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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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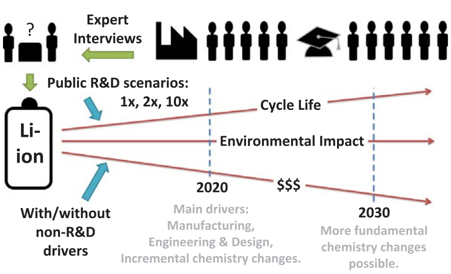
GRAPHICAL ABSTRACT



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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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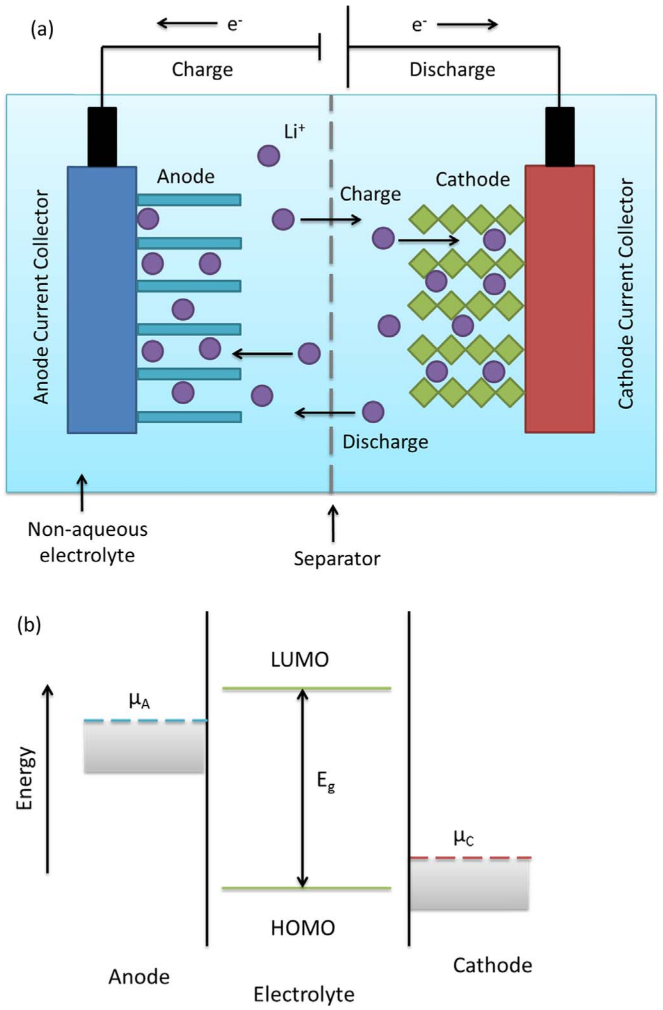

Fig. 1. (a) schematic intercalation and deintercalation of lithium in key components of an LiB cell (b) energy level diagram of electrode potentials and electrolyte gap in an LiB cell (after Roy and Kumar, 2015). Anode and cathode should have chemical potentials (μ_A and μ_C, respectively) which sit 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 (a mixture of organic compounds into which lithium salts and other additives are added) into which lithium ions are dissolved and a separator (typically a semi-porous membrane of polyethylene, polypropylene, or a mixture of the two) to ensure no contact between the cathode and the anode, whilst allowing conduction of lithium ions (Hao et al., 2013). Each electrode is connected to a metallic charge collector (typically copper on the anode and aluminium on the cathode side), which is in turn connected to an external circuit during charge and discharge.

When lithium is intercalated into the anode it is at a higher chemical potential than when it is intercalated into the cathode. Therefore during discharge the lithium ions spontaneously move from the anode to the cathode through the separator whilst the electrons must flow around the external circuit where they do useful work. During charging the process is reversed, but energy must be provided externally to overcome the potential difference. Where a lithium iron phosphate cathode and a graphite anode are used, these processes are associated with the following electrochemical reactions (Brandon et al., 2016):

$$\text{Cathode: } LiFePO_4 \leftrightarrow Li_{1-x}FePO_4 + xLi^+ + xe^-$$

$$\text{Anode: } 6C + xLi^+ + xe^- \leftrightarrow Li_xC_6$$

The back-and-forth motion of lithium-ions during this process has led this technology to be referred to as a “rocking-chair” battery.

Fig. 1(b) provides a schematic energy level diagram associated with an LiB cell. Material choices are as such constrained by energy level. In order to maximise voltage (and therefore energy density), chemical potentials of anode and cathode should be as far separated as possible without changing the oxidation state of lithium ions. However, for electrolyte stability, anode and cathode should not lie above or below oxidation/reduction levels of the electrolyte (see Supplementary material Section S1). In practice, this second requirement is often not quite met, and cathode and some anode materials are chosen such that the electrolyte would degrade but for the build-up of a protective solid-electrolyte interface (SEI) on each electrode. A good SEI allows lithium ions to pass through during cycling, but prevents further electrolyte degradation by blocking transport of electrons. Development of more stable electrolytes and electrolyte additives could help to improve cycle life, and, if it allows a higher depth of discharge, reduce capital cost of a battery system.

Areas of ongoing improvement include increasing quantities of silicon in anodes, which increases capacity for lithium intercalation, energy density, and potentially reduces cost per capacity. This comes at the cost of increased volumetric expansion associated with the absorption of a higher density of lithium ions, resulting in mechanical stress and decreased battery life (Cluzel and Douglas, 2012; Green et al., 2003). Novel methods of processing graphite could also increase intercalation capacity (Roy and Kumar, 2015), and the use of lithium titanate (LTO) in place of graphite can drastically increase cycle life, but also increases cost and reduces energy density. Different cathode materials have different costs, voltages, and intercalation capacities, and are associated with different levels of safety in a device. Development of new, higher voltage, higher capacity, and less costly cathode materials could improve energy density and, as such, reduce costs per storage capacity, provided safety and cycle life are not compromised (Brandon et al., 2016; Cluzel and Douglas, 2012; Schipper et al., 2017; Sendek et al., 2016; Wu and Yushin, 2017; Xie et al., 2017).

Many of the best performing cathode materials contain cobalt, a relatively expensive rare-earth metal which is challenging to source ethically (Scheele, Haan, and Kiezebrink, 2016). Historically, lithium cobalt oxide (LCO) has been most used, but many manufacturers have moved to lithium nickel manganese cobalt oxide (NMC) for increased safety in EV applications (Cluzel and Douglas, 2012). Lithium iron phosphate (LFP) represents another commercialised cathode material, giving a lower cell voltage and energy density than NMC, but increased electrolyte stability and cell cycle life (Cluzel and Douglas, 2012; Wang et al., 2011). A number of more drastic developments of this structure (sometimes referred to as “post lithium ion” batteries (Zhou, 2013)) are proposed. A few of the most promising are discussed in Supplementary material Section S4, alongside experts' perspectives of their potential.

Engineering improvements, such as that of the battery management system (BMS), based upon a better understanding of the factors which result in battery degradation (eg. depth of discharge, state of charge in which the battery is stored, charge and discharge rates, temperature, and the interplay between these factors) could lead to increased battery life, and, potentially, allow for a deeper discharge at acceptable levels of safety and performance degradation, potentially leading to lower costs. A more developed supply chain for battery management systems could also reduce the cost of this component. A reduction in quantity of materials used in packs, and more experience in pack construction, could lead to reductions in pack costs.

3. Prior projections of future cost and technical performance of lithium ion batteries

Projections of future technology costs typically fall into one of three categories (in some cases be used in combination):

- **Learning Curve Analysis** describes an approach whereby cost history to derive a cost reduction rate as a function of a “learning” parameter (Arrow, 1962; Wright, 1936) (typically cumulative production (BCG, 1968; Nagy et al., 2013)). Such an approach may be used to project future costs based upon assumptions about future technology deployment, or be implemented in a more complex energy system model via embedded learning modules (Kahouli-Brahmi, 2008). If sufficient data is available, this statistical method is straightforward to perform, condensing the multiple drivers behind cost reductions, such as learning-by-doing, economies of scale, technological advances through R&D, knowledge spillovers and consumer feedback into one single learning parameter. However, the learning curve approach can be too normative, and provide very different results depending on time period, geographical scope, and other factors contributing to observed changes (Rubin et al., 2015). The lack of insights learning curves provide into the drivers of cost reduction or performance improvement limit its usefulness to identify investment and research priorities (Abernathy and Kenneth, 1974). Additionally, due to confidentiality around costs, learning curve analyses are often reliant on scant data from manufacturers.

- **Bottom Up Modelling** describes an approach whereby a component-based model of a device (in this case, a battery) is used to project the influence of technical advances, future price trends in materials, and manufacturing savings associated with scaling up of production on cost and performance. Such a method has the advantage of being able to explicitly calculate the influence of technical advances and changes in material costs on battery cost and parameters, but may be limited by the level of detail with which the device is described, the quality of available input data, and the model's suitability for considering non-incremental technology advances.
- **Expert Elicitation** describes an approach whereby a structured interview is used to elicit probabilistic ranges for costs or technical parameters at a specified future date. This procedure is often repeated for different scenarios, such as differing levels of regional or global R&D funding. This method has the advantage of offering insights into technical advances which are likely in the near future, and may offer a more detailed understanding of how these advances may come about than the first two methods. Additionally, experts may use results derived from the first two methods when making their predictions, and may be able to highlight both positive aspects and shortcomings of other models. However, this method suffers from possible bias of experts (discussed further in subsequent

sections), and is subject to the challenge of finding individuals with sufficient expertise on questions of interest (Morgan, 2014). A novel variant of this approach involves the use of an online survey to elicit future costs, allowing for the input of many more experts than have been included in previous elicitation studies, but at the cost of detailed insights in to drivers which arise from face to face interviews (Wiser et al., 2016).

Nykvist and Nilsson used LiB costs inferred from market prices and industry statements, alongside estimates from a wide range of industrial and academic literature, to calculate a learning rate (Nykvist and Nilsson, 2015). This study indicated that market leader costs may already be below many projections of costs in 2020 and even 2030, identified significant uncertainty in current and future costs (140–620 $/kWh among market leaders in 2014), and calculated a cost reduction rate which could result in battery costs of market leaders and the industry as a whole reaching $230/kWh before 2020. Schmidt et al. adopt a similar approach to consider a wide range of electrical energy storage technologies (Schmidt et al., 2017).

Cluzel and Douglas used a bottom-up modelling approach, informed by expected trends in materials costs, economies of scale in certain components, and technological improvements anticipated by battery experts, to conduct a study of current and projected future cost and performance of LiB packs for automotive applications (Cluzel and Douglas, 2012). The authors conclude that improvements in fundamental chemistry and manufacturing improvements associated with scaling up of production are both likely to be important factors in battery development by 2020 and 2030. Depending on rate of uptake and pace of scientific progress, Cluzel and Douglas anticipate battery costs of $288 – 441/kWh in 2020 and $222 – 305/kWh in 2030 for a 21kWh battery pack. However, the study indicates large differences in cost per kWh depending upon battery size (2011 costs of $587/kWh and $1327/kWh for battery packs of 69 kWh and 12 kWh respectively).

Baker et al. interviewed academic and industrial battery experts in the US on the probabilities of LiBs reaching a number of cost and technical performance thresholds by 2050, and the impact of increased research, development, and demonstration (RD&D) funding on these probabilities (Baker et al., 2010). Catenacci et al. interviewed a series of policy and battery technology experts on how public R&D funding should be allocated, and resulting 2030 EV battery costs (Catenacci et al., 2013). These experts indicated that public RD&D funding in the EU should be divided between a range of battery technologies, and between basic, applied, and demonstration RD&D. In a scenario where the current level of investments in RD&D is maintained until 2030, roughly half of the experts provided an expected battery cost value ranging between $200 and $400/kWh, while the remaining experts provided more pessimistic projections. Further details of prior projections of future LiB cost and performance are provided in Supplementary material Section S1, and key results are presented graphically in Fig. S1.

4. Methods

We designed our elicitation protocol following best practice recommendations (Baker et al., 2010; Bistline, 2014; Catenacci et al., 2013; Morgan, 2014) to minimise the influence of bias and heuristics, the rationale behind which is presented in more detail in Table S1 in Supplementary material.

We selected a pool of experts from both academic and industrial perspectives with a wide range of expertise, including cell chemistry, cell and pack engineering, and cell and pack manufacture, based upon recommendations from LiB experts at Imperial College. Arranged by sector and surname, the experts were:

- **Shane Beattie,** *Technical Manager, Warwick Manufacturing Group (Academia)*
- **Nigel Brandon,** *Professor of Sustainable Development in Energy, Imperial College London (Academia)*
- **Michael Brunell,** *EngD Candidate, Warwick Manufacturing Group (Academia)*
- **Nikita Hall,** *Project Engineer, Warwick Manufacturing Group (Academia)*
- **Dave Howey,** *Associate Professor in Engineering Science, University of Oxford (Academia)*
- **Greg Offer,** *Senior Lecturer in Engineering, Imperial College London (Academia)*
- **Celine Cluzel,** *Associate Director, Element Energy (Industry)*
- **Tom Cleaver,** *R&D Programme Manager, Oxis Energy (Industry)*
- **Allan Paterson,** *Chief Electrochemist, Johnson Matthey Battery Systems (Industry)*
- **John Perry,** *Technical Director, Denchi Power (Industry)*
- **Ian Whiting,** *Business Development Director, AGM Batteries (Industry)*

We developed a "background information" document providing a concise overview of cost history, historical drivers, market growth, environmental impact, and public R&D funding for R&D in LiBs, iterated with battery experts at Imperial College London.[1] This document is provided in Supplementary Material, and was made available to experts days or weeks prior to interview.

Elicitation interviews took place between October 2015 and May 2016. Interviews were conducted face-to-face apart from two cases where logistical constraints made video calls necessary. Interviews took approximately two hours, the first spent reading through background information, to minimise the possibility of availability bias and to identify any shortcomings in the state of knowledge from the expert's perspective. The second hour was spent eliciting estimates of cost, cycle life, and embedded energy for 2020 and 2030 under continued current public R&D funding, and two increased levels (double and ten times current funding). Cost estimates were elicited separately based on technical improvements arising from R&D alone, and based on R&D alongside other factors (including, but not limited to, industrial learning-by-doing and economies of scale). Cycle life estimates were elicited separately at a depth of discharge (DoD) of 80% and 100%. For cycle life and environmental impact, R&D was considered only alongside other factors. Regarding efficiency, we note that dc-dc efficiencies of over 90% have already been demonstrated in commercial LiBs (Brandon et al., 2016; TESLA, 2016), and as such consider this parameter to be lower priority for elicitation.

To minimise technical ambiguity, we asked experts to consider what they expect would be the dominant LiB technology for an off-grid battery pack of the following specifications:

- Unit size 15 kWh
- C rate below 1 C
- Managed temperatures,

Experts were asked to provide estimates including cells, interconnectors, housing, battery management system, and thermal management, but excluding other system costs (eg. inverter) and installation cost. These specifications are based on specifications for off-grid systems published by the International Energy Agency (International Energy Agency, 2014b) and discussion with battery experts[i]. Finally, we asked experts to identify any other environmental impacts, important technical advances, or comments on areas not covered during earlier stages of our elicitation procedure. Question sheets used during the interview are provided in Supplementary material.

Shortly following the elicitation procedure, we prepared a document for each expert summarizing their quantitative answers and qualitative drivers identified, pointing out any potential

[1] Greg Offer and Nigel Brandon, co-authors of the study.

inconsistencies, to which experts responded with clarifications/amendments.

5. Results

5.1. Drivers of cost and cycle life improvements

Fig. 2 presents key improvements experts described as capable of having a large impact on costs and cycle life by 2020 and by 2030.[2] These are grouped into cell chemistry, engineering and design, and manufacturing. Experts also distinguished between incremental improvements to a fundamentally similar device, and more fundamental breakthroughs in chemistry or manufacturing. Industry-driven marginal improvements are expected to be more significant by 2020. More fundamental chemistry and manufacturing breakthroughs driven by academic research or academic/industrial partnerships are potentially significant by 2030.

Most experts expected incremental changes to battery chemistry recipes, and no expert expected significant chemistry changes in a commercialised battery pack by 2020. This is due to timescales associated with translating research funding to research output, scaling up of materials, and production testing of cells and battery packs. In engineering and design, experts anticipated a better understanding of usage patterns causing battery degradation (eg. importance of DoD, temperature, rate of charge/discharge, and state of charge when stored (Grolleau et al., 2014; Idaho National Laboratory, 2015; Wang et al., 2011)) could improve battery management systems and thermal control, increasing cycle life and allowing deeper discharge, thus decreasing the cost per usable kWh. Three industry experts stressed that cell format impacts battery life. Larger format EV cells are better able to withstand mechanical stresses arising from volume changes during charge and discharge of cells than smaller, more standardised cylindrical '18650' cells (named according to their 18 mm diameter and 65 mm length), developed for portable electronics, but also used in EV and off-grid batteries (McKinsey and Company and Amsterdam Roundtables Foundation, 2014).

The process of industrial "learning by doing", economies of scale, increased automation and standardisation in chemistry and manufacturing, were expected to be important in reducing costs by 2020. Some experts anticipated that new manufacturing methods, such as spray coating of anodes (Li and Wang, 2013) or structured electrodes (Green et al., 2003), could have an impact on costs. However, other experts expected that it would be challenging to realise a significantly different manufacturing technique in a commercial device by 2020. One industry expert noted that, from a cell manufacturing perspective, changing manufacturing technique is often more challenging than changing material, provided that the new material may be processed in a similar manner.

Alongside a continuation of 2020 drivers, developments in fundamental cell chemistry could reduce costs by 2030 (presented in Fig. 2(b)). In line with Cluzel and Douglas, experts indicated that increasing capacity and voltage of cathode and anode materials are promising routes towards cheaper, more energy dense battery packs. However, experts anticipated challenges in realising these Douglas (Cluzel and Douglas, 2012). Increasing voltage was regarded as challenging owing to the limited stability of current electrolytes (even at current cell voltages). New electrolytes (potentially a more robust solid-state polymer electrolyte), and/or the development of better stabilising electrolyte additives, could enable higher voltages, have significant implications for cycle life and also help to allow a deeper depth of discharge (DoD). One academic expert indicated that finding cathode materials that maintain high voltages during discharge, and thus realise theoretical improvements in cell density, is challenging. One industrial expert noted that producing cathodes with increased capacity could necessitate a more expensive manufacturing process, possibly cancelling out cost reductions associated with increasing energy density.

Experts indicated that reducing the proportion of cobalt in cathode materials, and making more use of cobalt-free cathode materials such as lithium iron phosphate (LFP) could lead to lower cost cells and packs, particularly where energy density is not a high priority. Improvements in binders, and moving to thinner separators, potentially made of cellulose, were also expected to reduce costs and increase cycle life. One academic expert raised the possibility of moving to a cell with both electrodes made of graphite based on the hybridisation of LiB and supercapacitor technology, leading to cycle lives of hundreds of thousands of cycles now more associated with supercapacitors, but with higher energy densities more associated with batteries. Such cells are currently under commercialisation (Power Japan Plus, 2014), but do not appear to have been reported as having exceptionally high cycle life (Read et al., 2014; Rothermel et al., 2014).

Under continued current R&D funding levels, the majority of experts (4/6 academic and 4/5 industrial) expected similar commercial cathode chemistry in 2030 to that in cells produced today. However, the majority of experts (5/6 academic and 4/5 industrial) specified that more drastic chemistry changes, such as a move to sodium-ion or lithium-sulphur, were conceivable by 2030, and much more likely in higher R&D funding scenarios. Most experts indicated that higher funding would allow attention to be directed towards more avenues of improvement, and increase the probability of some coming to fruition. Further insights on sources of cost and lifetime improvement, potential breakthroughs in LiB technologies, the role of publicly and privately funded activities could play in driving these improvements, and timescales over which these could take place, are presented in Supplementary material Sections S4–S9.

5.2. Cost estimates

Fig. 3 shows 10th, 50th, and 90th percentile estimates of costs in all funding and development scenarios in 2020 and 2030. Median values across experts in each of these percentiles and scenarios are summarised in Table S2 in Supplementary material.

Under continued current public R&D funding alongside industrial learning and other cost-reduction factors, eight of ten experts specify central pack cost estimates of 175–350 $/kWh in 2020 and 120–250 $/kWh in 2030.

These ranges are somewhat below Cluzel and Douglas' bottom-up estimates of 288–441 $/kWh in 2020 and 222–305 $/kWh in 2030 for a 21kWh EV pack (Cluzel and Douglas, 2012), and experts in Catenacci et al.'s study, the more optimistic half of whom who specify a range of 200–400 $/kWh by 2030 (Catenacci et al., 2013). However, these estimates appear relatively conservative compared to Nykvist and Nillson's projected cost of 230 $/kWh in 2017-18 (Nykvist and Nilsson, 2015). Ranges elicited here fall to 130–340 $/kWh in 2020 and 100–215 $/kWh in 2030 under a tenfold increase in R&D funding, a significant impact, but diminishing returns compared to a doubling of funding.

It would be desirable to pool expert responses from this and previous elicitations on LiB battery cost (Baker et al., 2010; Catenacci et al., 2013) in order to obtain a more robust result taking into account a larger number of experts, and to consider differences in perspective from different periods (as performed by Anadon et al. for future costs of a range of energy technologies (Anadon et al., 2016)). However, we consider that differences between studies in dates elicited, funding and deployment scenarios, scope (off-grid vs. EV) and rapid cost reductions in LiB pack costs in the intervening period (Nykvist and Nilsson, 2015) render this exercise impractical. It would be beneficial to design future

[2] It should be noted that Fig. 2 only includes improvements explicitly mentioned by experts, and the failure to include a particular type of improvement does not necessarily indicate that an expert does not consider this area important in driving cost reductions or performance improvements.

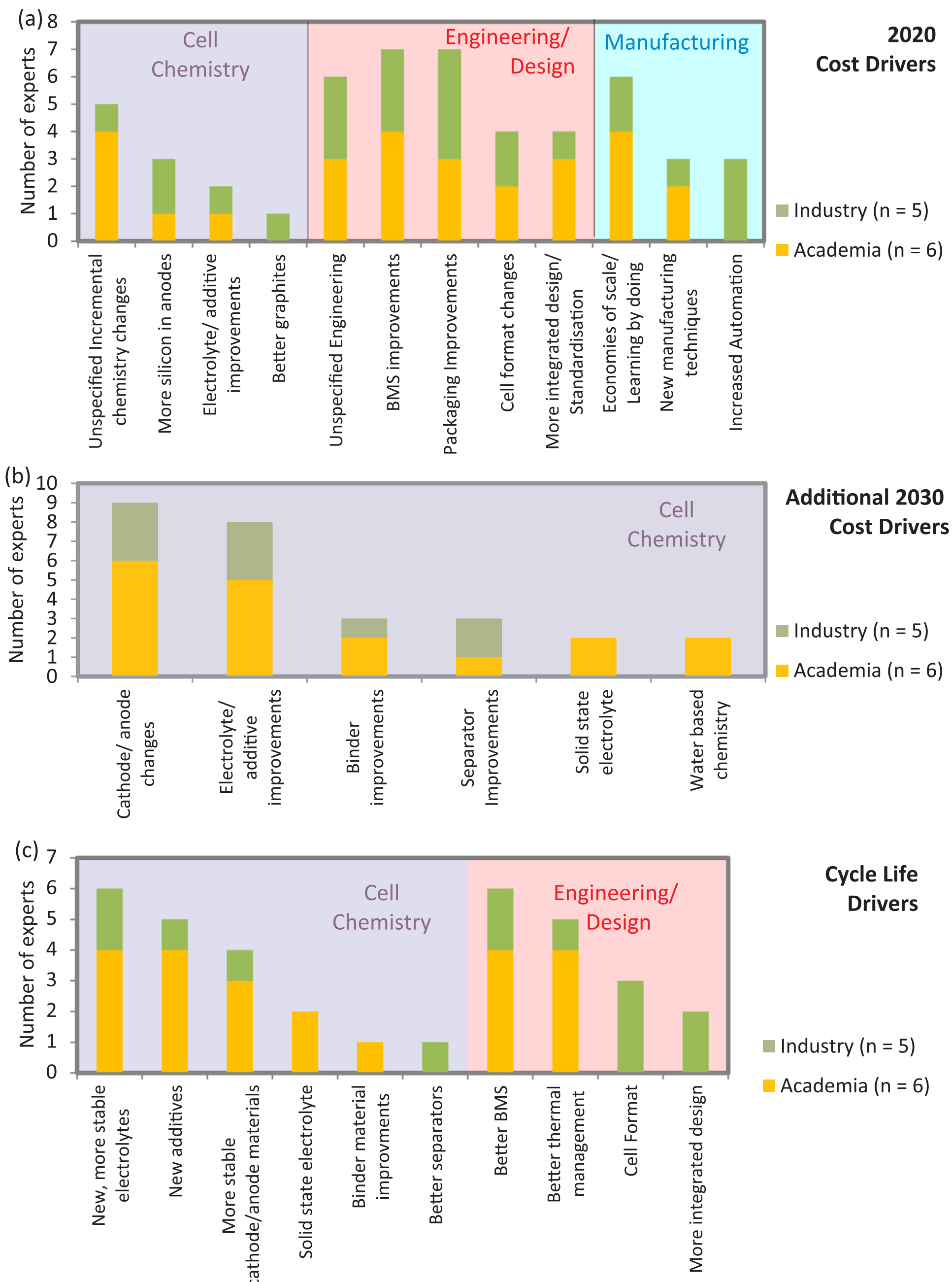

Fig. 2. Drivers of (a) cost reduction by 2020, (b) cost reduction to 2030 and beyond and (c) cycle life over an unspecified timeframe. Number of experts mentioning particular drivers of cost improvement within three core categories broken down into individual sources of improvement within these categories. In most cases experts did not mention timeframes for cycle life improvements, but generally indicated that engineering/design improvements could be implemented by 2020, but cell chemistry developments were more likely by 2030. BMS = battery management system.

elicitation studies so as to be more directly comparable with this study such that results could be meaningfully pooled. We have added our raw data to supplementary material in order to help facilitate this. Key results of our study are presented alongside those of previous elicitations in Fig. S2 in Supplementary materials.

The variability in estimates between experts is large. For example, 50th percentile estimates of 2020 battery costs under current R&D funding range from \$165/kWh to \$548/kWh. This is in part due to different assumptions of current cost and performance of LiBs. Many academic experts took the advertised 350 \$/kWh battery pack price of the 10kWh Tesla home battery as a benchmark for current battery costs (TESLA, 2016).[3] However, four of five industrial and one academic expert believed that these prices are set below current costs in order to gain market share, and/or to stimulate the market.

Academic experts tended to be more optimistic about cost developments than industrial experts. This is hard to separate from their lower assumed current cost level, but may reflect a closer interaction with fundamental science improvements that might make transformative changes to the device and/or less experience of the industrial development process.

In Fig. 4, the median reduction in 50th,10th, and 90th percentile cost estimates associated with increased R&D funding, non R&D related factors, and an additional ten years of development are summarised. Similar charts for academic and industrial experts separately, are provided in Figs. S3 and S4 in Supplementary material.

Consistent with drivers identified in the previous section, non-technical advances were expected to have a larger impact on battery cost than technical breakthroughs or increased R&D funding by 2020. While experts expected additional cost reductions when increasing R&D funding from double to tenfold, the additional funding above double is associated with significantly diminishing returns by 2020. Experts expected an additional ten years of development to 2030 to result in costs

[3] Both of these batteries are now discontinued (TESLA, 2016).

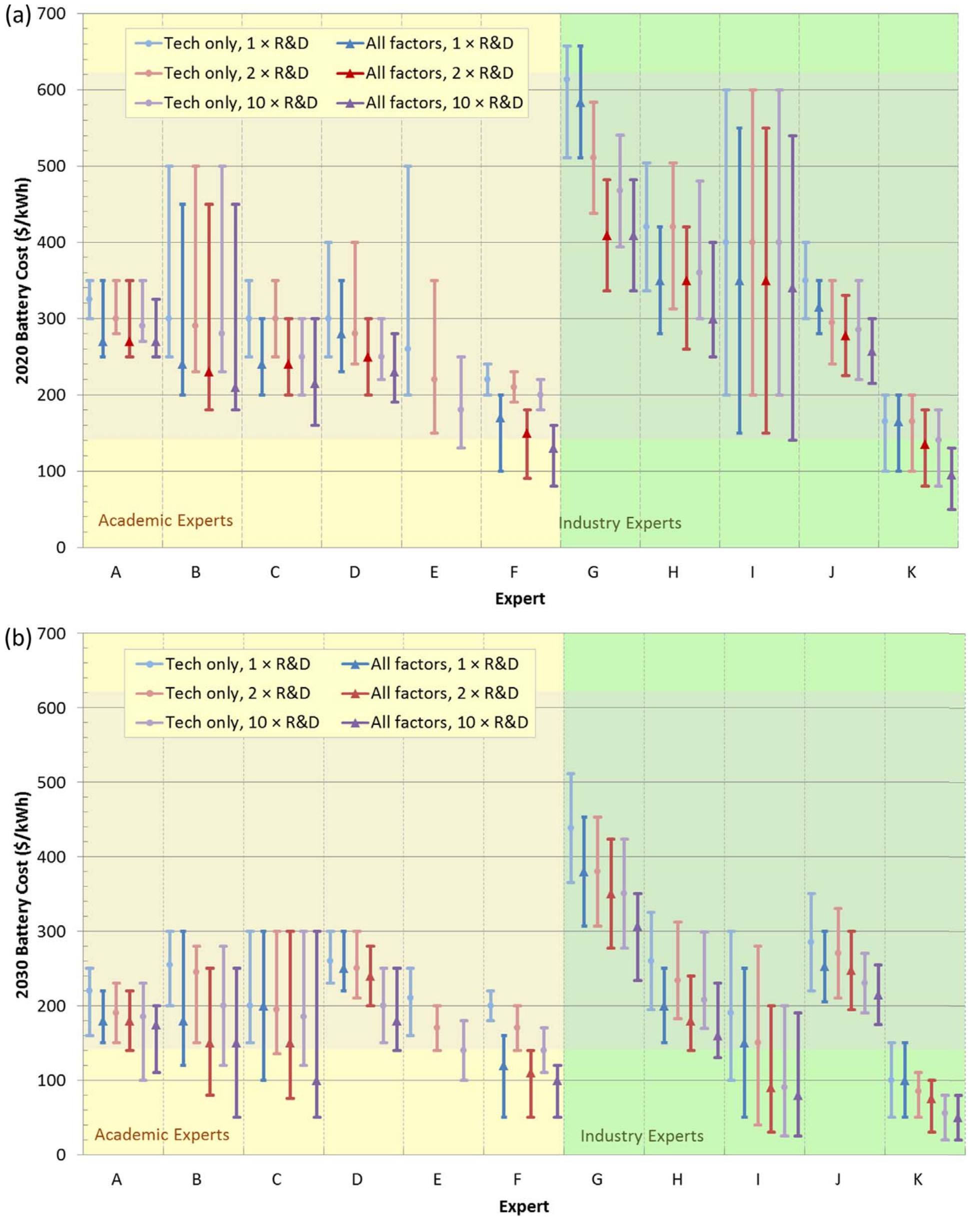

Fig. 3. 10th, 50th, and 90th percentile estimates of (a) 2020 and (b) 2030 battery costs amongst academic and industrial experts assuming continued current, 2, and 10 times current R&D funding. Estimates are included as a result of technical improvements alone assuming no industry growth ("Tech Only"), and when taking account of other cost drivers ("All factors"). Shaded region represents 90% confidence interval of market leader costs for 2014 specified by Nykvist and Nillson (Nykvist and Nilsson, 2015). Experts in each category are ordered in decreasing median 2020 "Tech Only" cost under continued current levels of R&D funding. Expert E indicated a lack of sufficient knowledge to estimate the impact of non-technical factors on costs. Raw data presented in this figure is included in Supplementary materials.

lower than those achieved in 2020 in any R&D funding scenario, indicating that, whilst significantly increased R&D funding and other factors such as scaling up of production can play a significant role in reducing costs in the near term, some processes are not easily accelerated. The percentage decrease in costs associated with non-technical developments is similar by 2020 and 2030, but R&D funding was expected to be more important by 2030, consistent with longer timescales to achieve fundamental chemistry changes in widespread commercial devices. Experts indicated that, whilst large R&D funding increases may not necessarily lead to breakthroughs by 2030, they have a significant impact on what could be achieved if research goes well. Consistently, whilst the median fall in 50th percentile cost estimate was not greatly different when going from current R&D funding to a doubling and a tenfold increase in funding (13% and 22% respectively), the median fall in 10th percentile cost differs more substantially (10% and 38% respectively, see Fig. 6). Experts indicated that judgements of whether such improvements are included in 50th or more extreme percentiles are very challenging.

5.3. Cycle life estimates

Fig. 5 shows 10th, 50th, and 90th percentile estimates of battery cycle life at 100% and 80% DoD in 2020 and in 2030 in all R&D funding scenarios. Median values across experts in each case are summarised in Table S3 in Supplementary material. Only one expert from industry provided estimates of cycle life at 100% DoD, whilst others stated that they considered this usage unrealistic. One expert provided no estimates for 2030, citing a lack of sufficient confidence to quantify improvements. One expert from industry provided no cycle life estimates, but indicated that cycle life would be engineered to meet product requirements.

Variability in estimates of future cycle life is larger than those of cost. 50th percentile estimates at 80% DoD under continued current R&D funding range from 1500 to 15,000. It is worth noting that there are large differences in cycle life of LiBs at present, depending upon the chemistry used, cell format, and quality of cell and battery pack, and that cost and cycle life cannot be easily separated (see Supplementary

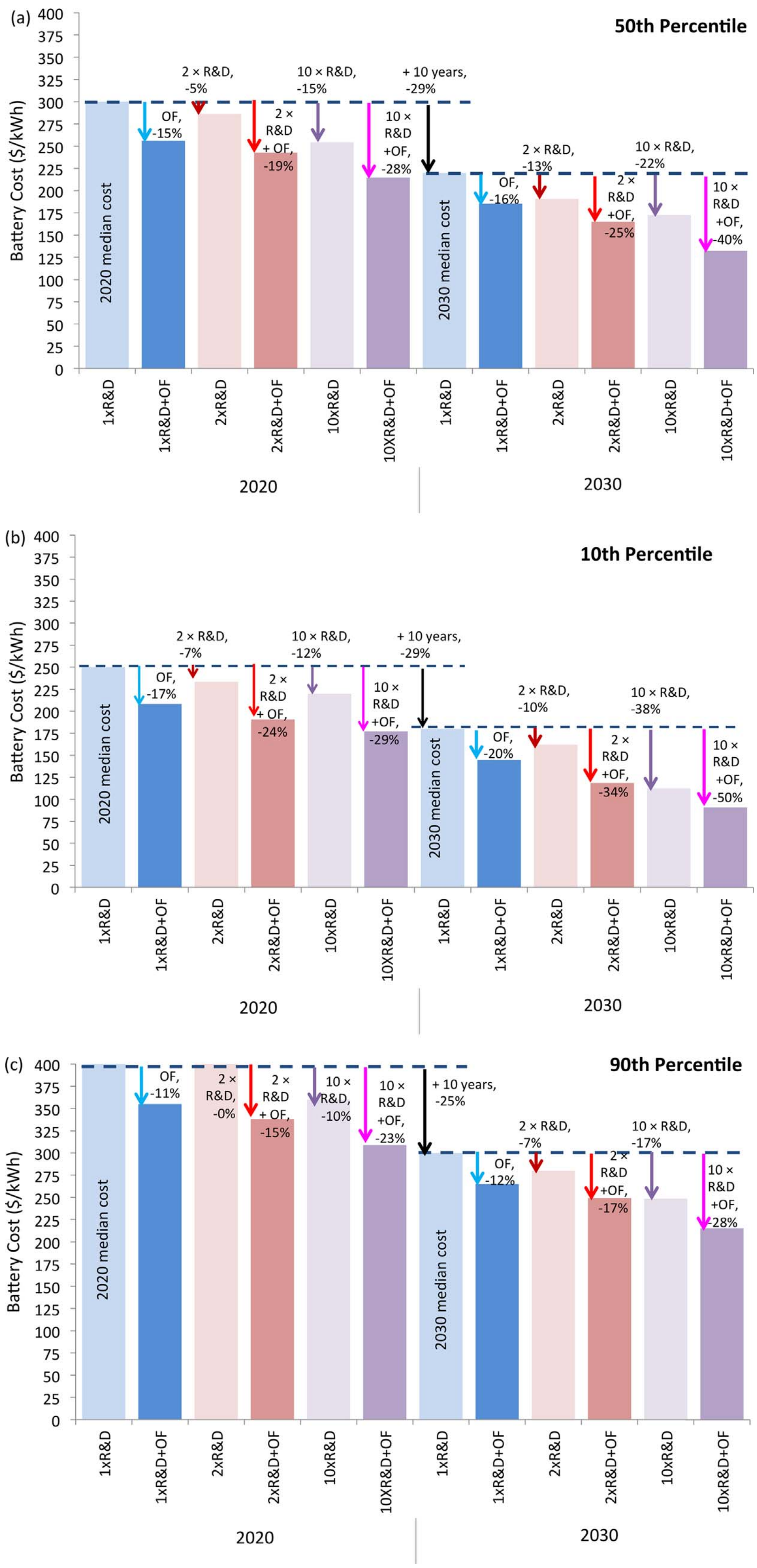

Fig. 4. Impact of increased R&D funding considering technical improvements alone and alongside other factors (OF), and an additional ten years of development from 2020 to 2030 on (a) 50th, (b) 10th, and (c) 90th percentile estimates of battery cost (academic and industrial experts aggregated). Median values for each percentile estimates with technical improvements alone under continued current funding are displayed, and median percentage reductions in cost as a result of each change are applied.

material Section S6). Many experts specified LFP as a particularly stable and relatively low-cost cathode, particularly suitable for meeting this application (albeit with a lower energy and power density, making it less suited for some transport applications). LiBs incorporating an LTO anode are exceptionally stable, with reported cycle lives of over 20,000 cycles (Siemens, 2014). No expert indicated that they were considering

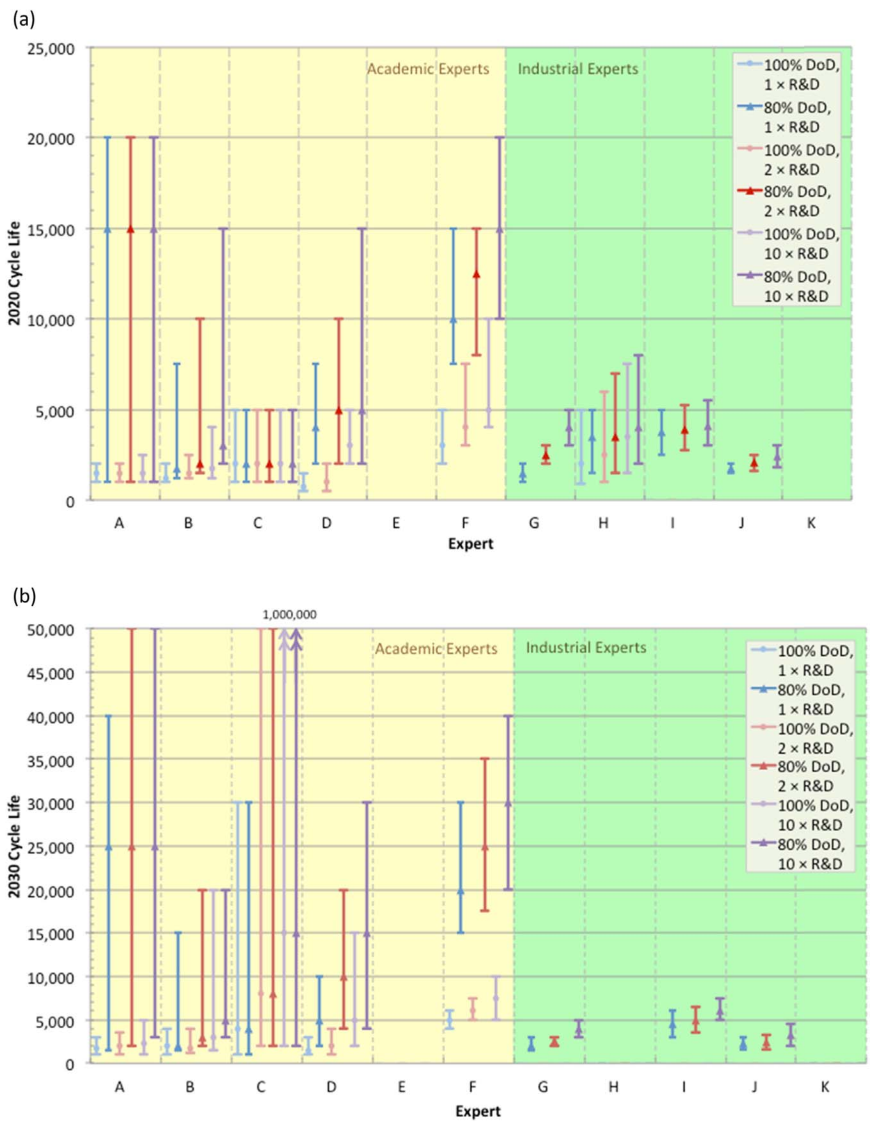

Fig. 5. 10th, 50th, and 90th percentile estimates of (a) 2020 and (b) 2030 cycle life amongst academic and industrial experts assuming continued current, 2, and 10 times current R&D funding. Estimates are included for 100% and 80% DoD. The majority of industrial experts did not provide estimates under 100% DoD, as they perceived this to be unrealistically high to be used in a practical system. Expert E indicated a lack of sufficient knowledge of cycle life to make estimates. Raw data presented in this figure is included in Supplementary materials.

LiBs incorporating a high cycling LTO anode, but some anticipated that it might be possible to achieve similar stability with other chemistries in the future.

The impact of R&D funding, restricting DoD, and an additional ten years of development from 2020 to 2030 on the median of 50th, 10th, and 90th percentile estimates of cycle life across experts are presented in Fig. 6. Experts expected that restricting the DoD to 80% under current R&D funding will have a larger impact on cycle life than increasing R&D funding either two or tenfold by 2020 (but indicated that a more sophisticated view of degradation could alter these usage requirements). However, experts indicated that R&D funding can have a large impact on cycle life at 80% DoD by 2030, with median 50th percentile estimates of 6000 and 10,000 cycles with a doubling and a tenfold increase in R&D funding, respectively. Some academic experts indicated that very large increases in cycle life could be possible, with four of five providing 50th and 90th percentile estimates of at least 15,000 and 30,000 cycles at 80% DoD with a tenfold increase of R&D funding.

The impact of reducing DoD from 100% to 80% may be somewhat underrepresented in Fig. 6 as a result of a number industrial experts (who tended to be more conservative about cycle life) specifying values at 80% and not 100% DoD. A similar chart derived only from experts who provided estimates for all values is presented in Fig. S5 in Supplementary Material, along with charts for other percentile estimates.

5.4. Environmental impact

No expert expressed sufficient confidence to provide estimates of the quantity of energy required to produce a battery (Barnhart and Benson, 2013). The majority of interviewed experts professed very limited knowledge of the environmental impacts associated with the production and disposal of LiBs, but acknowledged that this represents an area in which more research would be valuable. In line with Gaines, most experts acknowledged that recycling of LiBs is more challenging than lead-acid batteries, owing to the higher level of device complexity, and remains more expensive and potentially more energy-intensive than use of virgin materials (Gaines, 2014).

Experts indicate that ethical and affordable sourcing of nickel and cobalt (Scheele et al., 2016) is a challenge for LiB manufacturers, which is driving changes towards cathodes using a lower proportion of these materials, or those avoid them entirely (such as LFP). Some experts also expressed concerns surrounding lack of planning for disposal of toxic materials in LiBs, in line with Kang et al. (Kang et al., 2013). One academic expert mentioned research underway into alternatives to toxic materials in electrolytes, and in the manufacturing of binders. We consider the lack of detailed knowledge around environmental impacts and recycling procedures for LiBs amongst technical experts an important finding, and suggest that a greater emphasis should be placed upon design of technologies for sustainability from the R&D stage onwards.

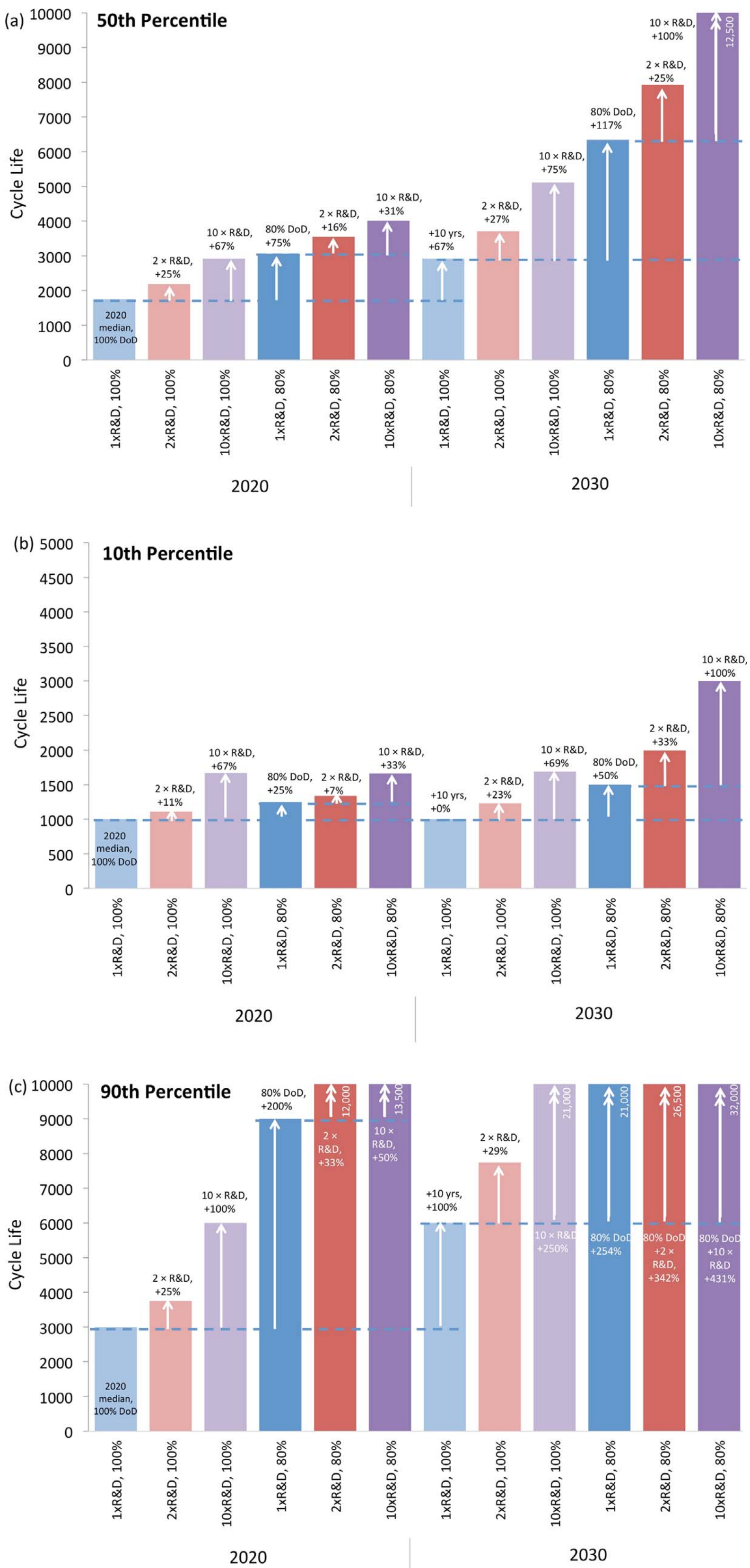

Fig. 6. Impact of increased R&D funding, restriction to 80% DoD, and an additional ten years of development on (a) 50th, (b) 10th, and (c) 90th percentile estimates for battery cycle life. Median 2020 value at 100% DoD under continued current funding is displayed, to which median percentage increases as a result of each change are applied.

6. Implications for rural electrification

Improvements in battery technology identified here could have a profound impact on the cost of electricity from renewable energy sources coupled with LiB storage. Under continued current levels of R&D funding, median 50th percentile battery cost estimates of \$275/kWh and \$180/kWh in 2020 and 2030 respectively, associated with cycle life of 3500 and 4500 at 80% DoD, result in a levelised cost of stored energy (LCSE) of ¢15.3/kWh and ¢8.3/kWh, respectively (details of calculation provided in Supplementary Material Section S12). Under an ambitious scenario of a tenfold increase in R&D funding, LCSE falls to ¢12.3/kWh and ¢4.2/kWh, respectively. These figures compare favourably to the IEA's estimates of ¢75–95/kWh and ¢25–75/kWh for an off-grid system in 2012 and 2030 respectively (International Energy Agency, 2014b), and to Chen et al.'s estimate of ¢15–100/kWh in 2009 (Chen et al., 2009). We note, however, that our costs are for a battery pack alone, and neglect costs associated with transport and installation alongside peripheral components such as inverters required to interact with high voltage AC networks (perhaps not necessary for an off-grid application). It is not clear whether these costs are considered by the IEA or Chen et al..

In a modelling study of an off-grid hybrid diesel/PV/battery system in rural India, Sandwell et al. find that, at current diesel prices (~$0.8/litre) and a battery cost below around $250/kWh (or $532/kWh usable capacity owing to an assumed maximum DoD of 47%), it is cost optimal to meet the majority of electricity demand with PV and storage rather than diesel generation (Sandwell et al., 2016). This is associated with a significant reduction in specific emissions from 1056 g CO2/kWh to 373–540 gCO2/kWh (depending on location). Under continued R&D funding, the majority of experts project that a cycle life close to 5000 could be achieved at 80% DoD by 2020 with a probability of between 10% and 50%. Combining a cycle life of 5000 with median 50th percentile battery cost estimates of $275/kWh at 80% DoD results in a cost per usable capacity of $343/kWh, at which cost Sandwell et al. calculate that it is cost optimal to meet around 80 – 90% of electricity demand with solar PV plus storage. Sandwell et al. also find the cost of electricity from an off-grid system is comparable to grid extension for distances of above 10–30 km (depending on terrain and insolation). Since grid electricity generation is predominantly coal in India (with carbon intensity 938 – 979 g CO2/kWh (US Energy Information Administration, 2016)), if falling battery costs and improved lifetimes can result in the cost of an off-grid solar PV system falling below grid extension in more regions, this could have significant implications for global emissions. This is provided that other possible barriers to adoption (such as access to capital, consumer awareness, and negative attitudes towards decentralised electricity systems (Bloomberg New Energy Finance and Lighting Global, 2016)) can be successfully overcome by rural communities who would stand to gain from such systems.

Analysis conducted by Szabo et al. indicates that provision of electricity from solar PV with lead-acid battery storage was already more economic than diesel generation or grid connection in large areas of Africa in 2012 (Szabó et al., 2011). Reductions in LiB costs, alongside increased lifetimes, could expand this region.

7. Conclusions and policy recommendations

This paper has quantified and identified a range of drivers of cost reduction and cycle life improvements in LiB battery packs. Up to 2020, these are mostly expected to arise from economies of scale, "learning by doing" in manufacturing, alongside engineering improvements related to battery management and incremental improvements in cell chemistry. Up to 2030, more fundamental improvements to battery chemistry are possible, which could lead to dramatic cost reductions and performance improvements, particularly under higher R&D funding scenarios, but are not necessarily expected. Experts indicate several years would be required to translate additional funding into effective research and most experts indicate that technical breakthroughs are likely to have a larger effect further in the future than 2030. Experts also indicate that making predictions to 2030 is very challenging owing to the large number of factors which could influence technology development over this timescale (see Supplementary material Section S13).

Factors other than R&D funding (predominantly scaling up of production, but also effective collaboration, research networks and favourable policy landscape for deployment) are expected to play at least as large a role as R&D funding in driving down costs both to 2020 and 2030. Effective collaborations and research networks, complementary research, and legislation to encourage deployment of energy storage were all expected to be significant. Experts suggest that funding for bringing technologies and materials from laboratory to commercial scale is in general lacking. Policymakers should ensure that these factors are not neglected in developing policy portfolios designed to support LiBs. We emphasise that estimates presented here are for battery packs alone, including cells, interconnectors, housing, battery management system, and thermal management, but excluding other system costs (eg. inverter) and installation cost.

Experts express concern, but little detailed knowledge, about environmental impact of LiBs, and acknowledged that recycling is likely to be challenging. Further research and improved regulation in this area would be beneficial. Experts also mention the importance of areas of future improvement not related to cost or cycle life, including safety, energy and power density.

The expert elicitation technique is useful for identifying future potential drivers of cost reduction and cycle life improvements, as well as understanding the technical challenges in further innovating LiBs. The in-depth interview process, coupled with the exercise of converting drivers into numerical values, allowed a high level of detail of understanding of these drivers, and their relative importance as perceived by experts.

Further work is required to understand the extent to which insights gained on technological innovation from this study may be applied to other technologies, to understand the development paths of other means of storing electrical energy. Whilst many of the insights presented here are also relevant to development of LiBs for other applications, such as EVs and grid scale storage, further work is required to better understand which variants with different cell chemistries and pack format may be relevant in these contexts.

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Supplementary material

Supplementary Material provides an overview of methods of future technology projection and prior projections for LiBs (S1); further details of our elicitation method (S2); an overview of post Li-ion technologies and experts' perspectives on promise and challenges associated with these (S3); representative quotes on sources of cost reduction (S4) and cycle life improvement (S5); qualitative findings on the role of R&D funding (S6), non-R&D drivers (S7), and timescales of innovation (S8); further quantitative details of cost (S9) and cycle life (S10) estimates; details of LCSE calculations (S11); and qualitative findings around the challenge in making technical estimates for 2030 (S12). Background information and question sheets used during the elicitation procedure and raw data emerging from elicitations are provided in separate supporting documents.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2017.12.033.

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