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Considerations on the need for electricity storage requirements: Power versus energy

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ABSTRACT

Different storage technologies enable an increasing share of variable renewable generation in the electricity system by reducing the temporal mismatch between generation and demand. Two storage ratings are essential to time-shift delivery of electricity to loads: electric power, or instantaneous electricity flow [W], and electric energy, or power integrated over time [Wh]. An optimal storage portfolio is likely composed of multiple technologies, each having specific power and energy ratings. This paper derives and explains the link between the shape of the time-varying demand and generation profiles and the amount of desirably installed storage capacity, both energy and power. An analysis is performed for individual storage technologies first, showing a link between the necessary power and energy capacity and the demand and generation profile. Then combinations of storage technologies are analyzed to reveal their mutual interaction in a storage portfolio. Results show an increase in desirability for storage technologies with low cost power ratings when the mismatch between generation and demand occurs in daily to weekly cycles. Storage technologies with low cost energy ratings are preferred when this mismatch occurs in monthly to seasonal cycles. The findings of this work can help energy system planners and policy makers to explain results from generation expansion planning studies and to isolate the storage benefits accountable to temporal arbitrage in broader electricity storage studies.

1. Introduction

The amount of installed renewable capacity has grown significantly in recent years and is expected to grow further in the future [1,2]. Some of these renewable energy sources (RES), e.g. wind and solar, are highly variable and have a limited predictability. A growing amount of RES in the electricity system therefore leads to an increasing need for flexibility. This flexibility can be provided by different means: dynamic operation of conventional generation, extension of the electricity grid, energy storage, demand response and curtailment of the intermittent energy sources [3–5]. It is clear that not all means are equivalent in use.

Storage, which is the focus of this paper, is interesting as it is one of the few flexibility options which can both absorb and generate electricity [3]. Especially in electricity systems with a high share (>50%) of variable renewable generation, storage can be one of the options to provide flexibility [6–8]. However, the precise role of storage will depend on the availability of other flexibility options in the electric power system under consideration. Many different electricity storage technologies exist [9,10], which are divided in two categories in this paper. A first type of storage technology refers to those where charging power, discharging power and energy rating are coupled, such as most types of batteries. For this type of storage technology, all power and energy ratings are fixed, or locked in, once one of them is determined. In the remainder of the paper this storage type is referred to as 'integrated storage'. For a second type of storage technology, charging power, discharging power and energy rating can be installed and operated independently from each other, such as power-to-gas-to-power, compressed air energy storage and redox flow batteries. This storage type is referred to as 'disjoint storage' in the remainder of the paper.

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1.1. Objective

The objective of this study is to assess how the temporal variations of a so-called remaining load profile[1] impact the desired installed storage capacity in an optimal storage portfolio. A new metric is presented and introduced to link the optimal installed storage capacity with the shape of the remaining load profile.[2] The remaining load can contain periods of both shortage and surplus electric power generation. In this study, special attention is given to the difference between power and energy ratings of the installed storage capacity.

A welfare optimal generation and storage portfolio can be calculated to serve a given load at lowest cost. The precise constellation of such optimal portfolio not only depends on numerous factors such as investment cost, operational costs, technical plant characteristics, environmental targets, but also depends strongly on the time-varying profile of load and variable RES generation. It is precisely this relationship between the optimal storage portfolio, both in terms of power and energy, and the specific shape of the remaining load profile that is the subject of this research. The objective of this paper is to determine the optimal portfolio for a given set of remaining load profiles, to derive the link between profile and portfolio and to formulate general rules regarding storage investments which are applied to historical load and RES generation profiles.

1.2. Related work

Different energy storage sizing studies exist which investigate storage sizing either for a specific scenario or in a general theoretical way. Many studies exist which analyze specific case studies [11,12]. We consider this a first category of studies. For example Kaldellis [11] determines the optimal storage size in combination with wind and PV to replace thermal generation in a micro grid. The same author analyzes the required size of a compressed air energy storage system to maximize wind energy contribution on the island of Crete [12]. This paper falls in a second category, i.e., of general theoretical storage sizing studies. Within such studies, the optimal storage size can be determined in combination with PV [13], in combination with wind [14] or in a system containing both conventional and renewable generation [15–17]. This paper contributes to the limited work of the last category where storage is sized in a general energy system setting. Ru et al. [15] propose an upper bound on storage size to minimize the electricity purchase cost from the grid in a PV battery system. They characterize the exact storage size for a case with ideal PV generation and constant load and show how the optimal storage size changes as a function of a change in constant load level. The energy storage capacity is optimized while the power capacity is assumed fixed. Makarov et al. [16] determine the maximum required storage system size, both in terms of power and energy, to balance wind generation and load. They therefore decompose the balancing power signal in four different frequency ranges, corresponding with different technical storage characteristics. Barton and Infield [17] use a probabilistic method to predict the ability of different storage technologies and sizes to increase the penetration of intermittent generation using the frequency spectrum of historic wind profiles. They focus solely on the installed power capacity however.

1.3. Contributions

This paper presents a contribution to the existing literature [15–17] by going beyond state of the art in the following aspects:

- This paper builds further upon the existing literature and optimizes not only storage power capacity, but both energy and power capacity for disjoint storage technology and compares this to integrated storage technology.
- Our study accounts for possible curtailment of variable RES generation, which allows storage to be used for temporal arbitrage in general rather than for compensating an imbalance signal.
- In comparison to Barton and Infield [17], in this paper the storage size is optimized to accommodate a remaining load profile rather than only accounting for a wind generation profile.
- Ru et al. [15] analyze the optimal energy storage capacity for a scenario with constant load and variable PV generation. This paper adds to their analysis as time varying profiles for both load and RES generation are investigated.

The paper is organized as follows: first, the energy system under consideration is described, the calculation approach and numerical model are presented, characteristics of the representative electric energy storage technologies are given and general storage principles are discussed. The determination of the optimal storage portfolio is presented in the following sections. The required storage capacity to serve a given remaining load profile is determined first analytically for simplified methodological block profiles to derive the basic storage principles in Section 3. Afterwards a numerical investment model is used for more complex methodological sinusoidal profiles in Section 4, followed by real profiles in Section 5. For each of these profiles, the necessary storage capacity is first calculated for integrated and disjoint storage individually. Afterwards, a portfolio consisting of both technologies is optimized for all three types of remaining load profiles. Conclusions finalize the paper in Section 6.

2. Input data, assumptions and general principles

In this section, the considered system is presented. The approach to calculate an optimal storage portfolio is given, followed by characteristics of generation and storage technologies. Finally the general storage principles are explained.

2.1. System description

This paper focuses on the electricity system with the demand and renewable generation profiles as key external parameters, subject to a renewable target and taking into account the characteristics of generation and storage technologies. Different demand and RES generation profiles are used to determine how different remaining load profiles impact the constellation of the optimal storage portfolio. In a first instance, a flat methodological remaining load profile is used to gain basic insights, followed by a sinusoidal profile to make the link with realistic profiles. Finally, real profiles from the Belgian electricity system [18] are used to apply the presented metric and verify the link between remaining load profile and installed storage portfolio which was found by studying methodological flat and sinusoidal profiles. The imposed renewable target is set at 100% of the electric energy demand for the methodological profiles. 100% implies that all electricity is generated from renewable sources, i.e., no electricity is generated from

[1] This remaining load is defined as the difference between the instantaneous electric power demand and electric power generation, both renewable and conventional and is thus the profile which should be served by storage. The remaining load differs from the "residual demand", "residual load" or "net load" often used in literature to describe the difference between overall demand and variable renewable generation but which does not account for conventional generation.

[2] This remaining load profile differs from an imbalance profile since the RES capacity (and thus instantaneous RES power generation) is co-optimized with the storage capacity.