Renewable and Sustainable Energy Reviews 80 (2017) 603–619

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems – a review

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ARTICLE INFO

Keywords:
Energy storage systems
Generation expansion planning
Optimization models for power system planning
Investment decision support
Operational flexibility
Variable renewable energy integration

ABSTRACT

Expansion planning models are often used to support investment decisions in the power sector. Towards the massive insertion of renewable energy sources, expansion planning of energy storage systems (SEP – Storage Expansion Planning) is becoming more popular. However, to date, there is no clear overview of the available SEP models in the literature. To shed light on the existing approaches, this review paper presents a broad classification of SEP, which is used to analyze a database of about 90 publications to identify trends and challenges. The trends we found are that while SEP was born more than four decades ago, only in the last five years increasing research efforts were put into the topic. The planning has evolved from adequacy criteria to broader targets, such as direct costs, mitigation of CO_2 emissions, and renewable integration. The modeling of the network, power system, energy storage systems (ESS), and time resolution are becoming more detailed. Uncertainty is often considered and the solution methods are still very diverse. As outstanding challenges, we found that (1) the large diversity of ESS, in contrast to conventional generation technologies, and (2) the complex lifetime and efficiency functions need to be addressed in the models. (3) Only a high temporal and spatial resolution will allow for dimensioning the challenge of integrating renewables and the role of ESS. (4) Although the value of ESS lies beyond shifting energy in time, current SEP is mostly blind to other system services. (5) Today, many flexibility options are available, but they are often assessed separately. In the same line, although cross-sectorial (power, heat, transport, water) SEP is becoming more frequent, there are many open tasks towards an integrated coordination. The planning of future energy systems will be multi-sectorial and multi-objective, consider the multi-services of ESS, and will inherently require interdisciplinary efforts.

1. Introduction

Worldwide population growth, the greenhouse effect, and sustainable policies demand an increasing use of renewable energy sources around the world. Indeed, the deployment of wind, solar and hydropower resources has been remarkable and is still rising [1]. However, integrating such massive amounts of variable renewable energy sources (vRES) into power systems poses several technical and economic challenges. In particular, vRES are difficult to predict and deliver a highly fluctuating power output [2], thus adding uncertainty and variability to the planning and operation of power systems. Moreover, the potential of vRES is usually spatially distributed and rarely correlates in time with the load profiles. These characteristics of vRES challenge the power system's adequacy (energy and power balance) and voltage and frequency regulation [3]. Thus, in order to successfully integrate large shares of vRES, the planning and operation of power systems need to become more flexible than they are today [4–7].

The required flexibility can be provided through several approaches (see Fig. 1). These include operational strategies (e.g. energy curtailment [8], power output controls [9–12], more frequent dispatches [13], industrial and residential demand-side management (DSM) [14]),

Abbreviations: AC, Alternating current; BESS, Battery energy storage systems; CAES, Compressed air energy systems; CAP, Capacitors; CHP, Combined heat and power; CSP, Concentrated solar power plants; DC, Direct current; DSM, Demand-side management; DW, Drinking water installations; EL, Electrolyzers; ESS, Energy storage systems; EV, Electric vehicles; FC, Fuel cells; FW, Flywheels; G, Generic storage; GEP, Generation expansion planning; GT, Gas turbines; H_2, Hydrogen; HT, Heat technologies; LP, Linear Programming; MILP, Mixed Integer Linear Programming; MINLP, Mixed Integer Nonlinear Programming; NLP, Nonlinear Programming; P2G, Power to gas; PHS, Pumped hydro storage; PV, Photovoltaic; SEP, Storage expansion planning; vRES, Variable renewable energy sources; *WR*, Water reservoirs

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http://dx.doi.org/10.1016/j.rser.2017.05.201
Received 13 June 2016; Received in revised form 16 May 2017; Accepted 22 May 2017

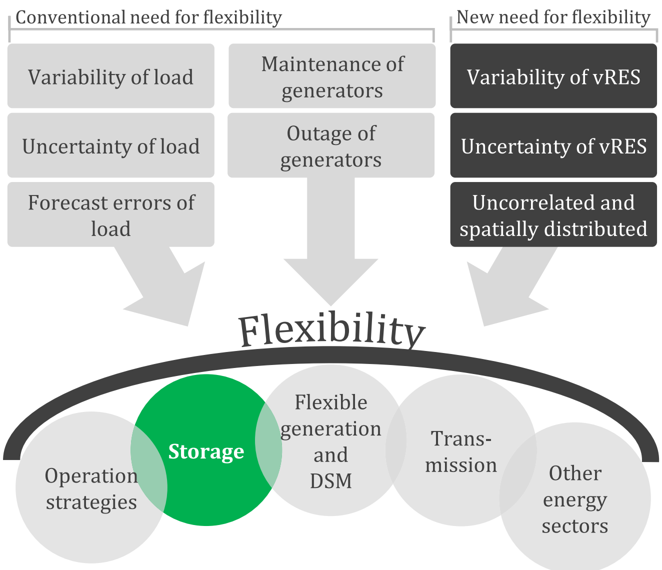

Fig. 1. Need for flexible power systems and flexibility sources.

new market structures, and integration between different energy vectors such as the heat, transport and power sectors [15–18]. Alternatively, one can modify the power system infrastructure by reinforcing the transmission infrastructure [19,20], adding flexible generation technologies (e.g. gas turbines) [21,22], and energy storage systems (ESS) [23,24].

Particularly, ESS are widely esteemed as potential solutions for high shares of vRES [25–27]. The available ESS technologies (e.g. batteries, pumped hydro storage and hydrogen) differ vastly in terms of investment costs per power capacity and per energy capacity, lifetime, storage losses, efficiency, ramping rates and reaction times [23,25,28]. Moreover, current research concludes that there is no single ideal -or even supreme- ESS technology [24,25,28–30]. Indeed, the requirements for ESS depend on the characteristics of the power system under study and on the characteristics of the vRES. Consequently, the key question is: what combination of storage technologies is needed to tackle the challenges of vRES integration?

Expansion planning [31] is conventionally used to deal with this kind of questions. For example, generation expansion planning (GEP) [32–34] determines an optimal investment plan for generation capacities during a given study horizon. Its goal is to serve the energy demand while satisfying a set of economic and technical constraints. GEP is frequently employed by policy and decision makers to decide when and in which generation technology to invest. Depending on the decision variables, energy expansion approaches can traditionally be classified into generation expansion planning [35] and transmission expansion planning [36,37]. When the focus is put on investment decisions of ESS, we refer to it as storage expansion planning (SEP). In practice, generation, transmission, and storage can also be planned jointly [38,39].

Many research and review papers about expansion planning of the energy sector can be found in the literature, including power generation [40,41], power transmission [37,42,43], and gas- and power-transmission [44]. A comprehensive review of the available GEP software is shown in [45] and [46]. However, reviews about SEP remain scarce. Our paper aims to fill this gap.

This review makes three contributions to the existing literature. First, it provides a clear classification and overview of SEP models. We analyze the modeled ESS, energy sectors and flexibility options, the planning goal, the modeling detail of the systems, the time treatment of the investment and operational decisions, the consideration of uncertainty, and the solution methods. Second, we identify trends in how current SEP literature evolves in dealing with these aspects. Third, by contrasting newer SEP approaches to conventional GEP, we outline the challenges of planning ESS expansion. In these challenges, we focus on the diversity of ESS, the lifetime and efficiency functions of ESS, the required temporal and spatial resolution for an adequate modeling of ESS, the multiple services ESS can provide, and the inter-sectoral coupling through ESS.

The remainder of this paper is structured as follows. Section 2 provides a classification of models for SEP. Section 3 analyses the trends of ESS investment planning, while Section 4 identifies the remaining challenges. Finally, Section 5 presents the conclusions and recommendations for future work on SEP.

2. Classification of storage expansion planning models

Similarly to GEP, SEP considers the total costs of the system, given by operational and investment decisions over a time horizon of typically 10–30 years. Its most basic version is an energy balance that matches (e.g. yearly) generation with demand assisted by the use of ESS.

The planning models for ESS have evolved in time. However, current approaches still make strong simplifications when compared to real systems. Thus, we classify existing SEP can be classified according to their abstraction level: (1) considered ESS, (2) goal and planning perspective of models, (3) considered energy sectors and flexibility options, (4) network modeling, (5) detail of power system and ESS, (6) time treatment of investment decisions and (7) of system operation, (8) treatment of uncertainty, and (9) solution methods for the resulting model. This classification is explained in more detail in Section 2.1 to 0.

2.1. Modeled ESS

SEP can be classified according to the types of ESS and the number of different ESS that are taken into account in the planning process. ESS types can again be classified based on their storage capacity, spatial distribution, and mobility.

First, according to their storage capacity, it is possible to divide ESS into short-term and long-term systems (although to date there is no consensus in the literature about a clear limit). Reference [47] considers short-term storage to have an energy capacity from seconds to days, such as flywheels (FW), capacitors (CAP), battery energy storage systems (BESS) and molten salts (in concentrated solar power plants – CSP) and compressed air energy systems (CAES). The same reference considers long-term systems to have an energy capacity from weeks to seasons, such as water reservoirs (W*R*) and gas or hydrogen (H2) storage. Pumped hydro storage (PHS) and heat storage, depending on their size, can serve both the short- or the long-term [47]. CAP and FW have particularly low energy capacities and are suited for high-power applications up to 10 s. Consequently, CAP and FW are commonly not considered in SEP.

Second, ESS can be grouped in centralized and distributed systems. The former includes large installations, such as PHS, while the latter refers to modular units such as home-batteries in combination with roof-top photovoltaic (PV) systems [47].

The third and last criterion considers their mobility. Systems fixed to one location comprehend most of the centralized and many of the distributed ESS [47]. Mobile storage is given mainly by electric vehicles (EV) or gas trucks, all of which are distributed ESS.

The number of considered ESS types allows classifying SEP into single- or multi-storage approaches. In contrast to the former, multi-storage SEP can detect the synergies between different ESS systems.

2.2. Goal and planning perspective of models

In SEP, a cost minimization is usually applied by central planners (e.g. vertically integrated power companies) or policy makers (of a