Renewable and Sustainable Energy Reviews 43 (2015) 478–494

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Life-cycle analysis of flow-assisted nickel zinc-, manganese dioxide-, and valve-regulated lead-acid batteries designed for demand-charge reduction

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ARTICLE INFO

Article history:
Received 12 November 2013
Received in revised form
5 September 2014
Accepted 22 October 2014

Keywords:
Lead-acid
Nickel-zinc
Manganese dioxide
Life-cycle analysis
Cumulative energy-demand
Global-warming potential

ABSTRACT

This paper presents a comprehensive literature review and a full process-based life-cycle analysis (LCA) of three types of batteries, viz., (1) valve-regulated lead-acid (VRLA), (2) flow-assisted nickel–zinc (NiZn), and (3) non-flow manganese dioxide–zinc (MnO_2/Zn) for stationary-grid applications. We used the Ecoinvent life-cycle inventory (LCI) databases for the VRLA battery, coupled with inventory data from the CUNY Energy Institute (EI) for the NiZn and MnO_2/Zn batteries under development there. In doing so, two indicators were tracked: the cumulative energy demand (CED) and global warming potential (GWP) of the upstream processes for producing, manufacturing, and transporting the finished product, as well as the effects of end-of-life impacts. We conducted a normalization of CED and GWP according to Wh of battery capacity to illustrate the effects of discharge rate on this commonly reported metric. We subsequently normalized according to the cumulative kWh of electricity throughput ($kWh_{throughput}$) to account for cycle life and efficiency data. This was done considering slow- and fast-discharge parameters for PbA chemistry and for current- and projected- parameters for the NiZn and MnO_2/Zn chemistries to examine all possible effects. Additionally, the effects of recycle content on reducing CED and GWP were considered. Discharge rate was seen to have a significant effect for the VRLA system, with impacts over 41–46% higher in terms of CED and GWP at the 2-h discharge time, versus an 8-h discharge time, when considering the entire life cycle ($kWh_{throughput}$ normalization). With $kWh_{throughput}$ normalization, the NiZn- chemistry under development has lower CED and GWP than PbA-VRLA batteries for both current and projected targets of round-trip efficiency and cycle life. MnO_2/Zn performs poorer than VRLA currently (41–52% higher CED and 35–38% higher GWP), but performs significantly better than VRLA when using projected targets (43% lower CED and 47% lower GWP). The energy requirement for battery production and transport is most significant for PbA and MnO_2/Zn batteries. This is the case for PbA due to its relatively short service life– and this battery was found to be most sensitive to changes in battery service life and efficiency. For MnO_2/Zn this was a result of low specific energy.

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http://dx.doi.org/10.1016/j.rser.2014.10.072
1364-0321/

1. Background

Grid-scale batteries are part of a global solution for energy sustainability and reliability because of their site versatility and modularity that allows wide scalability. Ref. [1] categorizes energy storage applications by hours of discharge and by frequency of cycling. Storage times less than one hour have applications in frequency regulation and power quality. Longer duration bulk storage (4–8 h operation) has applications in load leveling, and arbitrage, traditionally. Batteries typically operate in distributed storage timescales (1–4 h). Applications of note include aiding with peak shaving, load shifting, frequency regulation, grid integration of renewables, and uninterruptable power supply (UPS) [2]. For decades, the telecommunications industry successfully deployed batteries for UPS applications to protect data centers and servers. Utility-scale stationary applications emphasize cost and discharge time as primary concerns, and are widely thought to be insensitive to size and weight. Utility battery markets are emerging, as cost reductions allow for realistic monetary payback periods.

Recent regulations in many countries enforce demand-charges on large users of electricity as a way of reducing peak demand, creating a market for batteries to reduce these electricity costs [3]. The application of demand-charge reduction for residential and commercial loads is considered in this report. Discharge times are within the 1–4 h range and require daily charge-discharge cycling.

1.1. Review of current technologies for utility applications

Technologies that are used in the field include sodium/sulfur (NaS), lead-acid (PbA), nickel/cadmium (NiCd), and lithium ion (Li-Ion), with newer chemistries in pilot demonstrations. Redox flow batteries (RFBs) represent one of the most recent technologies for stationary energy storage, with the best researched being the vanadium redox battery (VRB) [2]. The RFB technology has not yet reached full commercial potential and significant reductions are expected in cost and size to make them commercially competitive. NaS accounted for 54% of the market in 2011 [4,5]. The lead-acid battery claims the lowest capital cost and lowest cradle-to-gate (CTG) environmental footprint, partly attributable to its highly successful recycling infrastructure [6,7]. PbA batteries have remained attractive due to their low cost and high specific power [7]. Valve-regulated lead-acid (VRLA) arrangements, in gel or absorbed glass matt (AGM) design, represent an improvement over the initial "flooded" for its maintenance free design. AGM technology is examined in this report, as it dominates the VRLA market share. Gel batteries are primarily selected for standby power due to long-lifetimes when held at top of charge (float-life) [7]. Variations of carbon-enhanced advanced PbA batteries are under development [8–10], but limited information is available on their performance, and they are not included in our study.

The CUNY Energy Institute (EI) has sought to develop batteries (MnO_2/Zn and NiZn) for utility installations that can meet power and energy requirements with significant improvements in cycle life (i.e., number of cycles during the life of the battery) and lower capital cost compared to existing technologies, e.g. a capital cost target of 100$/kWh for its MnO_2/Zn chemistry [11,12]. Although nickel is costlier than lead (approximately 6.5 times costlier as of September, 2013 [13]), it is 71.7% lighter and has the capability of retaining capacity during fast charge and discharge usage. Historically, commercial offerings of NiZn batteries had problems with separator penetration and electrode shape change. In 1997, the Energy Research Corporation (ERC) overcame several hurdles, significantly increasing cycle life to $\sim$500 cycles at 80% depth of discharge (DoD) [14–16]. EI took alternative approaches for the design of both MnO_2/Zn and NiZn batteries to achieve much greater cycle life and reduced cost in both technologies. Data from EI's testing and fabrication research circa 2013 are used in this LCA of NiZn- and MnO_2/Zn- chemistries, which was conducted at the Center for Life Cycle Analysis, Columbia University [17].

Alkaline manganese dioxide/zinc (MnO_2/Zn) cells constitute the majority of the primary battery market (single use and dispose) [18]. Research into rechargeable alkaline manganese batteries has produced interest for their use as secondary cells [19–22]. EI develops flow assisted- and non-flow-assisted variants of the rechargeable MnO_2/Zn technology [23]. The non-flow assisted variant is considered in this report due to its relative maturity and hence superior performance.

The operating conditions considered are within a 2-h discharge time period for application in demand-charge reduction for the three batteries examined. Table 1 summarizes key parameters of the batteries. DC/DC efficiencies are gathered from literature data and from unpublished tests at EI. EI measures all DC/DC efficiencies at a 2-h charge and discharge rate to 90% Depth of Discharge (DoD) of the nameplate capacity. The EI data in Table 1 are presented in terms of *current*- and *projected*- efficiency, and they include the pump's energy requirements in the case of NiZn. The projected values reflect forecasted improvements anticipated to occur within five years.

Little information on the efficiency of PbA batteries at the 1–5 h discharge time was found. Efficiency data in the literature for PbA at a total discharge time of 2 h was verified through cycle testing a 1.4 Ah PS-614 AGM battery, replicating a scenario for overnight charging employed in demand-charge reduction applications. The PbA battery was tested at a $0.4C_{20}$ discharge current to 1.75 vpc (volts per cell), and charged under current limited CV (constant voltage) at $0.1C_{20}$ to 2.45 vpc cutoff, and then held at 2.45 vpc for a total of 10 h (constant voltage charging is necessary for cyclic