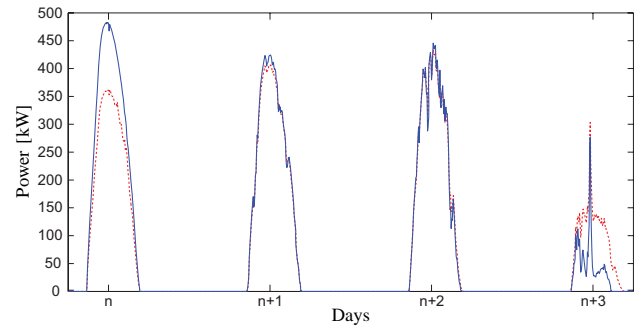


Fig. 4. Example of the actual time series (—) and a generated time series (···) with an  $f_{err}$  (RMSE) of 50%.

the ESD. A low  $\beta_{usage}$ , on the other hand, corresponds to a lower planned infeed level, which will be achievable often also without the ESD – resulting in a high fulfillment rate of the planned infeed, but at the price of more excess power (see Fig. 3). The role of the storage capacity in this context will be discussed in the case study (section IV) in more detail.

Depending on the balancing market structure and penalties for positive and negative deviations from the planned amounts of energy, an operator might be willing to incur more surplus energy by choosing a lower  $\beta_{usage}$  in order to reduce penalty costs for not accomplishing the planned infeed. The quantity  $\beta_{usage}$  has to be defined depending on the operation strategy and the actual system parameters.

### B. Calculation of Forecast

At the beginning of every planning period, a forecast of the stochastic generation is produced to be used for defining the hourly constant infeed profile. Various methods and approaches for the calculation of forecasts for different sources exist. The focus of this study however lies not primarily on the accuracy and advantages and disadvantages of different methods. The general question addressed here, is how the magnitude of the forecast error influences the ability of the system to meet the planned generation and to what extent forecast errors can be compensated with a storage device.

Therefore, a way had to be found to select the forecast error at the beginning of a simulation run. Only then it is possible to investigate the sensitivity of the results and the influence of the forecast accuracy on the storage capacity. An exponentially weighted moving average procedure with a weighting factor  $\alpha$  ( $0 \leq \alpha \leq 1$ ) was found to fulfill the requirements [7]. To be able to simulate a forecast with any forecast error magnitude, the actual measurement series – which is known at the beginning of a forecast period – can be incorporated into the forecasting simulation procedure. The more this actual measurement is weighted, the more similar to it the forecast will be and hence the smaller the forecast error. The forecasted power  $\vec{P}_{fc,n}$  for the period  $n$  can then be defined as the sum of the weighted actual time series  $\vec{P}_n$  of day  $n$  and e.g. the 7 preceding periods<sup>2</sup>.

<sup>2</sup>The vector symbols represent daily time series, whereas the bold variable is used for the total time series.

$$\vec{P}_{fc,n} = \alpha \cdot \vec{P}_n + \alpha(1-\alpha) \cdot \vec{P}_{n-1} + \dots + \alpha(1-\alpha)^6 \cdot \vec{P}_{n-6} + (1-\alpha)^7 \cdot \vec{P}_{n-7} \quad (2)$$

Setting  $\alpha$  equal to 1 results in a perfect forecast, as it is exactly the measured curve. For forecast errors  $f_{err} > 0$ , a look-up table with the corresponding  $\alpha$  is created. This is achieved by calculating the forecast series for various values of  $\alpha$ . Then the forecasted series  $\mathbf{P}_{fc}$  is compared with the actual measurement series  $\mathbf{P}_{source}$ . The difference of the two curves can in turn be used to calculate the root mean square error (RMSE), which corresponds to the forecast error [6].

$$f_{err} = \frac{1}{\overline{\mathbf{P}}_{source}} \cdot \sqrt{\frac{1}{T} \sum_{t=1}^T [\mathbf{P}_{source}(t) - \mathbf{P}_{fc}(t)]^2} \quad (3)$$

The look-up table finally is created by assigning each calculated forecast error  $f_{err}$  to its corresponding  $\alpha$ . A section of the actual time series and of a time series generated with a forecast error of 50% is shown in Fig. 4. Effects like comparatively slower raise or more expected energy can be well seen.

### C. Definition of in-feed profile

As already mentioned, the network infeed profile is kept constant over an hour, corresponding to market settlement procedures. In this step of the algorithm it is thus necessary to find the average power value for every hour, which can be met according to the forecast and the ESD's charge state. To account for the conversion losses in the ESD, the infeed plan further has to be multiplied with the  $\beta_{usage}$ , as already discussed.

Instead of using a constant  $\beta_{usage}$  for the whole simulation, it is possible to define a dynamic  $\beta_{usage}(t)$  that depends on the actual content of the storage at the beginning of a period. In other words, if the ESD is fully charged at the beginning of a forecast period (and thus at the beginning of an in-feed profile planning period), the average hourly value can be chosen higher than if the ESD were only half charged or even completely discharged. In the case of a fully charged ESD, it could even be beneficial to set  $\beta_{usage}(t) > 1$  for the next forecast period, depending on the forecast accuracy.

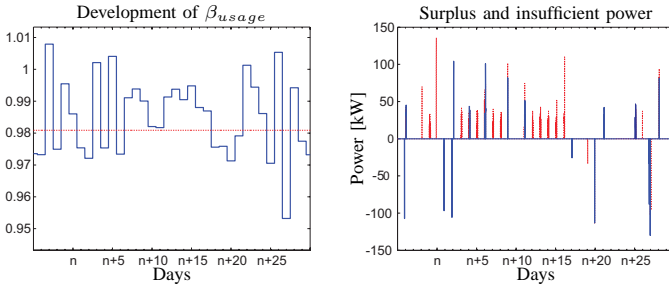


Fig. 5. Example of the evolution of the constant  $\beta_{usage}$  ( $\cdots$ ) and the dynamic  $\beta_{usage}(t)$  ( $-$ ) on the left with the corresponding insufficient and surplus power values on the right.

The use of a dynamic usage factor generally results in reduced amounts of both insufficient and surplus power, thereby increasing the usage of the storage device (see Fig. 5). The lower and upper limits of the dynamic usage factor depend both on the magnitude of the forecast error and on the energy storage capacity. They have to be found empirically as will be shown later in section III-D.

#### D. Operation of storage

In the actual operating phase of the algorithm, the storage device is used to balance the difference between the actual generation of the stochastic source  $\mathbf{P}_{source}$  and the planned infeed profile  $\mathbf{P}_{planned}$ . Assuming that the storage device can switch immediately from charge to discharge state makes it possible to define the power  $P_{st,dem}$ , which is demanded from the ESD, for every time step  $t$  as

$$P_{st,dem} = P_{planned} - P_{source} \quad (4)$$

Hence, a negative  $P_{st,dem}$  stands for charging periods and a positive  $P_{st,dem}$  for discharging periods. The ability of the ESD to fulfill the required  $P_{st,dem}$  depends both on its power rating and its actual charge state. First it is checked whether the power rating  $P_{st}$  is lower than the required power and – if necessary – accordingly adjusted. The effective power flow  $P_{st,eff}$  from or into the ESD is then found as

$$P_{st,eff} = \begin{cases} P_{st}, & |P_{st,dem}| > P_{st} \\ P_{st,dem}, & |P_{st,dem}| \leq P_{st} \end{cases} \quad (5)$$

Then it is checked whether the charge state  $E_{st,ch}$  of the ESD allows to deliver or absorb the required amount of power. For the charge state, i.e. when  $P_{st,dem}$  is negative, the following relation holds true

$$P_{st,eff} = \begin{cases} P_{st,eff}, & E_{st,ch} - P_{st,eff} \cdot \Delta t \cdot \eta_{ch} \leq E_{st} \\ -(E_{st} - E_{st,ch}) \cdot \Delta t^{-1} \cdot \eta_{ch}^{-1}, & \text{else} \end{cases} \quad (6)$$

whereas  $\Delta t$  represents the frequency of time step related to an hour (e.g.  $\Delta t = 1/12$  for 5 min measurements). For the discharge state, the according formula can be found as

$$P_{st,eff} = \begin{cases} P_{st,eff}, & E_{st,ch} - P_{st,eff} \cdot \Delta t \cdot \eta_{dch}^{-1} \geq E_{st,min} \\ (E_{st,ch} - E_{st,min}) \cdot \Delta t^{-1} \cdot \eta_{dch}, & \text{else} \end{cases} \quad (7)$$

The term  $E_{st,min}$  stands for the minimum energy capacity of the storage device. Depending on the storage technology,  $E_{st,min}$  is not necessarily equal to zero. In particular kinetic storage devices as e.g. flywheels cannot be discharged below a certain level, as the remaining energy is not sufficient to reach the required level of power [5]. The effective storage activity  $\mathbf{P}_{st,eff}$  will possibly often be lower than the demanded  $\mathbf{P}_{st,dem}$ , particularly for smaller energy capacities  $E_{st}$ ; the planned infeed profile cannot be fully met. To incorporate this, the vector  $\mathbf{P}_{infeed}$  is defined, containing the actual amount of power that is fed into the network during every time step.

Before the loop is terminated by updating the time step  $t$  to  $t + 1$ , the storage charge level  $E_{st,ch}$  has to be adjusted according to the operation during the just passed time step.

The following section presents three analysis methods, which can be used to analyze the results from the simulation.

### III. ANALYSIS

The overall target of combining the stochastic generator with an ESD is to achieve a predefined deterministic infeed profile. The effective accuracy and efficiency of how this target is reached thus serves as benchmark. Three measures have been identified and are discussed in this chapter.

#### A. Profile fulfillment

The basic idea of combining the generator with a storage device is to eliminate or at least alleviate the non-deterministic fluctuations inherent to the stochastic source. This allows to better incorporate this source into the production planning and dispatching, thus increasing the operational value of the energy generated from that source.

Therefore, the predefined deterministic infeed profile should be fulfilled as reliable as possible. As the infeed profile can be regarded as a load for the generator-ESD system, known measures can be applied to calculate the accuracy or reliability of reaching the target. From the measurement series and the simulation output files, indices similar to the expected energy not served (EENS) and to the loss of load probability (LOLP) can be calculated. The measure corresponding to EENS is the so-called insufficient energy  $E_{insuff}$ . It is defined as the total energy of all incidents, where the actual network infeed is lower than planned. As  $\mathbf{P}_{infeed}$  will not only be below the planned infeed power  $\mathbf{P}_{planned}$  but also above it, the function  $\sigma(t)$  had to be defined, to not incorporate the incidents with excess power infeed.

$$E_{insuff} = \Delta t \cdot \sum_{t=1}^T [\mathbf{P}_{planned}(t) - \mathbf{P}_{infeed}(t)] \cdot \sigma(t) \quad (8)$$

$$\sigma(t) = \begin{cases} 1, & \mathbf{P}_{planned}(t) > \mathbf{P}_{infeed}(t) \\ 0, & \mathbf{P}_{planned}(t) \leq \mathbf{P}_{infeed}(t) \end{cases} \quad (9)$$

The second index is designated as fulfillment factor  $F$ , and corresponds to  $1 - LOLP$ . It basically relates the amount of insufficient energy to the planned infeed amount.

$$F = 1 - \frac{E_{insuff}}{\Delta t} \cdot \left[ \sum_{t=1}^T \mathbf{P}_{planned}(t) \right]^{-1} \quad (10)$$

This measure will later-on be used to identify the influence of the forecast error on the required energy capacity of the ESD in order to perform with an accuracy of e.g.  $F = 99\%$ .

### B. Conversion losses

The storage device usage is expected to increase with the forecast error, balancing not only the fluctuations within each hour but also compensating the differences of the time series. The total amount of energy  $E_{lost}$ , lost for conversions in the energy storage device, can thus be used as an efficiency measure. The vector  $\mathbf{P}_{st,eff}$ , which represents the power flows into and out of the storage device can be split into a vector  $\mathbf{P}_{ch}$ , containing only the charging power flows and a vector  $\mathbf{P}_{dch}$  that contains the discharging activities. The total conversion losses can then be expressed as

$$E_{lost} = \Delta t \cdot \left[ \sum_{t=1}^T \mathbf{P}_{ch}(t) \cdot (1 - \eta_{ch}) + \sum_{t=1}^T \mathbf{P}_{dch}(t) \cdot (\eta_{dch}^{-1} - 1) \right] \quad (11)$$

As most of the energy generated from the stochastic source is never stored at all but fed immediately into the network, the amount of conversion losses will take a comparatively small share of the original generation  $\sum \mathbf{P}_{source}$  (see case study IV). Furthermore, assuming that all other components are lossless, the conversion losses correspond to the overall system losses. Otherwise, the components' losses have to be kept track off to be accordingly incorporated.

### C. Balancing energy

Besides the two measures profile fulfillment and conversion losses, a third measure can be identified, designated as balancing energy. The quantity  $E_{bal+}$  stands for the total amount of energy that exceeds the planned network infeed and  $E_{bal-}$  stands for the total amount of energy by which the planned infeed could not be met.

$$E_{bal-} = \Delta t \cdot \sum_{t=1}^T [\mathbf{P}_{planned}(t) - \mathbf{P}_{infeed}(t)] \cdot \sigma(t) \quad (12)$$

$$E_{bal+} = \Delta t \cdot \sum_{t=1}^T [\mathbf{P}_{infeed}(t) - \mathbf{P}_{planned}(t)] \cdot (1 - \sigma(t)) \quad (13)$$

As  $E_{bal-}$  is equal to  $E_{insuff}$ , this measure can be regarded as an extension to address not only technical but also monetary or market issues. Delivery shortages require up regulation by the network regulator and surplus infeed correspondingly down regulation. Regulation demands are penalized according to the regulating market policy, whereas up regulation usually is clearly more expensive than down regulation [4]. The terms  $E_{bal+}$  and  $E_{bal-}$  thus have been introduced separately to be weighted according to market conditions if needed.

### D. The influence of $\beta_{usage}$

The meaning of the usage factor  $\beta_{usage}$  was already discussed in sections II-A and II-C and illustrated in Figs. 3 and 5. Generally,  $\beta_{usage}$  indicates how much of the originally generated energy is in the end fed into the network at all. Due to the structure of the simulation algorithm,  $\beta_{usage}$

directly influences the infeed level for every hour. This in turn influences both the fulfillment factor as well as surplus and insufficient power.

The measures  $E_{bal-}$  and  $E_{bal+}$  are inversely proportional; a high infeed level will result in little surplus power and many incidents with insufficient power and vice versa for a low infeed level. If the two measures are equal,  $\beta_{usage}$  can be considered as a good compromise.  $E_{bal-}$  and  $E_{bal+}$  are thus used to find a matching  $\beta_{usage}$  for a given set of simulation parameters.

Prior to every simulation, the correct usage factor has to be defined. This is done by running the simulation algorithm with an arbitrarily chosen value for  $\beta_{usage}$  and by comparing the results for  $E_{bal-}$  and  $E_{bal+}$ . As long as they don't match,  $\beta_{usage}$  has to be adjusted. The procedure can be summarized as follows:

- run simulation with  $\beta_{usage} = 0.98$ <sup>3</sup>
- calculate  $E_{bal-}$  and  $E_{bal+}$
- adjust  $\beta_{usage}$ :
  - if  $E_{bal-} > E_{bal+}$ , reduce  $\beta_{usage}$
  - if  $E_{bal-} < E_{bal+}$ , increase  $\beta_{usage}$
  - if  $E_{bal-} = E_{bal+}$ , terminate

Regulating market characteristics can be accounted for by introducing a weighting factor  $\omega$ . The factor  $\omega$  relates the magnitudes of the costs for up regulation ( $\propto E_{bal-}$ ) to those for down regulation ( $\propto E_{bal+}$ ).

$$\omega = \frac{\text{cost of up regulation per kWh}}{\text{cost of down regulation per kWh}}$$

In the above procedure,  $E_{bal+}$  must then be compared with  $\omega \cdot E_{bal-}$ .

The concept of a dynamic usage factor  $\beta_{usage}(t)$  is based on the idea to incorporate the charge level of the ESD into the planning procedure. This allows to more effectively use the storage device.

The relation between the charge level of the ESD and the magnitude of  $\beta_{usage}(t)$  is found in a similar way as for the constant factor and with the same stopping criteria. However, the algorithm from Fig. 2 has to be adjusted: at every beginning of a planning period, the charge level  $E_{st,ch}$  is reset to a certain level (e.g. 25%), independent of its actual charge state (i.e. it is pretended as if the ESD would only be charged to that certain level). Then the above procedure is run. The resulting value for  $\beta_{usage}(t)$  is the value to be used by the algorithm, if the ESD is at that level at the beginning of a planning period. It is recommended to perform this procedure for several charge states and to then interpolate between the resulting values for  $\beta_{usage}(t)$ . This eventually gives a function or look-up table, relating a charge level to the corresponding  $\beta_{usage}(t)$ .

Alternatively, the matching  $\beta_{usage}$  could also be defined as the  $\beta_{usage}$  minimizing the total deviations  $\min(\sum E_{bal-} + \sum E_{bal+})$ , i.e. trying to fulfill the planned infeed as closely as

<sup>3</sup>0.98 was found to be a good starting value for photovoltaic measurements.

possible. Or, by simply running a simulation with  $\beta_{usage} = 1$  and then setting  $\beta_{usage} = F$ .

The following case study will show, that the proposed method defines a dynamic  $\beta_{usage}$ , which allows to plan the network infeed more accurately, resulting in an overall better performance.

#### IV. CASE STUDY

This case study investigates whether the generation from a large photovoltaic (PV) installation can be efficiently leveled with a storage device and how the storage capacity should be sized. Moreover, the case study is used to demonstrate the application and usability of the presented simulation and analysis methods.

Earlier work [5] used measurement data from the same facility to investigate under which circumstances the daily production could be adjusted to a pre-determined infeed that was kept constant over several hours. The results showed that the required energy capacity would be significant and hardly feasible.

Thus, suitable simulation and analysis methods were developed for focusing on hourly leveling of the infeed. The major issues with fluctuations from stochastic sources are not primarily the fluctuations per se but the difficulty to accurately predict them. Therefore it would already be an improvement if the fluctuations could be leveled to hourly constant and pre-determinable values by operating an ESD.

The measurement series is from a 500 kWp photovoltaic system that is installed on Mont Soleil, in Switzerland. The PV array covers an area of roughly 20'000 m<sup>2</sup> and is in operation since 1992. The data series consists of various measurements (e.g. irradiation, temperature, rectifier losses) for every 5 min from the years 2002 to 2004, whereas for this study the output of the rectifier was used as input data.

The storage device is modeled with a charge efficiency  $\eta_{ch} = 0.9$ , a discharge efficiency  $\eta_{dch} = 0.9$  and minimal energy capacity  $E_{st,min} = 0$  kWh. This corresponds to a cycle efficiency of 81%, as e.g. certain types of batteries have on the long run. To select the ESD's energy capacity and power rating for a base case study, a simulation series was run to identify their influence on the fulfillment factor. Fig. 6 shows a surface plot where the energy capacity varies from 10 kWh to 200 kWh and the power rating from 25 kW to 500 kW, with  $f_{err} = 0$  and  $\beta_{usage} = 0.98$ .

As could be expected, the energy capacity has noticeably more influence on the fulfillment factor  $F$  than the power rating. The figure also shows that any values above  $P_{st} \geq 150$  kW and above  $E_{st} \geq 100$  kWh do not change  $F$  significantly. For the base case the energy capacity of the ESD was thus defined as  $E_{st} = 100$  kWh and the power rating as  $P_{st} = 500$  kW. The power rating is kept at this level, assuming that the ESD is connected to the same components that have been designed for the power rating of the PV array.

Fig. 7 additionally shows the distribution of the charge and discharge activities for the chosen characteristics, confirming

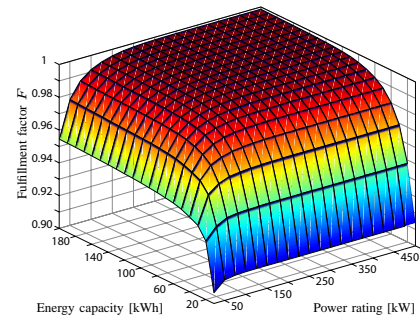


Fig. 6. Fulfillment factor  $F$  for varying energy and power capacities of the ESD;  $f_{err} = 0$ ,  $\beta_{usage} = 0.98$

the above statement that most of the ESD activities are significantly below 150 kW.

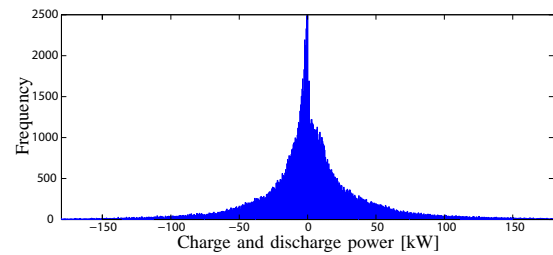


Fig. 7. Distribution of the charge and discharge power flows for  $P_{st} = 500$  kW and  $E_{st} = 100$  kWh.

The following section contains several analyses for the case of a perfect forecast, i.e.  $f_{err} = 0$ . Then a section follows investigating the influence of the magnitude of the forecast error  $f_{err}$  on the results.

##### A. Perfect forecast

A perfect forecast is difficult to be accomplished, particular with an increasing time horizon, and is therefore nonrealistic. It can however be considered as the ideal case and serve as a reference.

As mentioned in section III-D, prior to any simulation, the usage factor has to be determined. For the case study, it is assumed that up and down regulation are equally penalized and hence  $\omega = 1$ .

In the case of  $P_{st} = 150$  kW and  $E_{st} = 100$  kWh, a constant  $\beta_{usage} = 0.98089$  was calculated. The left side of Fig. 8 shows the dynamic  $\beta_{usage}(t)$ , ranging from 0.95057 to 1.02016. The right hand side displays the changing values for  $E_{bal-}$  and  $E_{bal+}$  and their intersection at  $\beta_{usage}$ .

The results of simulations run with both a constant and a dynamic usage factor are displayed in Table I. All numbers show that incorporating the ESD's charge level into the planning process results in better overall performance, i.e. higher fulfillment factor and less surplus power. To see how the initial generation  $\sum \mathbf{P}_{source}$  is used with the ESD present, some values are also expressed relative to  $\sum \mathbf{P}_{source}$ . The amount  $\sum \mathbf{P}_{infeed}$  is practically equal to  $\sum \mathbf{P}_{planned}$ , whereas it must be considered that a small amount of  $\sum \mathbf{P}_{infeed}$ , equal to  $E_{bal+}$ , was not infeed according to plan, as indicated by  $F$ .

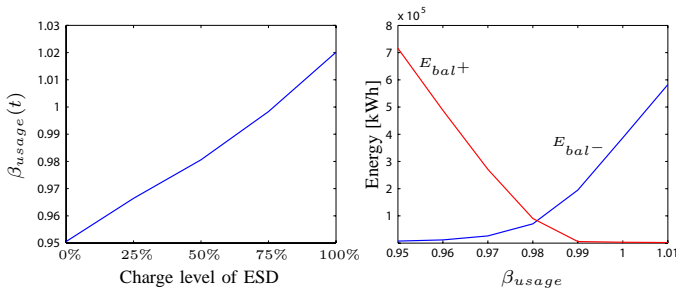


Fig. 8. Left:  $\beta_{usage}(t)$  for the different charge level at the beginning of the planning period. Right:  $E_{bal-}$  and  $E_{bal+}$  for different constant  $\beta_{usage}$ .

TABLE I  
RESULTS FOR THE BASE CASE

	constant $\beta_{usage}$		dynamic $\beta_{usage}(t)$	
$\sum \mathbf{P}_{source}$ [kWh]	1'804'069	100.00%	1'804'069	100.00%
$\sum \mathbf{P}_{planned}$ [kWh]	1'769'585	98.09%	1'769'647	98.09%
$\sum \mathbf{P}_{infeed}$ [kWh]	1'769'585	98.09%	1'769'049	98.06%
$E_{conv}$ [kWh]	34'461	1.91%	34'980	1.94%
$E_{bal+}$ [kWh]	6'457	0.36%	4'039	0.22%
$E_{bal-}$ [kWh]	6'458	0.36%	4'637	0.26%
Fulfillment $F$	0.9963		0.9974	

The table shows that although the total  $\sum \mathbf{P}_{planned}$  is slightly larger for  $\beta_{usage}(t)$ , it nevertheless is fulfilled more closely, as the comparatively smaller deviations from the planned infeed level  $E_{bal-}$  and  $E_{bal+}$  show. On the other hand, adjusting the planned infeed level to the charge level of the ESD results in a more intensively used ESD and hence in more energy lost for conversions  $E_{conv}$ .

Fig. 9 shows the duration curve of the ESD charge level  $E_{st,ch}$  on the left side and on the right side the duration curve for the network infeed  $\mathbf{P}_{infeed}$ , compared to the original generation  $\mathbf{P}_{source}$ . Although the network infeed is very similar,

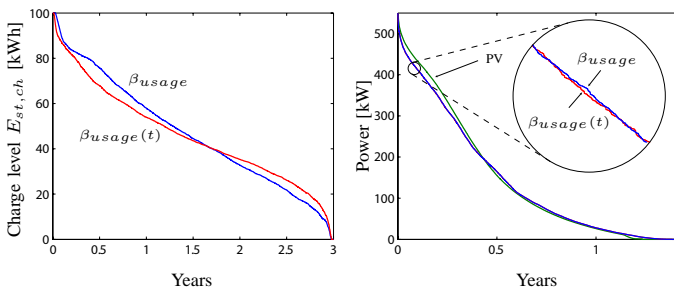


Fig. 9. Left: Duration curve of the storage level for  $\beta_{usage}$  and  $\beta_{usage}(t)$ . Right: Duration curve of the original generation and actual infeed with zoom to show the marginal differences between  $\beta_{usage}$  and  $\beta_{usage}(t)$ .

the utilization of the storage device is quite different. With  $\beta_{usage}(t)$ , only the range between roughly 20% and 80% is used, and the question can be raised, whether a capacity of  $E_{st} \approx 60 \text{ kWh}$  would be sufficient. This question will be addressed later, when investigating minimal energy capacity requirements for different forecast error magnitudes. An "optimally" or evenly used ESD would in any case have a duration

curve, which linearly decreases from 100% to 0%.

Concerning the energy capacity  $E_{st}$  of the ESD, another interesting relation can be found. Fig. 10 shows for  $E_{st} = 100 \text{ kWh}$  and  $E_{st} = 300 \text{ kWh}$  the distribution of the deviation magnitudes of the actual infeed from the planned infeed profile. For both storage capacities, most events with surplus power are of a size  $< 50 \text{ kW}$ , whereas the events with insufficient power are more evenly distributed. Fig. 11 shows a

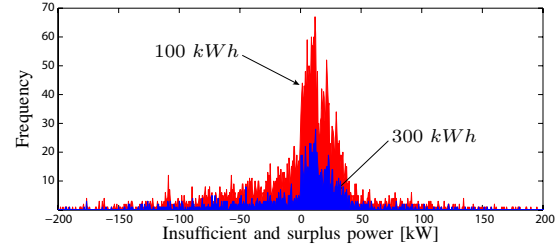


Fig. 10. Distribution of the deviations of the actual infeed from the planned infeed for  $P_{st} = 500 \text{ kW}$  and  $E_{st} = 100 \text{ kWh}$ , respectively  $E_{st} = 300 \text{ kWh}$ , constant  $\beta_{usage}$ .

similar plot, however for  $E_{st} = 100 \text{ kWh}$  and both a constant and a dynamic usage factor. Incorporating  $\beta_{usage}(t)$  into the planning process obviously leads to a similar distribution compared with a larger ESD capacity, as in Fig. 10. Generally,

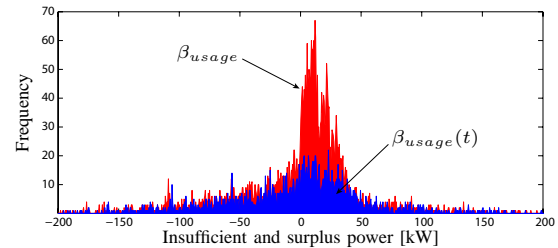


Fig. 11. Distribution of the deviations of the actual infeed from the planned infeed for  $P_{st} = 500 \text{ kW}$  and  $E_{st} = 100 \text{ kWh}$ , constant and dynamic  $\beta_{usage}$ .

it can be stated that a well-designed infeed planning algorithm leads to slightly more conversion losses on the one hand, but on the other hand allows to accurately follow the infeed pattern with a comparatively smaller energy capacity. The following section will discuss how forecast errors change these findings.

### B. Imperfect forecast

As mentioned, calculating a perfect forecast is difficult to achieve and represents the major issue with non-dispatchable generators. When designing the appropriate ESD capacity this constraint has to be addressed. In section II-B, a method was introduced with (2), which allows to simulate a certain forecast error and to investigate its influence on the result.

This section thus discusses some analyses showing the influence of the forecast error on the overall system performance. As a first investigation, the fulfillment factor  $F$  is analyzed while keeping the ESD's energy capacity  $E_{st}$  constant. The result is shown on the left side of Fig. 12. The right illustration in Fig. 12 shows the maximal value  $\beta_{usage}$  can be if the

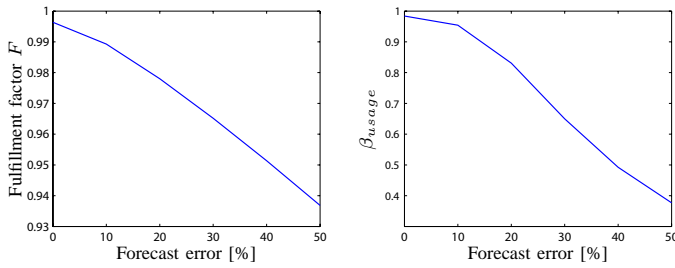


Fig. 12. Left: Fulfillment factor for increasing forecast error,  $E_{st} = 100kWh$  and dynamic  $\beta_{usage}(t)$ . Right: Maximum constant  $\beta_{usage}$  to maintain a fulfillment factor  $F \geq 0.995$ ,  $E_{st} = 100kWh$ .

planned infeed profile should be fulfilled with  $F \geq 0.995$ . Both figures show that the system performance decreases with an increasing forecast error. Moreover, with increasing  $f_{err}$ , an energy capacity  $E_{st} = 100 kWh$  is not sufficient for balancing the differences and deviations between the forecast and the actual generation; this could only be achieved by significantly lowering  $\beta_{usage}$ .

The lack of sufficient storage capacity  $E_{st}$  can also be identified in Fig. 13, showing the duration curves of the storage levels for the different forecast errors.

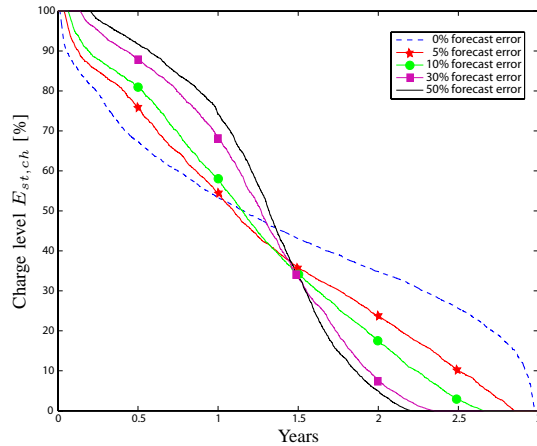


Fig. 13. Duration curve of the storage level for different forecast errors  $f_{err}$ , dynamic  $\beta_{usage}(t)$ .

As discussed for Fig. 9, the illustration shows that a capacity of  $E_{st} = 100 kWh$  is larger than needed for  $f_{err} = 0\%$ . It seems that a capacity of  $E_t = 100 kWh$  is appropriate for  $f_{err} = 5\%$ , as it uses the storage quite evenly. However, the more the forecast error increases, the steeper the duration curve becomes. This implies increasing accumulated intervals with a fully charged ESD (top left corner) and with a completely discharged storage device (bottom right corner). This means that the system is not capable of operating the ESD in a favorable way for larger forecast errors; often the ESD is either full or empty.

To close the case study, table II shows the minimal required energy capacities in order to be able to fulfill the planned generation with an accuracy of  $F = 0.99$  and a constant  $\beta_{usage} = 0.95$ . The values are expressed relative to the initial

TABLE II  
MINIMAL REQUIREMENTS FOR  $E_{st}$  TO ACHIEVE  $F \geq 0.99$

$f_{err}$	$E_{st}$	$E_{conv}$	$E_{bal-}$	$E_{bal+}$	$\sum \mathbf{P}_{infeed}$
%	[kWh]	%	%	%	%
0	39	1.52	0.92	4.40	94.08
5	47	1.56	0.94	4.38	94.06
10	64	1.62	0.94	4.31	94.06
20	143	1.79	0.94	4.14	94.06
30	262	2.00	0.95	3.94	94.06
40	406	2.23	0.95	3.70	94.07
50	585	2.48	0.95	3.44	94.07

generation  $\sum \mathbf{P}_{source}$ . The table shows the increasing required  $E_{st}$  and the hence reducing  $E_{bal+}$ , as more surplus energy can be stored. This on the other hand implies that more energy again is lost for conversions.

## V. CONCLUSION

This publication investigated the benefits of combining a grid-connected photovoltaic system with an energy storage device. The goal was to feed into the network with repeatedly pre-determined hourly constant power levels.

The major finding is that the dispatchability of a stochastic generator can be improved already with smaller storage devices with energy capacities around  $50 kWh$ . For accurate generation forecasts, the predefined levels can be fulfilled 99, 5% of the time. With increasing forecast errors, either the reliability of fulfilling the planned infeed decreases, or the energy capacity of the ESD has to be significantly increased. Incorporating the momentary charge level of the storage into the daily infeed planning process on the other hand, allows to slightly lower the energy capacity requirements.

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## REFERENCES

- [1] S. J. Ehnberg and M. H. Bollen, "Reliability of a small power system using solar power and hydro," *Electric Power Systems Research*, vol. 74, no. 1, pp. 119–127, 2005.
- [2] Bagen and R. Billinton, "Evaluation of different operating strategies in small stand-alone power systems," *Energy Conversion, IEEE Transactions on*, vol. 20, no. 3, pp. 654–660, 2005.
- [3] R. Billinton and Bagen, "Incorporating reliability index distributions in small isolated generating system reliability performance assessment," *Generation, Transmission and Distribution, IEE Proceedings-*, vol. 151, no. 4, pp. 469–476, 2004.
- [4] H. Holttinen, G. Giebel, and T. Nielsen, "Wind energy in the liberalised market - forecast errors in a day-ahead market compared to a more flexible market mechanism," in *2nd International Symposium on Distributed Generation*. Stockholm: Royal Institute of Technology, 2002.
- [5] B. Kloeckl, P. Stricker, and G. Koepfel, "On the properties of stochastic power sources in combination with local energy storage," in *CIGRE symposium on power systems with dispersed generation*, Athens, Greece, 2005.
- [6] M. Korpås, "Distributed energy systems with wind power and energy storage," Ph.D. dissertation, Norwegian University of Science and Technology, 2004.
- [7] J. Hull, *Options, futures, and other derivatives*, 6th ed. Upper Saddle River, NJ: Pearson, Prentice Hall, 2005.