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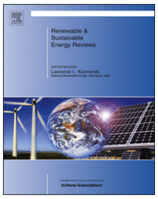

A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications

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ABSTRACT

In future electricity systems with a high share of intermittent renewable power generation, battery technologies have the potential to support power quality and security. The growing scientific literature on batteries reflects the high attention that currently rests on these technologies. This paper reviews the existing literature on lifecycle costs of batteries in stationary applications. The primary result of this review is that, despite the current high degree of variance in technological and economic battery data, a systematic assessment of the underlying uncertainty is lacking. The present paper addresses this disparity with an investigation of the impact of uncertainty in input parameters on lifecycle costs of four battery technologies across six electricity system applications. Based on input data collected from literature and via expert interviews, a probabilistic techno-economic model was built that calculates lifecycle costs and systematically addresses uncertainty in input parameters by applying a Monte Carlo simulation. The main conclusion of this paper is that the present uncertainty in cost and technical parameters of batteries exceeds by far the differences in lifecycle costs across technologies. For most electricity storage applications, the absolute differences in mean lifecycle costs across technologies are negligible compared to the uncertainty ranges of the mean lifecycle costs. Therefore, a competition still exists between the four analyzed battery technologies and so far a leading technology has yet to emerge in any of the investigated applications.

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1. Introduction

In order to cope with a rising electricity demand while also attempting to mitigate climate change, many governments have begun to introduce ambitious targets and incentives for the diffusion of renewable power generation technologies [1–4]. However, the non-deterministic and intermittent nature of wind and solar power generation—which are expected to contribute the majority of future renewable power generation—may entail serious challenges for the energy system [5,6]. Besides demand side management and grid expansion, energy storage technologies are promising response options due to their ability to decouple generation and load [7].

Within the field of energy storage technologies, electrochemical batteries have a potential to play an important role to pave the way towards an energy system with a high share of renewable power generation. First, due to their fast response time and scalability, battery technologies can serve both power and energy applications and thus cover a wide range of storage applications in the electricity system[1]. Second, further advantages of battery technologies are that they can be centrally located or distributed, along with their suitability for on-, off-, and weak-grid applications [8].

While much attention rests on battery technologies, uncertainty about costs and performance of battery technologies is still impeding their large-scale deployment in the electricity system [9]. Four main factors drive this uncertainty. First, multiple battery technologies in various states of maturity with highly diverging performance characteristics compete in the market. Second, a complex set of electricity storage applications exists, ranging from power quality and reliability for end-consumers to renewables integration and ancillary services on the grid level [10]. Third, scientific sources investigating costs and performance of battery technologies are often inconsistent and exhibit high variations, even for main input parameters. Lastly, complicating this inconsistency, the actual costs of a battery system do not only depend on the technology parameters but also on the specific application in which the system is used [11]. While most literature on battery technologies compares the investment and operating costs, a fair basis for comparison of technologies should factor in lifecycle costs, as lifecycle costs vary depending on the specific application.

Previous studies on storage lifecycle costs advanced the knowledge of battery costs and performance across applications. Yet, despite the present high degree of variation of input parameters in the literature—especially for immature technologies such as stationary lithium-ion and vanadium redox flow—uncertainty in input parameters has not been taken into account systematically.

In order to address this gap in the literature, the present paper investigates the impact of uncertainty in input parameters on lifecycle costs of battery technologies across electricity system applications. To this end, four battery technologies were analyzed within six stationary electricity storage applications in two steps[2]. First, based on an extensive literature review and expert interviews, battery and application input values were derived. Second, a probabilistic techno-economic model was developed that calculates lifecycle costs and systematically addresses uncertainty in input parameters by conducting a Monte Carlo simulation. Thereby, this study strives to improve the understanding of battery costs and performance for researchers, practitioners and policy makers.

The paper is structured as follows: Section 2 shortly describes battery technologies and storage applications before reviewing the literature on lifecycle costs assessments of battery technologies. Section 3 explains the methodology and data used in the lifecycle costs modeling. The obtained results are presented and discussed in Section 4. Section 5 concludes by stating possible avenues for future research while summarizing the paper's principle contributions.

2. Description of battery technologies and applications; review of lifecycle costs assessments

This section is comprised of two parts: A brief overview of battery technologies and their applications within the electricity system, followed by a review of previous literature on battery lifecycle costs.

2.1. Battery technologies and their role in the electricity system

Generally, energy can be stored thermally (e.g., hot water tank), mechanically (e.g., pumped hydro storage, compressed air energy storage or flywheels), chemically (e.g., hydrogen), electrically (e.g., supercapacitors or superconducting magnetic energy storage) or electrochemically (e.g., batteries and flow batteries). The general principle behind the mechanism of a battery is as follows: As soon as a load is connected to the cell's terminal, electrochemical reactions take place inside the cell in which electrons are set free and transferred from one electrode to another through an external electrical circuit. Depending on the required output voltage and energy capacity, single or multiple cells are connected within a series or in parallel, or both [12]. The manifold combinations of chemicals and materials used as electrodes, electrolytes or membranes span a wide spectrum of battery technologies: From lead–acid, lithium-ion, nickel–metal hydride, nickel–cadmium, zinc–air to high-temperature batteries, such as sodium–sulfur or the so-called ZEBRA battery.[3]

Flow batteries store energy externally, i.e., the storage medium and the reaction cell (cell stack) are arranged separately [13]. In general, flow batteries consist of two electrolyte solutions—which are stored in external tanks if not in use—that are pumped into the cell stack to complete the redox reactions to create electricity [14]. Flow batteries are highly flexible and can easily be tailored for diverse applications because their energy capacity can be scaled up by either augmenting the volume or the concentration of electrolytes and because their power capacity can be increased by installing additional cell stacks [14]. The materials and chemicals used in flow batteries can vary from vanadium, polysulfide–bromide, zinc–cerium, and iron–chromium to zinc–bromine.

This paper focuses specifically upon the four battery technologies—lead-acid, lithium-ion, sodium–sulfur and vanadium redox flow batteries—that are generally perceived as promising technologies with a significant potential for grid-scale electricity storage [14,15]. Moreover, these technologies are either mature (sodium–sulfur and lead–acid) or first commercial products are available (lithium-ion[4] and vanadium redox flow), and they exhibit relatively few environmental issues (in contrast to, e.g., nickel–cadmium batteries).[5]

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[1] In contrast, pumped hydro, compressed air energy storage and hydrogen storage are mostly suitable for long-term storage of large energy capacities (“energy applications”), whereas flywheels, supercapacitors and superconducting magnetic energy storage are rather considered for applications with a fast release of comparatively small amounts of energy (“power applications”) [19,61].

[2] We model lifecycle costs of lead-acid, lithium-ion, sodium-sulfur, and vanadium redox flow for the six applications *Utility Energy Time-shift, T&D Investment Deferral, Energy Management (community scale), Increase of Self-consumption, Area and Frequency Regulation*, and *Support of Voltage Regulation.*

[3] The Zero Emission Battery Research Activity (ZEBRA) battery is a sodium–nickel chloride based high temperature battery.

[4] While lithium-ion batteries are well established for portable devices, this technology is described as not mature for grid-scale electricity storage [9,10].

[5] Although lead can have adverse effects on the environment at high concentrations, the actual impact of lead acid batteries is typically limited due to high recovery and recycling rates [62].