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Lithium-ion battery based renewable energy solution for off-grid electricity: A techno-economic analysis

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ABSTRACT

Small renewable energy solutions such as solar home lighting system (SHLS) provide reliable electricity supply to off-grid bottom-of-pyramid (BoP) households and thereby improve status of living. Commercial SHLS employs polycrystalline silicon photovoltaic (PV) and flooded lead–acid battery technologies for energy generation and energy storage, respectively. Flooded lead–acid battery is a 150-year-old, mature and inexpensive energy storage technology but has a short lifetime. In SHLS, flooded lead–acid battery requires replacement every 4–5 years and can cost up to 70% of the total cost over the 20 years lifetime of the system. In this paper, seven advanced lithium-ion battery chemistries were evaluated as a potential replacement for flooded lead–acid battery in SHLS using HOMER microgrid software. Three lithium-ion battery chemistries – NCA, LFP and LFP/LTO – were found to be viable alternatives based on economic and performance metrics. The three lithium-ion battery based SHLS showed comparable initial capital cost to that of the commercial SHLS but provided significant advantage over the system lifetime as no/fewer battery replacements were required, which resulted in a total net present cost (TNPC) that was as low as 45% of the commercial SHLS. Price of lithium-ion battery technology is decreasing at 8–16% annually in real terms and the cost advantage of SHLS based on lithium-ion battery is expected to increase significantly in the future.

1. Introduction

1.1. Access to electricity and social development

Access to reliable electricity is a key driver behind economic development and raising basic standards of living. This is especially applicable to rural countryside of developing countries, like India, where access to reliable and affordable electricity can allow use of modern lighting and appliances, enabling income generation activities after daylight hours, improved healthcare and sanitation and improved food storage. However, grid electricity connectivity and supply has been lacking in rural India. Estimates suggest that about 45% of rural households do not an electricity connection in 2011 and rural areas face frequent and long supply interruptions [1–4].

1.2. Solar home lighting system

Multiple renewable energy technologies are available for off-grid, distributed electrification including biofuel powered generator, biomass plant, micro-hydro, wind hybrid and solar photovoltaic (PV) [3]. Solar PV based solutions are ideally suited for Indian climatic conditions as abundant solar energy is available throughout the year and in most of the country. Moreover, small solar PV solutions such as solar home lighting system (SHLS) are suitable for self-ownership in households and small businesses [3]. Financial support from rural banks and microcredit organizations to manage high upfront cost of SHLS has been successful in adoption of small solar PV solutions by bottom-of-pyramid (BoP) customers [5]. SHLS is cheaper to operate compared to kerosene burners, provides much better quality of light and does not produce harmful gases. Cost of electricity (COE) generated by SHLS is ~1 USD/kWh or ~10 times the price of grid electricity [6]; high COE of SHLS demonstrates the "willingness to pay" in BoP customers for energy solutions.

Commercial SHLS, based on polycrystalline silicon PV and flooded lead–acid battery technologies, suffer from two limitations. Firstly, the battery requires replacement every 4–5 years and effectively constitutes a major fraction of the system lifetime cost [5]. Operationally, battery replacement is a huge burden on BoP households as financial support for replacement battery is not available. Secondly, as the lead–acid battery is a 150-year-old, mature technology, future cost reductions in commercial SHLS can be expected to be small [7].

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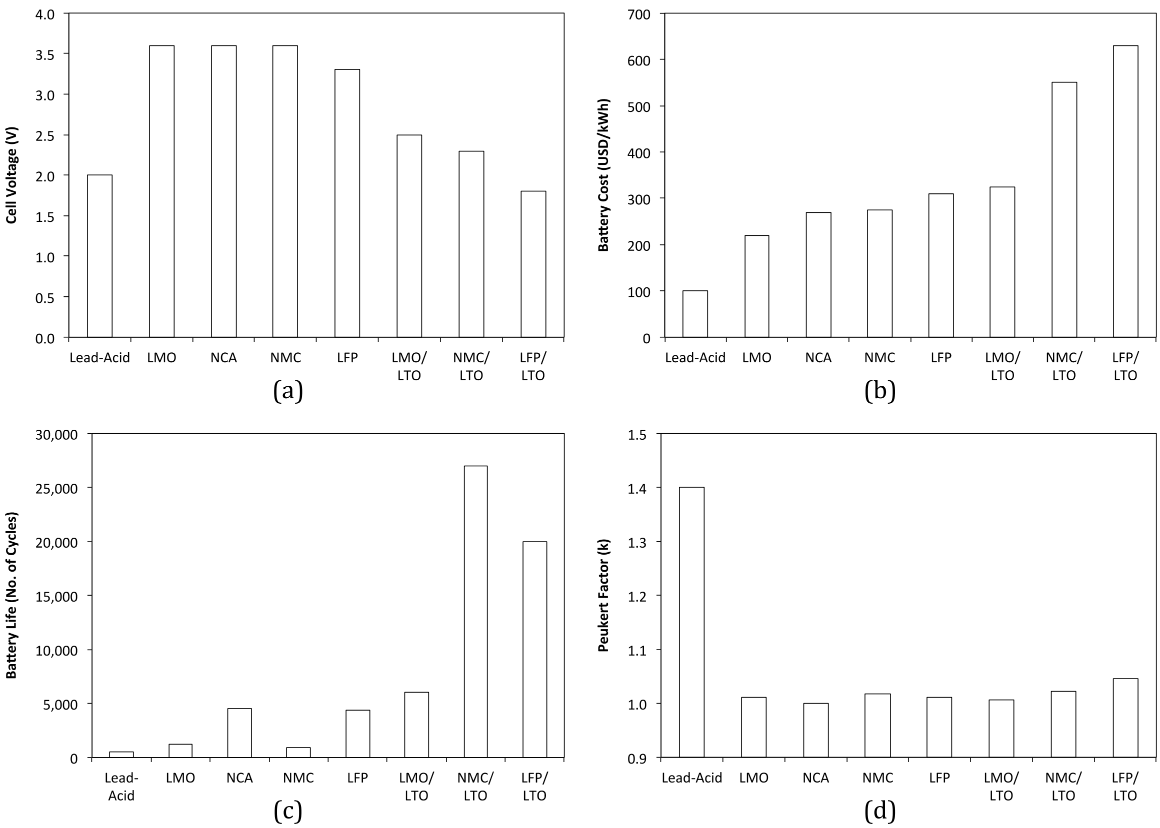

Fig. 1. Cell voltage (a), battery cost (b), cycle life (c) and peukert factor (d) of seven lithium-ion battery chemistries; values of flooded lead–acid battery are also presented.

1.3. Lithium-ion battery technology

Lithium-ion battery technology was developed in early 1990's and enabled the portable electronics revolution. The technology is now under development for application in electric vehicles (EVs) and grid storage. Lithium-ion battery technology is expensive compared to the conventional flooded lead–acid battery technology and, hence, so far has been targeted for premium applications. This paper evaluates the potential of lithium-ion battery as a replacement for flooded lead–acid battery in SHLS from both technical and economic perspectives.

There are multiple lithium-ion battery chemistries (variants) with characteristic cell voltage, energy density, rate capability (peukert factor), cycle life and cost [8]. The characteristics of seven main lithium-ion battery chemistries and of flooded lead–acid battery are presented in Fig. 1. The dataset presented is based on manufacturer's datasheets, industry reports and a handbook [9–17]. For SHLS application, the primary battery parameters are cost, cycle life and safety. Nominal cell voltage is also an important factor as it determines the number of cells in series required to get the desired battery voltage and, therefore, impacts the battery cost. As the application is for stationary energy storage at low charge/discharge rates, energy density and rate capability are secondary factors for consideration.

The seven lithium-ion battery chemistries can be divided into two categories based on the type of anode – graphite or lithium titanium oxide (LTO). Graphite is the conventional anode for lithium-ion batteries but it has limitations in cycle life, rate capability and safety. LTO anode addresses these limitations but at the expense of cost and energy density [18,19]. LTO anode has a higher redox potential of 1.55 V (vs. Li) and a lower specific capacity of 175 mAh/g, compared to 0.2–0.3 V (vs. Li) and 372 mAh/g of graphite, which results in lower cell voltage, lower energy density and higher cost. However, the higher redox potential of LTO avoids the formation of secondary electrolyte interface (SEI) layer, resulting in improved rate capability, performance at low temperatures and safety characteristics. In graphite anode, SEI layer blocks lithium-ion diffusion reducing rate capability and breakdown of the SEI layer is the trigger point for thermal runaway [20]. LTO anode also reduces the risk of lithium metal plating at low temperatures, as observed for graphite anode [15,16]. Lastly, crystal structure of LTO is resilient to lithiation/delithiation with only ~0.2% change in crystal volume, resulting in long cycle life of the battery.

The characteristics of the seven lithium-ion battery chemistries are briefly described below –

a) Lithium-ion battery chemistries with graphite anode

1. Lithium manganese oxide (LMO)

   LMO chemistry is well established and utilizes cheap, abundant manganese-based spinel cathode [21,22]. The chemistry is comparatively much safer than those that use cobalt/nickel based cathodes and it can be used with inexpensive battery management system (BMS) [22]. The main limitation of LMO is the manganese dissolution in the cathode, which reduces the cycle life and calendar life at high temperature (> 50 °C) operation [8, 23, 24].
2. Lithium nickel cobalt aluminum oxide (NCA)

   NCA chemistry has been developed to improve the safety characteristics and cycle life of layered nickel-based cathode by co-doping with aluminum and cobalt [21,22]. Compared to LMO, NCA is expensive but has the advantage of high energy density and long life; calendar life for NCA cells is projected to be extremely long (> 15 years). However, nickel based cathodes are thermally unstable and degrade at high state of charge (SoC). Some EV manufacturers are using NCA chemistry in battery packs with sophisticated BMS [25].
3. Lithium nickel manganese cobalt oxide (NMC)

   NMC chemistry is another variant of the nickel-based cathode family, which has been developed to improve cost and safety characteristics over NCA but it has lower rate performance and shorter cycle life [21,22]. Like other nickel-based cathodes, NMC is