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Probabilistic tools for planning and operating power systems with distributed energy storage[1]

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Stochastic energy flows are an increasingly important phenomenon in today's power system planning and operation. They are – among other reasons – caused by large amounts of stochastic generation such as wind. The inclusion of energy storage devices, distributed in future systems (distributed energy storage – DES), is continuously being mentioned as a possibility to alleviate some of the problems arising from stochastic generation. The authors show that the potential ownership of the DES systems is an important criterion on which probabilistic methods will be applied for assessment. The potential owners are either the grid operators, the generation owners, or the energy traders. For the grid operators being the DES owners, storage operation will have to be integrated into the planning of the system, therefore multivariate nonparametric time series analysis and synthesis methods have to be applied to recorded data of stochastic energy resources. Together with suited storage models, the implications of DES on the planning of the system can then be assessed. For the producers or traders being the owners of the DES, the topic to be addressed is the real-time operation of each storage device in the power system, which is linked to the optimisation of the economic value of the stochastic resources. In this case, forecasting and operations research issues are paramount. Recently developed methods including scenario development from non-parametric forecast models for the following trading period and probabilistic assessment of necessary storage capacities for hedging with given financial risks are explained.

It is generally stated that the non-standard distributions of the stochastic infeeds, as well as complex chronological persistence and interdependence phenomena complicate the modelling procedure and leave space for a large range of research activities on DES in the future. The exact description of how the owners of storage assets are embedded into the energy market frameworks of the future is crucial for the probabilistic quantification of benefits introduced by DES.

Keywords: energy storage; stochastic generation; renewable energy; forecasting; wind power; correlation; planning; operation

1. Introduction

The political commitment for a growing share of new renewable energy infeed into the European electricity system has triggered a considerably increasing interest in new system solutions such as sophisticated grid connections for renewables, new system operation strategies, more detailed grid codes, elaborate market models for renewables, etc. Distributed energy storage (DES) as a means to alleviate many of the problems associated with renewable generation has been mentioned in many research articles, political statements, and investigation programs. The basic idea of DES is to shift the consumption of unneeded renewable energy in time instead of space (by transporting it along large distances to places where it is actually needed), and, by doing so, creating additional value for grid operators, generation companies, and the economy in general. Figure 1 shows a general illustration of the role of energy storage devices (ESDs) as a technological option for changing the power flows in a system by influencing the statistical properties of the system nodal power injections. If the generation X and the ESD terminal power flow D are appropriately modelled, the system infeed vector Y is known and the implications of the distributed ESDs on the power system can be assessed.

Fig. 1. General illustration of DES (*Klöckl, 2007*)

An outstanding feature of all DES concepts is that the related technologies are not technically mature and the further development continues to be slow compared to other new technologies such as wind energy. In this way, the developers of energy storage hardware are few and are currently developing products that are hardly comparable to each other. We believe that one of the reasons for this slow technological progress is a wide-spread uncertainty on which party would be the potential beneficiary of DES and this uncertainty in turn is grounded on a lack of theoretical knowledge on its modelling and assessment. The biggest part of the uncertainty is in turn related to the *physical* uncertainty of stochastic infeed through renewables in the systems, which, together with so far inconsistently defined modelling strategies for storage technologies, create an open field of investigation and model development.

The authors have contributed to this discussion through work on modelling of energy storage in combination with stochastic generation (*Klöckl, 2007*), mathematical concepts for stochastic generation in general (*Papaefthymiou, 2007*), and forecasting techniques for wind power (*Pinson, 2007*), which is in turn strongly linked to the quest for DES. We will explain the basic findings from these work packages and set up a general picture on answered and unanswered questions in this extraordinarily complex topic.

In this article, we will elaborate on the properties of stochastic generation in general and the necessary probabilistic concepts

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for the assessment of DES for the different possible parties involved. The focus will be laid on explaining the theoretical problems in the assessment, the pitfalls due to the complexity and the solution paths so far developed.

2. Power market parties interested in energy storage

In the environment of today's liberalised energy markets, the basic question on the potential owners of an upcoming or yet to be developed DES technologies is: Who might be interested in the investments into new and immature technological options? Answering this question, we may identify*, the grid operators*, *generation companies*, or even the *energy traders* as possible storage owners. What is not widely accepted or at times mixed up in the related literature, is that these parties do not necessarily have the same objectives from the use of ESDs, which in turn results in entirely different sizing, siting and operational options and thus in totally different technological requirements.

Grid operators might certainly show major interest, but cannot own storage due to a lack of the appropriate regulatory environment. The question is, if a grid operator may possess and manage certain amounts of energy except for loss energy. Under the current EU legislation, the answer is rather ''NO'' than ''YES''. The system design implications would be considerable if this possibility would exist, as has been shown in (*Klöckl, 2007*). The goal of developing probabilistic methods for this purpose is the exact quantification of a technological option's value on the overall system design. The task is a planning task, since a regulated grid company has to quantify the costs of a given option and oppose them to the expected technical benefits. These can be the delay of system investments or the avoidance of system contingency situations. Hence, under current conditions, only the grid operators can be interested in storage-intrinsic and much-mentioned services such as peak shaving in power networks.

Generation companies have in turn vital interest in owning and operating energy storage assets. The existing and recently planned large pumped hydro schemes, especially in the Alps, are the best example. In deregulated electricity markets, storage assets can increase the value of a generation portfolio or simply generate value through exploiting the spread between peak- and off-peak spot prices. However, pumped hydro schemes are just an indication on what benefits DES could provide in the future, because,

- they make use of natural resources with a multitude of complex boundary conditions such as strongly seasonal additional inflow (which of course depends a lot on the site) or water flow restrictions in pumping as well as generating mode
- they are typically large in terms of installed power, thus have to be connected to the transmission system and will therefore not influence local energy balances, rather have impacts on the power flows on a continental scale. The prices zones currently in effect in Europe are large and include large numbers of nodes on transmission level each, which in turn does not provide for effective local signalling to pumped hydro owners.

Yet to be developed technical storage systems such as flow batteries or compressed air storage would however be restricted mainly by deliberately chosen technical parameters such as the rated energy content and can be supposed to appear on distribution level, due to generally low ratings. The questions of generation companies in relation to DES are typically in the field of operation, i.e. 'how can one make the most of money with an existing energy storage device' (ESD), which is related to the entire energy market model. In no way, one can be sure that the resulting storage behaviour will influence the system design positively, although presently the market price behaviour would incentivise owners of DES to charge the assets in times when demand is low, and discharge in times of high demand, which in turn would theoretically relieve T&D networks. The same behaviour can today be observed from generation companies that own large pumped hydro assets. If a generation company operates DES only to increase the market value of stochastic generation, probabilistic methods should be adopted to decrease the necessary size of ESDs for given financial risk, with the boundary case of no storage being necessary at all (for perfect forecasting of the stochastically generated power in the next trading period). This is applicable only in energy markets with program responsibility for renewables, since in the market models currently in place in many European countries, infeed prices are fixed for renewable generators and therefore renewable generation companies generally would have limited interest in DES investments.

Energy traders would finally be interested in hedging options for the uncertainty of renewable generation, which would however not point directly to DES. These possibilities would be a financial transaction rather than a physical one, and would, if at all, be effectuated at a physical point in the price zone that would be subject to internal optimisation process of the generation company. This means in other words, that it is unclear if the system would be relieved by such mechanisms or even additionally loaded.

3. Stochastic generation in power systems

3.1 Renewable – intermittent – stochastic: some remarks

We refer to stochastic generation (SG) as power generation driven by an uncontrolled prime energy mover (*Papaefthymiou, 2007*). The designation 'SG' should not be mixed up with non-dispatchable or intermittent generation, since any type of power grid participant can be non-dispatchable or intermittent, e.g. the gas-fired power station that ramps up in high price situations as well as the common domestic consumer that takes power out of the distribution system at random times. Solely the type of generation intermittency that cannot or will not be influenced by the operators (e.g. because of the market setting for renewables) and that is driven by natural stochastic processes should be called 'stochastic generation'. Note that SG is a subset of intermittent generation while non-dispatchable generation can mean any type of infeed that is not being controlled by the system operators (*Klöckl, 2007*). The power output of a stochastic generator is defined by the stochastic prime mover (the type of primary energy source used for electrical power generation) and the energy conversion system (according to the converter technology, the power output of the generator for each input value of the prime mover can approximately be defined by a deterministic relationship).

Thus, the power output distribution is obtained as a transformation of the prime mover distribution. Due to this transformation, non-standard SG power distributions are obtained. We will illustrate this issue by mentioning the case of a wind turbine generator (WTG). There, the prime mover, i.e. the wind speed activity in a specific location, typically follows a standard Weibull distribution. The energy conversion system is given by the wind speed/power output characteristic. The obtained power distribution shows a concentration of probability masses at zero and nominal output power, which is due to the effect of the non-monotonic WTG characteristic. Similar figures can be obtained for the description of other SG such as photovoltaic installations. In this particular case, the periodic part of the time series is more pronounced (zero power production at night, full power production at noon) and the power infeed distribution for the individual hours of the day are highly variable and also non-standard. It is clear that the mathematical modelling of this behaviour is at least challenging, especially if different types of SG are mixed in one power system. The basic principles to be relied upon will be discussed in the following section.

3.2 Modelling of stochastic generation

3.2.1 Statistical properties of stochastic generation

A set of stochastic generators feeding into a spatially distributed power system can be regarded as a multivariate stochastic process with the following properties:

- Non-standard marginal distributions of the individual infeeds (as mentioned above), that is, stochastic generators can hardly be modelled by Gaussian or other standard distributions,
- a pronounced serial dependence of the individual infeeds, showing periodical components, that is, diurnal, multi-diurnal, and seasonal cycles,
- at times complex stochastic dependence structures between individual infeeds.

We present the illustration of three neighbouring wind parks in the Netherlands (*Klöckl, 2007*). A strong serial dependence (high wind power in one hour means high wind power in the next hour and vice versa), a clear multi-diurnal cycle, and a strong interdependence between the three parks (Fig. 2) may be observed. Stochastic dependence has a major impact on the determination of the aggregate of a number of stochastic infeeds (and an even higher one for stochastic generators with DES). To illustrate this, in Fig. 3 the aggregate power output distribution of 50 wind turbine generators is shown for three cases of stochastic dependence. The marginal distributions of the individual generators are kept equal, while the stochastic dependence varies from the case of independence (where $\rho = 0$, which is a necessary, but not a sufficient condition for independence in the mathematical sense) up to the case of perfect dependence. We see that although the output of each generator is the same for all cases, each dependence structure leads to a new aggregate distribution around the same mean value. In the case of independence, the applicability of the central limit theorem leads to an aggregate distribution that is close to normal; as the dependence increases, the variability of output increases. Thus, not taking into account the stochastic dependence (by using sampling procedures based on the independence assumption, as it is done in many investigations) will lead to system design decisions that severely underestimate the system risk. Since the utilisation of distributed ESDs is in tendency increasing the dependence between the individual infeeds, neglecting the dependence structures further increases the degree of misinterpretation in the case of DES deployment.

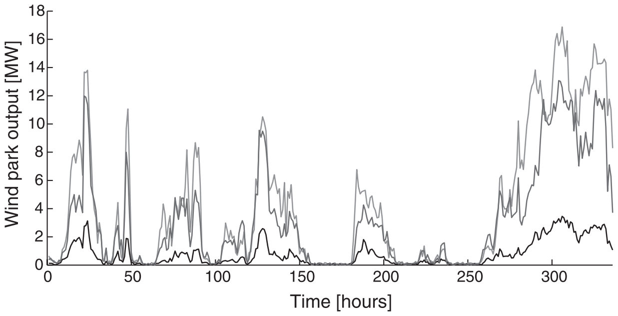

Fig. 2. A sequence of three wind park infeeds; the serial correlations and interdependence are both well visible

3.2.2 Simulation and its role in investigations on DES

Information on the properties of stochastic generation is typically drawn from measured time series of stochastic prime movers or power infeeds. This information might be sufficient to draw conclusions on the distributions of power flows in the network or on the economic value of storage for a generation owner. However, since investigations on storage include the integrating properties of the ESDs themselves, the statistical relevance of the conclusions depends on the type of storage devices and the operating strategies used. In other words: The same set of measured infeeds can bear sufficiently accurate results for a certain type of ESD distributed in a given system, while it can be entirely insufficient for another type. Generally, if ESDs are operated together with the system (i.e. the grid operator is supposed to be the owner), increasing storage capacity implies the need for increasing length of the time series for convergence of the results and planning safety (see later, Fig. 6). The more complex the operating strategy, the higher the need for long time series. Clearly, this requirement cannot always be fulfilled by measured time series, and Monte Carlo methods are needed to simulate synthetic time series.

3.2.3 Challenges in time-domain modelling

For the assessment of distributed energy storage, *time-domain information is needed in addition to information on marginals and interdependence structures* (*Klöckl, 2007*). As an example, we mention the case of storage device with different capacities, fed by stochastic processes with equal distributions but varying persistences, expressed by the lag-1-correlation coefficient ρ_1. The failure rate (defined as the fraction of time during which the ESD does not fulfil its task due to being fully charged or empty) increases considerably with increasing chronological persistence, which is an intuitively clear conclusion. The discrepancy in the failure rate between $\rho_1 = 0.1$ and $\rho_1 = 0.9$ can be as large as one order of magnitude, as can be shown in suited simulation experiments. These requirements on the quality of chronological information make the modelling considerably more complex. An approximate methodology has been introduced in (*Klöckl, 2007*), which is based on simplifying

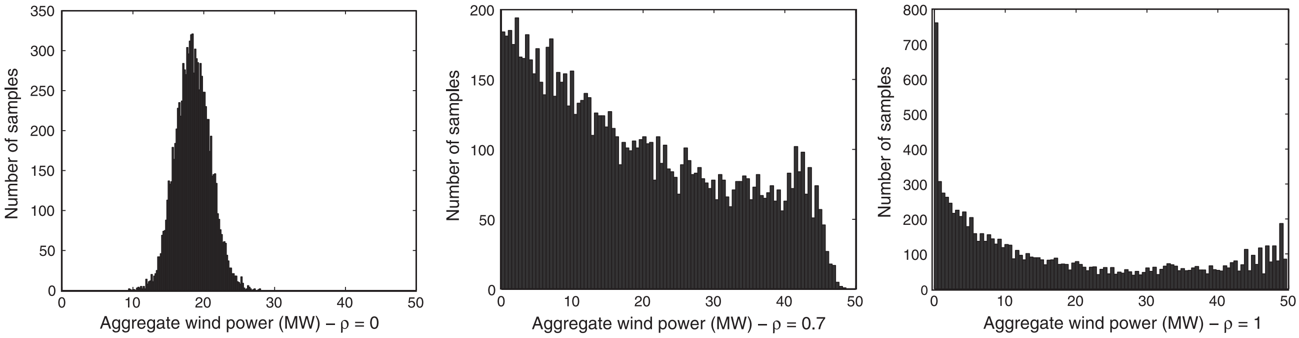

Fig. 3. Aggregate power output from 50 wind turbine generators for different dependencies, expressed by the linear correlation coefficient ρ

assumptions on the multivariate stochastic processes typically encountered in SG. The method is based on

- the hourly transformation of individual infeeds to normality by the inversion method
- the identification of a VAR (vector autoregressive) process that fulfils the statistical properties of the measured and transformed multivariate process
- the sampling and back-transformation of the synthetic process as input of arbitrary length to the storage and power system simulation models.

This method can capture all kinds of diurnal and multi-diurnal serial persistence effects, the non-standard marginal distributions, as well as the typical dependence structures between individual stochastic infeeds (*Klöckl, 2008*).

3.2.4 Forecasting and scenario-development techniques

Forecasting is a key aspect for an optimal management of stochastic generation in a power system. Today, most research efforts on forecasting methodologies are related to wind generation. Improvement of prediction systems' performance is one of the priorities in wind energy research needs for the coming years (*Thor, Weis-Taylor, 2002*). Forecasting also has a significant value for solar energy, even though this alternative renewable energy source exhibits more predictable variations. Most of the existing wind power prediction methods provide end-users with point forecasts. A state-of-the-art on wind power forecasting has been published in (*Giebel, Kariniotakis, Brownsword, 2003*), while a discussion on level of accuracy is available in (*Madsen et al., 2005*). Such point forecasts correspond to the conditional expectation of wind generation, i.e. the mean of the distribution of potential generation, for each lead time in the future. However, a large noise component is present around this expected generation value, with magnitude of potential deviations strongly dependent on a large number of factors, e.g. the level of predicted power or the prevailing meteorological situation (*Lange, Focken, 2005*). Therefore, a large part of the recent research works in wind power forecasting has focused on associating uncertainty estimates to these point forecasts. (*Pinson et al., 2007*) introduce two complementary approaches that provide forecast users with skill forecasts (in the form of risk indices) or alternatively with probabilistic forecasts. This latter form of uncertainty estimates is the most commonly used today, for which a large of alternative methods have been proposed, see e.g. (*Pinson, 2007*). Probabilistic forecasts of wind generation may take the form of quantile, interval or density forecasts and are generated on a per look-ahead time basis. They do not inform on the development of the prediction errors through prediction series, since they neglect their interdependence structure. Such interdependence structure may be omitted for some decision-making problems for which successive decisions are independent, which is for instance the case of the optimal design of trading strategies on day-ahead electricity markets (*Pinson, Chevallier, Kariniotakis, 2007*). However, for a large range of decision-making problems for which successive decisions to be made are interdependent, the information on the interdependence structure of prediction errors is paramount. The optimal operation of DES falls into that category, with an interdependence both at the spatial and temporal level. Methods for the generation of production scenarios with interdependence at the temporal level are described in (*Pinson et al., in press*), while the spatial case in considered in (*Papaefthymiou, Pinson, 2008*). Figure 4 gives an example of forecasts of wind generation for horizons up to 2-day ahead, for a multi-MW wind farm in the North of Denmark. This set of forecast products includes the commonly provided point forecasts of wind power, which are then dressed with probabilistic predictions given by series of prediction intervals with various nominal coverage rates. Corresponding power measurements at the wind farm are also given for comparison. In parallel, Fig. 7 depicts a set of 50 scenarios of power production derived from probabilistic predictions based on the method described in (*Pinson et al., in press*). Such scenarios can then be used as input to e.g. Monte-Carlo simulations for investigating on optimal storage operation strategies.

4. DES in planning and operation

4.1 Planning

If DES is considered to be part of a system planning strategy, the ownership of the ESD can be assumed to be in the hands of the system operator. The operational rules for the ESDs then typically degenerate to statistical interpretations of the stochastic infeed, as has been demonstrated in (*Klöckl, 2007*). The most prominent one is

$$P_{ESD} = P_G - \mu_{P_G} \tag{1}$$

where P_{ESD} is the terminal power of the energy storage device, P_G is the power of the SG, and μ_{P_G} is its mean. This control law is independent of the assumed future of the stochastic infeed, is universally valid for lossless, infinitely large ESDs and leads to sustainable ESD operation. In reality, the control laws have to respect complex loss mechanisms as well as the finite energy capacity of the ESDs to attain sustainability. For a detailed discussion and a solution path of this problem, again see (*Klöckl, 2007*).

Figure 5, l.h.s. shows the shift of power flows on a critical line of a meshed 14-bus/18-branch example network due to the utilisation of DES by the grid operator. The same simulation has been performed once for no storage installed in the meshed, stochastically fed network at all, and once with ESDs installed in each of the nodes. It is important to understand that the assumed underlying

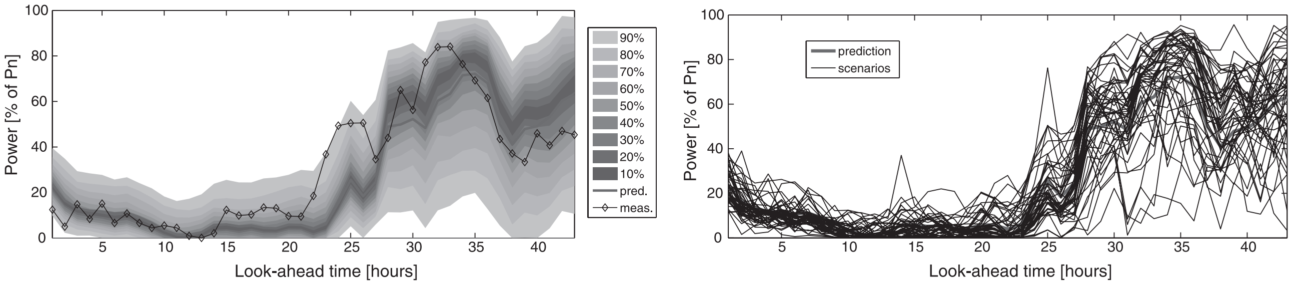

Fig. 4. Example of probabilistic predictions of wind generation (right) in the form of a fan chart. Each color band corresponds to prediction intervals with a given nominal coverage, ranging from 10 to 90 %, with 10 % increments. Corresponding scenarios of short-term wind generation (left) rely on the most recent information on the interdependence structure of prediction errors

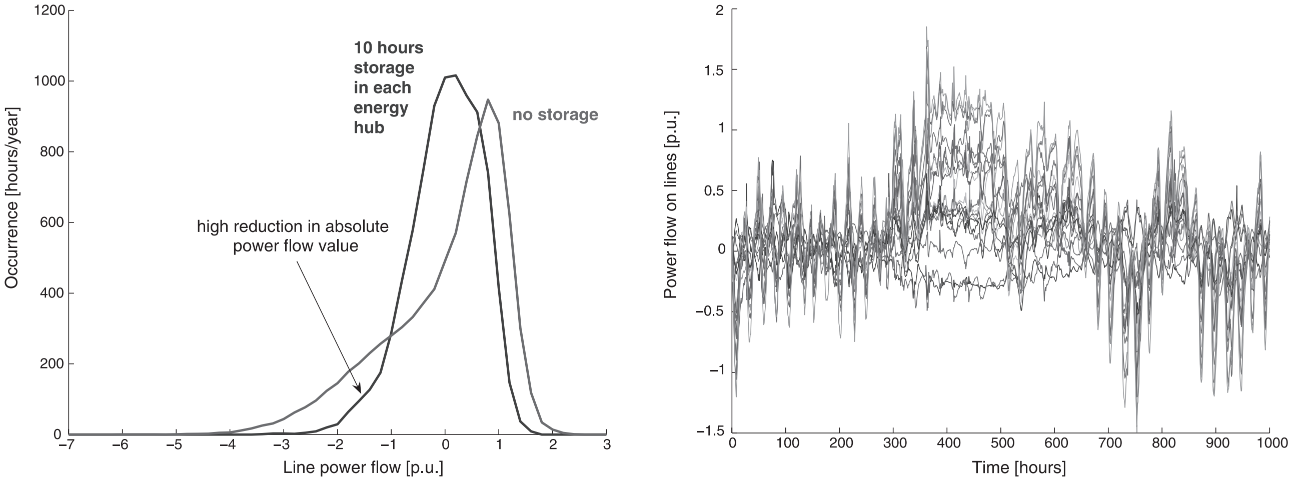

Fig. 5. Shift of the power flows on the most critical line of a meshed example system, fed by stochastic generators, with and without DES (right), and the respective power flows on the system branches with DES (left)

operating strategy of the ESDs is optimal from the point of view of the grid operator, no optimisation for a generation company has been assumed. Figure 5., r.h.s. shows a short sequence of power flows on all lines. It can clearly be detected that the line flows tend to increase overpropotionally and synchronously on all lines, which is connected to diurnal load cycles, and is amplified by synchronously reaching the upper and lower limits of the DES system; that means, as a consequence of the persistence of the stochastic infeed processes and their interdependence, the distributed storage devices are out of function (empty or fully charged) in the same periods of time, thus increasing the power flows on the transmission lines. In addition, there are periods during which there is no clear reason for the general increase of overall power flow activity (in the middle section of the time series), and which are also due to complex persistence and interdependence effects. Figure 5, r.h.s. clearly shows that the mixing of this complex multivariate stochastic process has to be observed for a long period of time to be able to draw statistically meaningful conclusions on the power flow distributions. This means that for many investigations (especially for large systems), time series as long as some decades in equivalent time are necessary to find stable distributions such as the one shown in Fig. 5, l.h.s. Note that such long time series can only be generated in computationally expensive repetitive power flow simulations. Equally important, they do not represent the future in some decades' time, rather the probabilistic assessment of what may happen in the present by assessing a large number of interdependent situations that may occur due to the probabilistic structure in the stochastic process.

4.2 Operation

Generally, the operation aspects of DES are a typical topic of interest for the owners of SG assets. Then, optimal storage operation is more complex compared to strategies such as the one from Eq. (1). Moreover, it is not understood that ESDs used for increasing the value of the stochastic generation are indeed distributed in the system, unless a nodal pricing scheme is applied. Generally, one has to consider that in an electricity market environment that does not favor wind power against other energy sources, a crucial decision-making aspect is related to the targeted amount of energy contained in a local storage device at the end of the trading period – and thus at the beginning of the following one. One may choose for instance to have the energy level low at the beginning of the trading period since overproduction is more likely than under production. One might also consider that since electricity prices are expected to

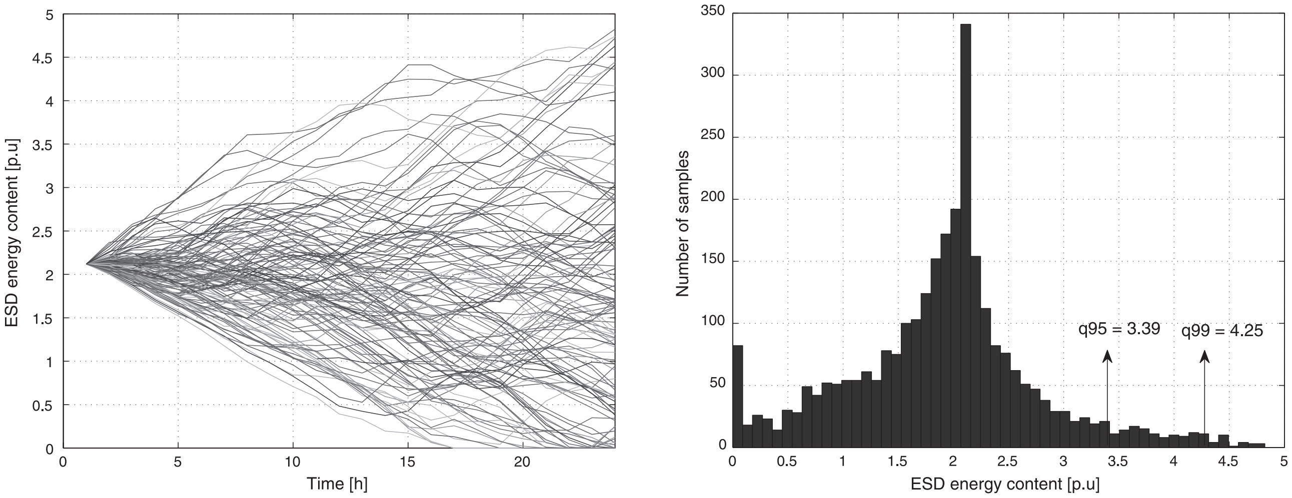

Fig. 6. Assessment of the day-ahead ESD energy content for a combined wind/ESD plant. Based on the level of risk exposure defined as a quantile of the distribution of the energy content, a decision can be made on the necessary ESD size for hedging risk of imbalances

be low in the coming period, it would be a clever choice to store as much energy as possible and release it in the following trading period. The mathematically correct approach is a multi-period stochastic optimization, as applied already nowadays in the annual operation of large seasonal storage pumped hydro plants. All these aspects of optimal operation of storage in combination with stochastic energy source have been illustrated and discussed in a feasibility study related to a demonstration hybrid wind-storage system to be operated in Ireland, see (*Tapbury, 2007*). Finally, it may be envisaged that in the future owners of storage capacity would propose arbitrage as a service to electricity traders. In such a case, the storage owner would have to decide before each trading period what energy content would be allocated to the providing of this arbitrage service. The storage size necessary for balancing activities depends on the forecast error for each delivery period; since this error varies between successive delivery periods, the necessary storage is also not constant.

In (*Papaetfhymiou et al., 2008*), a methodology has been presented on how this decision can be made based on the use of probabilistic forecasts and the most recent information on the time evolution of the forecast errors for the specific hours ahead. By assessing the combined wind/storage plant operation for all possible wind power scenarios for the next delivery period, a distribution for the necessary energy content may be obtained (Fig. 6). Further, one may decide upon the desired risk exposure by choosing a storage capacity corresponding to a specific quantile of this distribution. In such a context, the size of the necessary system energy storage is directly related to the bidding process and the performance of the forecasting system for each market player. The better the forecasting tools become, the lower will be the interest of power producers either in physical storage or in a storage service defined by market rules. The correlation of the performance of different forecasting systems will be central for the determination of the aggregate storage. If the forecast errors between different market players are not correlated, we may expect a levelling of the total uncertainty. Therefore, the necessary aggregate system storage will be less than the case of dedicated energy storage for each producer. In the presence of positive dependence between the forecast errors from different market players, the necessary aggregate storage for risk aversion will be increased.

5. Conclusions

The methods so far known for the modelling of stochastic infeed, although not widely applied today, are sufficiently well developed for rough interpretations on the impact of DES on power system planning. Operational issues, especially for storage assets owned by generation companies (in particular owners of stochastic generation), include forecasting techniques for the immediate future of generation and electricity prices and are currently under development. The existing solutions include scenario generation from statistical information on forecast quality, and dynamic energy storage sizing for risk hedging. Future developments may include the probabilistic assessment of different regulatory and market regimes on the behaviour of storage owners, in conjunction with its impact on the support for renewables dissemination and positive effects on system utilisation.

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