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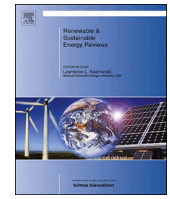

Flexibility requirements of renewable energy based electricity systems – a review of research results and methodologies

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ABSTRACT

It is expected that an energy system faces increasing flexibility requirements in order to cope with increasing contributions from variable renewable energy sources (VRE). In general, the instant balance of temporal and spatial inequalities of the electricity system can be achieved by many compensating measures. However, a thorough and precise quantification of the flexibility demand of a VRE based energy system turns out to be a complex task. So far, literature on energy economics and engineering has provided analyses concerning various aspects of the system requirements for flexibility. Accordingly, this review paper primarily aims to categorize the scientific approaches that have been used in "flexibility demand" studies. In this context, we classify exemplary study results from the German and European energy systems into technical, economic, and market potential categories to enhance their comparability. Moreover, we conduct a methodological evaluation of the literature findings to determine further research requirements. Against this background we also discuss a conceptual framework to quantify the market potential of flexible technologies.

Contents

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1. Introduction

1.1. Motivation

Among renewable energy technologies, wind and solar powers are variable renewable energy sources (VRE) as their power output is determined by weather conditions, in contrast to conventional dispatchable power plants that adjust their output with respect to market conditions. According to [1–3], the variability of wind and solar powers can be attributed to three intrinsic technological properties:

a) VRE supply is *variable* in a narrower sense since power generation is determined by weather conditions,
b) VRE supply is *uncertain* in advance because specific power output is unclear until realization, and
c) VRE supply is *location-specific* as the technical potential of wind and solar power is not necessarily correlated to the load centers.

Along that line of reasoning, the economic effects of introducing large amounts of VRE to energy systems can be attributed to profile, balancing and grid-related costs that occur either as a reduction in revenues for the supply of VRE or as additional cost (so-called integration costs) for specific market participants [1,4]. From the perspective of the whole energy system, the total levelized cost of electricity (the so-called system LCOE) of VRE generation comprise the LCOE of the technology itself [5] and the integration cost [3,6].

The actual magnitude of VRE integration costs depends on the flexibility of the specific energy system, i.e. to what extent demand-side and supply-side can cope with the inherent variability of wind and solar power. According to [7], “flexibility is the capability to balance rapid changes in renewable generation and forecast errors within a power system.” As defined by [8], “system flexibility can be described as the general characteristic of the ability of the aggregated set of generators to respond to the variation and uncertainty in net load.” In that sense, this paper addresses the short-term flexibility demand due to VRE integration, as opposed to the research question of securing sufficient back-up capacity which is also called system adequacy.

1.2. Literature review

In general, flexibility options for efficient VRE integration are allocated on the supply-side and the demand-side of the energy system, respectively:

1) Highly flexible power plants that could cope with increasing ramping requirements [9–11],
2) energy storage in large-scale applications [12–20],
3) curtailment of renewable surplus generation [10,21–22],
4) Demand-side Management (DSM) [23–27].
5) Grid extension [8,13,22,28],
6) virtual power plants [29],
7) linkage of energy markets like those satisfying the electricity and heat demand [30–32].

Literature reviews on technical characteristics of energy storage in general, as well as technically specified analyses, can be found in [17,19,33–40,33] focus on the applicability, advantages, and disadvantages of various electrical energy storage technologies (EES) for large-scale VRE integration. It is concluded that there is no single EES technology that consistently outperforms the others in various applications. Moreover [19] review state-of-the-art development of ESS technologies with respect to a classification in function (power vs. energy rating) and form (electrical, mechanical, chemical, and thermal energy storage). The imperativeness, applications, and techno-economic characteristics of ESS are intensively discussed.

In contrast [41] analyze the opportunity for pumped-hydro storage plants (PHS). They expect a renaissance of new PHS plants with an additional capacity up to 7.5 GW in Europe due to ambitious political support of increasing VRE capacity in that region. Although a lot of pre-permits (ca. 22 GW) were observed in the USA, actual construction is highly uncertain as it is shown by historic developments. Among others [34] give an overview of modeling techniques for batteries with respect to economic or power system reliability and stability studies. In [20] a model-based analysis is developed for four energy storage technologies and their cost-effectiveness for different applications is examined. Both energy-intensive (peak shaving) and power-intensive (frequency regulation and wind integration) applications are represented.

From a system point of view, energy policy scenario analyses are widely used to deal with the following research questions:

a) How much flexibility is necessary for the electricity system?
b) Which specific technology should cover a given flexibility demand?
c) What is the temporal shape of the flexible capacity extension path?
d) Does the current market design trigger investors to follow the efficient flexible capacity extension path?

Ref. [10] shows that any market design that incentivizes investments in least (total system) cost generation investment does not need additional incentives for flexibility. In a competitive market, the cost-efficient technologies that are most likely to be installed provide flexibility as a by-product. For Europe an electricity system mainly based on wind and solar power is investigated in [42–44]. The storage and balancing requirements are derived for various mixes of renewable energy sources. The paper of [45] derives the required amount of storage backup for a solar and wind based electricity system in Japan (100% renewable power generation). In the best case, the system needs about 41 TW h of storage capacity aside from biomass, hydro and pumped power to be balanced.

Ref. [12] presents a firm-level case study for a wind/CAES system located in the ERCOT area, though finding no business case at current costs and historic spot market prices. Similar approaches to determine the economic viability of wind and CAES were done in [13] and [46]. Ref. [8] provides a model-based analysis for the ERCOT electricity market. It addresses necessary changes to the grid, and the potential role of energy storage, with VRE providing 80% of electricity supply (assuming no transmission related curtailment).