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Prospective improvements in cost and cycle life of off-grid lithium-ion battery packs: An analysis informed by expert elicitations

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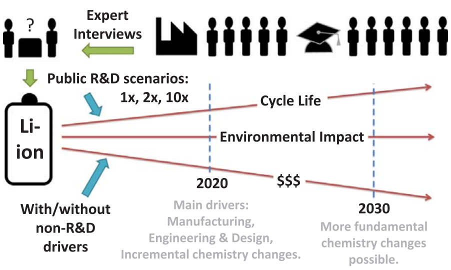
GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents probabilistic estimates of the 2020 and 2030 cost and cycle life of lithium-ion battery (LiB) packs for off-grid stationary electricity storage made by leading battery experts from academia and industry, and insights on the role of public research and development (R&D) funding and other drivers in determining these. By 2020, experts expect developments to arise chiefly through engineering, manufacturing and incremental chemistry changes, and expect additional R&D funding to have little impact on cost. By 2030, experts indicate that more fundamental chemistry changes are possible, particularly under higher R&D funding scenarios, but are not inevitable. Experts suggest that significant improvements in cycle life (eg. doubling or greater) are more achievable than in cost, particularly by 2020, and that R&D could play a greater role in driving these. Experts expressed some concern, but had relatively little knowledge, of the environmental impact of LiBs. Analysis is conducted of the implications of prospective LiB improvements for the competitiveness of solar photovoltaic + LiB systems for off-grid electrification.

1. Introduction

Lithium-ion batteries (LiBs) are the dominant technology for portable electronic applications (Hanna et al., 2015), and are rapidly growing for electric vehicle (EV) applications (International Energy Agency, 2013, 2016; Lacey, 2016), where deployment is reducing costs

Abbreviations: BMS, Battery management system; DoD, Depth of discharge; EV, Electric vehicle; LCO, Lithium cobalt oxide; LCSE, Levelised cost of stored energy; LFP, Lithium iron phosphate; LiB, Lithium-ion battery; LTO, Lithium titanate; NCM, Nickel cobalt manganese; PV, Photovoltaic solar panel; R&D, Research and development; RD&D, Research development, and demonstration; SEI, Solid-electrolyte interface

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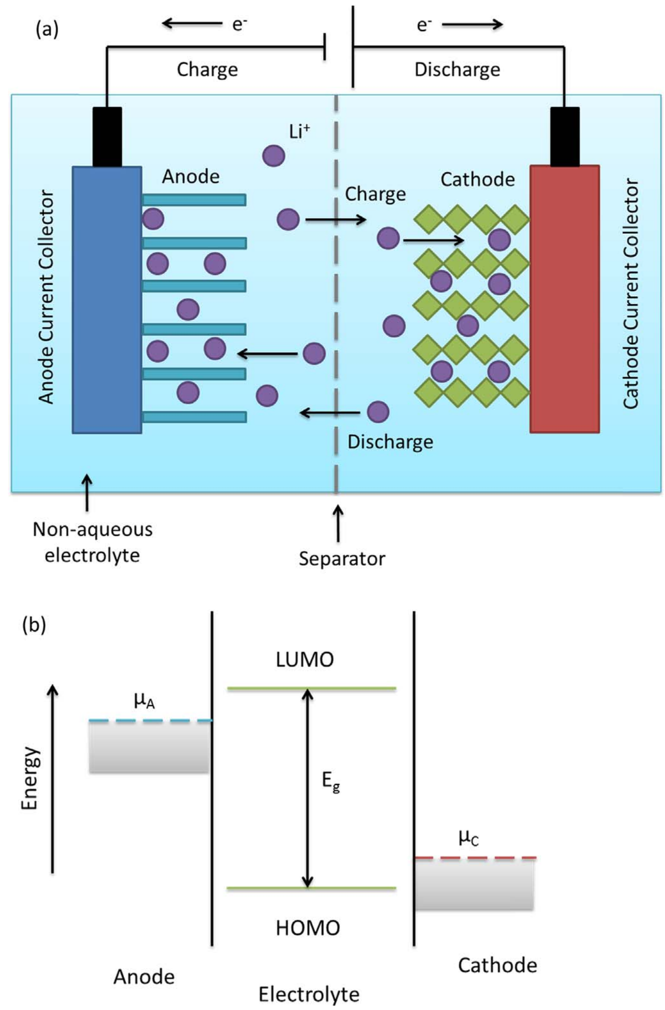

Fig. 1. (a) schematic intercalation and deintercalation of lithium in key components of an LiB cell (b) energy level diagram of electrode potentials and electrolyte gap in an LiB cell (after Roy and Kumar, 2015). Anode and cathode should have chemical potentials (μ_A and μ_C, respectively) which sit above and below the redox potential of Li/Li^+. In order to maximise voltage, μ_A and μ_C should be as far apart as possible. However, for electrolyte stability, μ_A should sit below the lowest unoccupied molecular orbital (LUMO), and μ_C above the highest occupied molecular orbital (HOMO), of the electrolyte material.

through learning by doing and economies of scale. LiBs have the potential to play a huge role coupled with variable renewables for off-grid electrification in for example India (International Energy Agency, 2015), and sub-Saharan Africa (International Energy Agency, 2014a). Whilst a number of studies have examined future cost and performance of LiBs for EVs (Baker et al., 2010; Catenacci et al., 2013; Cluzel and Douglas, 2012; International Energy Agency, 2016; Nykvist and Nilsson, 2015; Sandalow et al., 2015), relatively few have focussed on off-grid applications.

LiBs remain subject to much academic and industrial research at a fundamental chemistry level directed towards the development of new materials at a laboratory scale (Brandon et al., 2016; Cluzel and Douglas, 2012; Crabtree et al., 2015), new processing techniques (Green et al., 2003; Li and Wang, 2013), and better understanding of behaviour and degradation (Grolleau et al., 2014; Hunt et al., 2016; Idaho National Laboratory, 2015; Wang et al., 2011). Intergovernmental programmes (Breakthrough Energy Coalition, 2015) and previous elicitation studies (Anadon et al., 2016; Anadón et al., 2012; Baker et al., 2015, 2010; Bosetti et al., 2012; Catenacci et al., 2013; Fiorese et al., 2014; Nemet and Baker, 2009) appear to imply that increased research and development (R&D) funding is the most effective way to reduce cost and improve performance of low-carbon energy technology to accelerate changes to our energy system to meet climate goals such as those in the Paris Agreement (Fawcett et al., 2015; Gambhir et al., 2015; United Nations Framework on Climate Change, 2015). However, historical evidence suggests that timescales from invention to market introduction, and market introduction to widespread commercialisation, both take a number of decades (Hanna et al., 2015; Kramer and Haigh, 2009). Whether such processes can be accelerated, and whether R&D funding is the most effective way to do so, is a pertinent, but so far little addressed question (Winskel and Radcliffe, 2014). Here, we aim to address these questions through an expert elicitation study on LiBs for off-grid stationary applications. We develop this technique to better understand and separate the role of R&D funding from other factors (such as scaling up of production) in driving improvements in battery technology over multiple timescales. We introduce novel scenarios to consider the limits of what R&D funding could achieve under exceptionally high ambition. We consider multiple timescales to 2020 and 2030 to elucidate the rate at which technology is able to progress.

Environmental impact represents an additional concern if larger LiBs are to become widespread. Lifecycle analyses identify the potential for toxicity of materials used in producing LiBs if improperly disposed of (Hawkins et al., 2013; Kang et al., 2013), and that recycling is more challenging for LiBs than lead-acid batteries (Gaines, 2014). For incumbent lead-acid batteries, whilst effective recycling procedures are well established in the EU and USA, informal recycling is associated with widespread lead poisoning in developing regions, identified as a major concern by the World Health Organisation (World Health Organisation, 2015). Additionally, analysis suggests the energy required to build a storage device (embedded energy) per energy delivered over its lifetime is much higher for batteries than mechanical storage technologies (Barnhart and Benson, 2013). Thus, the potential for reduction of embedded energy and for increased cycle life are of interest from an environmental perspective.

This paper is organised as follows: the following section provides background information on LiB technology and sources of past and projected future improvement. Section 3 provides an overview of methods of cost projection, and prior cost projections for LiBs. Section 4 provides an overview of the methods used in our elicitation study, including novel features designed to separate the influence of R&D from other cost and technology drivers, use of exceptionally high R&D funding scenarios, and multiple timescales to 2020 and 2030. Section 5 presents drivers of improvements in battery cost and lifetime identified by experts, alongside quantitative estimates of these parameters in a range of scenarios by 2020 and 2030. Section 5 also discusses expert perspectives on environmental impact of these technologies, and drivers of improvements outside of cost and lifetime that experts consider of importance. Section 6 considers the implications of technical cost and performance levels projected by experts for off-grid electrification. Finally, Section 7 provides concluding remarks, discusses methodological insights arising from the elicitation process itself, and offers a number of policy recommendations and suggestions for further work.

2. Lithium-ion battery technology

An LiB pack typically consists of a number of LiB cells connected together with: a battery management system, which monitors the pack to determine state of health and charge of individual cells; power electronics which distribute high currents and help to ensure safety of the device; a thermal management system, which may include heat sinks, fans, or other heating or cooling mechanisms depending on the context in which the battery is to be used; and wiring, harnessing, and packaging to hold the cells together (Cluzel and Douglas, 2012).

Fig. 1(a) shows the basic structure of a Li-ion battery cell. The cell consists of an anode (typically graphite layers) and cathode (typically layers of a lithium based ionic compound), separated by an electrolyte