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Modelling and assessment of the contribution of demand response and electrical energy storage to adequacy of supply

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HIGHLIGHTS

- We model specifically the operational flexibility and constraints of DR and EES.
- DR and EES contribute to adequacy of supply by reducing system peak demand.
- Energy payback deteriorates the reliability performance of individual interruptions.
- Decommissioned generation must be less than the peak reduction owing to DR and EES.

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ABSTRACT

Demand response (DR) and electrical energy storage (EES) are key attributes within the context of smarter and more sustainable power systems. However, little work has so far systematically investigated the reliability implications of deploying DR and EES at the system level, including the impacts of characteristics such as the energy payback and flexibility of DR or the capacity and efficiency of EES. Nevertheless, this is fundamental to address the questions as to how DR and EES affect system reliability and whether and to what extent they could displace generation capacity while maintaining sufficient system adequacy. Therefore, this paper aims at developing a general framework to evaluate the contribution of DR and EES to adequacy of supply by specifically modelling and analysing their operational flexibility parameters and constraints. Specific studies are run using sequential Monte Carlo simulation that allows capturing the relevant inter-temporal constraints. The results suggest that, given a prevailing generation portfolio, DR and EES could reduce the frequency and cumulative duration of interruptions, although these might become more severe. The amount of generation that could be displaced is then quantified, which is found to be less than the peak reduction provided by DR and EES while preserving system adequacy. The models and findings of this work are thus critical to quantitatively inform the energy policy debates about the potential of DR and EES to provide system capacity and participate in relevant markets.

1. Introduction

The deployment of demand response (DR) and electrical energy storage (EES) is a key attribute that characterizes the smart grid paradigm, which has emerged to address the electricity supply and environmental challenges [1–4]. While DR and EES are appreciated for providing different services to power systems, they may also be alternative supply resources, which are qualitatively different from traditional power plants. In this light, a fundamental question arises as to what are the implications of deploying DR and EES for providing adequacy of supply? More specifically, from the system operator's point of view how is the system's adequacy of supply altered by different operational characteristics of DR and EES? In fact, in principle DR and EES could be dispatched to "*supply*" load in the form of load reductions seen by generation systems at peak times, thus potentially displacing the need for generation capacity and therefore contributing to adequacy of supply. However, some or the entire load curtailed would have to be shifted to other times, as part of either the load restoration involved in DR or the charging processes of EES. Ultimately, all changes in the load profile will be

Abbreviations: DR, Demand response; EES, Electrical energy storage; EENS, Expected energy not supplied; EEUI, Expected energy unserved per interruption; LOLD, Loss of load duration; LOLE, Loss of load expectation; LOLF, Loss of load frequency; ICSE, Individual capacity shortfall event; RTS, Reliability Test System; SMCS, Sequential Monte-Carlo simulation.

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seen by the generation system, and therefore potentially affect the level of adequacy of supply along with the attained load reduction. However, so far there are no specific modelling framework and analysis in the literature that systematically address the impact of these DR and EES attributes on system adequacy. In contrast, it is critical to address the above questions and indicate whether and to what extent we could rely on these technologies rather than generation to guarantee reliability.

Load restoration is a key operational characteristic of DR, which can be more appropriately referred to as "payback" [5]. The payback may be as flexible as described by the models in [6–8], whereby DR would shift load from on-peak to off-peak times. In this case, valley-filling is the relevant payback of peak-clipping. However, flexibility and operational constraints of the payback effect are a function of the specific loads that are controlled. For example, building ventilation systems can only be interrupted for a short period due to the requirement to maintain acceptable air quality. On the other hand, for loads such as offices' lighting and some air conditioning systems, once the comfortable level is forgone, the amount of load that needs to be restored would be less than the amount that is interrupted. Therefore, it is essential to consider the interplay between the load reduction and payback when investigating the contribution of DR to adequacy of supply and properly assess the role that flexibility and operational characteristics have in this analysis. In terms of EES, Hu et al. [9] and Wang et al. [10], have studied the effect of the coordinated operation of EES and wind power on the system adequacy level. However, the coordination of EES and wind power is only one of the means to operate EES. In particular, as carried out here, it is important to study how the different operating parameters of EES, such as energy capacity, charging and discharging power ratings and efficiency, affect the level of adequacy of supply when EES is dispatched independently to supply load. Moreover, the reliability implication of displacing generation with high penetration of DR and EES has not been investigated yet in the existing studies [6–14]. This is also essential to inform the current energy policy debates regarding the deployment of DR and EES to provide system capacity through various market mechanisms [15].

In terms of reliability assessment, the existing literature [6–14] has measured the system reliability through various indices such as *Loss of Load Expectation* (LOLE), *Expected Energy not Supplied* (EENS), and *Loss of Load Frequency* (LOLF), which all demonstrate the overall reliability performance during the period that is analysed (e.g., one year). On the other hand, there is so far no special attention given to the reliability performance of individual interruption events in the reliability assessment and analyses, which can be quantified through other indices such as *Loss of Load Duration* (LOLD). However, this is crucial to comprehensively understand the reliability implications of DR and EES.

On the above premises, this paper presents a framework for the proper estimation of the contribution of DR and EES to adequacy of supply. Novel models of DR and EES are developed within this framework, taking specific consideration for DR flexibility and payback characteristics as well as EES operating parameters. Consistently with the above models and the relevant load scheduling algorithm proposed for peak reduction, a general methodology for assessing the impact of displacing conventional generation is also developed so that the corresponding reliability implications can be explicitly addressed. The adequacy of supply assessment is performed by sequential Monte Carlo simulation (SMCS) in order to take proper account of the inter-temporal impact of DR and EES on the load profile seen by the generation system and provide various reliability indicators. In this respect, in addition to LOLE, EENS and LOLF, LOLD is assessed to indicate the expected duration of an *Individual Capacity Shortfall Event* (ICSE) [16,17]; besides, *Expected Energy Unserved per Interruption* (EEUI) is proposed in this paper to measure the average energy unserved during an ICSE. Further insight into the reliability performance of ICSE is provided by applying boxplot to illustrate the variation in samples of ICSE. This framework will be demonstrated using numerical examples applied on the IEEE Reliability Test System (RTS) [17]. However, the discussions and conclusions that are drawn in this paper are of general validity and can be extrapolated beyond the scenarios and cases applied in the numerical study.

The rest of this paper is organized as follows: the developed models of DR and EES and load scheduling algorithm are presented in Section 2; Section 3 introduces the adequacy of supply assessment and the proposed methodology of generation displacement; Section 4 demonstrates the numerical study based on different scenarios of DR and EES, and further discussions are presented in Section 5; finally the conclusions are summarized in Section 6.

2. Models of demand response and electrical energy storage and load scheduling algorithm

2.1. Model of demand response

DR could be dispatched to "*supply*" load in the form of load reductions (denoted by R). As a result of the load reductions, a certain amount of the load curtailed has to be restored, namely the payback of DR (denoted by P). Then, the load *modified* by DR (denoted by M) can be calculated from (1), where O refers to the *original* load, and t denotes time:

$$M_t = O_t - R_t + P_t. \quad (1)$$

According to (1), the modified load M_t could be higher than the original load O_t, considering the fact that the load that can be reduced at time t (R_t) could be less than the one that has to be restored at the same time (P_t) due to load reductions at other times. This phenomenon is modelled as valley-filling effect in [6–8]. However, the DR customers may not be so flexible to enable the restoration of the entire reduced load during off-peak times. This implies that the payback may be required shortly after the load reduction and therefore creates a new peak at a later time.

As seen in (2), the reduced load R_t and the payback load P_t can be expressed by considering specific payback settings (d is one of the payback settings D^i considered in a customer group i among the entire customer groups I):

$$R_t = \sum_{i}^{I}\sum_{d}^{D^i} r_t^{d,i}, \qquad P_t = \sum_{i}^{I}\sum_{d}^{D^i}\sum_{\tau,\tau\neq t}^{T} \alpha_{t,\tau}^{d,i}\cdot r_\tau^{d,i} \quad (2)$$

where r represents the breakdown of the load that could be reduced at a time, while t and τ are distinct times such that the load is shifted ahead if $\tau < t$; or postponed if $\tau > t$. In addition, T is the time window during which DR is dispatched. Moreover, the payback coefficients $\alpha_{t,\tau}^{d,i}$ represent the proportions (%) of $r_\tau^{d,i}$ that are restored at time t and are organized as a T by T matrix. In other words, this matrix provides a map of load restorations at different times following certain reductions. Furthermore, as appeared in (2), the sum of $\alpha_{t,\tau}^{d,i}$ with respect to t (i.e., the total percentage based on $r_\tau^{d,i}$) reflects the "efficiency" of DR. More specifically, a sum less than 100% would mean that a part of the original load is foregone by customers (due to loss of customer comfortable level); on the other hand, a sum greater than 100% would imply that DR incurs energy losses (e.g., pre-heating). Finally, in the cases of lossless shiftable loads, the sum will be 100%, for example washing machines and dish-washers.

In order to perform DR, a number of customers need to be contracted to provide the service [15]. This implies that the load