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Indicative energy technology assessment of advanced rechargeable batteries

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HIGHLIGHTS

- Several ‘Advanced Rechargeable Battery Technologies’ (ARBT) have been evaluated.
- Energy, environmental, economic, and technical appraisal techniques were employed.
- Li-Ion Polymer (LIP) batteries exhibited the most attractive energy and power metrics.
- Lithium-Ion batteries (LIB) and LIP batteries displayed the lowest CO_2 and SO_2 emissions per kW h.
- Comparative costs for LIB, LIP and ZEBRA batteries were estimated against Nickel–Cadmium cells.

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ABSTRACT

Several ‘Advanced Rechargeable Battery Technologies’ (ARBT) have been evaluated in terms of various energy, environmental, economic, and technical criteria. Their suitability for different applications, such as electric vehicles (EV), consumer electronics, load levelling, and stationary power storage, have also been examined. In order to gain a sense of perspective regarding the performance of the ARBT [including Lithium-Ion batteries (LIB), Li-Ion Polymer (LIP) and Sodium Nickel Chloride (NaNiCl) {or ‘ZEBRA’} batteries] they are compared to more mature Nickel–Cadmium (Ni–Cd) batteries. LIBs currently dominate the rechargeable battery market, and are likely to continue to do so in the short term in view of their excellent all-round performance and firm grip on the consumer electronics market. However, in view of the competition from Li-Ion Polymer their long-term future is uncertain. The high charge/discharge cycle life of Li-Ion batteries means that their use may grow in the electric vehicle (EV) sector, and to a lesser extent in load levelling, if safety concerns are overcome and costs fall significantly. LIP batteries exhibited attractive values of gravimetric energy density, volumetric energy density, and power density. Consequently, they are likely to dominate the consumer electronics market in the long-term, once mass production has become established, but may struggle to break into other sectors unless their charge/discharge cycle life and cost are improved significantly. ZEBRA batteries are presently one of the technologies of choice for EV development work. Nevertheless, compared to other ARBT, such batteries only represent an incremental step forward in terms of energy and environmental performance.

1. Introduction

1.1. Background

Energy systems pervade industrial societies whilst providing heat and power for human development. But they also put at risk the quality and longer-term viability of the biosphere as a result of unwanted, ‘second order’ effects [1]. Arguably the principle environmental side-effect of energy supply is the prospect of global warming due to an enhanced ‘greenhouse effect’ induced by combustion-generated pollutants [1,2]. The most recent (2013) scientific assessment by the *Intergovernmental Panel on Climate Change* (IPCC) states that “it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th Century” [2]. They argue that ‘greenhouse gas’ (GHG) emissions from human activities trap long-wave thermal radiation from the earth’s surface in the atmosphere (not strictly a ‘greenhouse’ phenomena), and that these are the main cause of rises in

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Nomenclature

Abbreviations

ARBT	Advanced Rechargeable Battery Technologies
CCS	carbon capture and storage (facilities)
CO_2	carbon dioxide
defra	UK Department of Environment, Food and Rural Affairs
GHG	greenhouse gas emissions
IPCC	Intergovernmental Panel on Climate Change
ISO	international organisation for standardization
KOH	potassium hydroxide
$LiCoO_2$	Lithium Cobalt Oxide
Li-Ion	Lithium-Ion battery (LIB)
Li-Ion Polymer	Lithium-Ion polymer (LIP) battery
$LiPF_6$	Lithium hexafluorophosphate
LCA	(Environmental) life cycle assessment
NaNiCl	Sodium Nickel Chloride
NaS	sodium–sulphur battery
Ni–Cd	Nickel–Cadmium battery
$NiCl_2$	Nickel Chloride
NiO(OH)	Nickel Oxide
PEIW	Proportion of Energy Inputs that are Wasted
PM	particulate matter
SO_2	sulphur dioxide
USA	United States of America
ZEBRA	ZEolite Battery Research Africa (high-temperature electric batteries that use molten salts as an electrolyte)

climatic temperatures. The IPCC believe that the evidence for anthropogenic climate change has grown since their previous science report in 2007 "thanks to more and better observations, an improved understanding of the climate system response and improved climate models" [2]. Carbon dioxide (CO_2; the main GHG) is thought to have a 'residence time' in the atmosphere of around one hundred years [1,3]. There is consequently a worldwide need to cut down GHG emissions by more than 80% in order to stabilize the climate change at a moderate 2 °C temperature rise by 2050 [4]. This implies major changes in the way in which energy is sourced, generated and consumed in the UK over the coming four decades. Alongside the negative environmental 'side-effects' of heat and power generation there remain concerns about the security of energy supplies into some industrialised countries. The depletion of fossil fuel resources also presents a challenge, particularly in regions dependent upon conventional sources of fossil fuels.

Achieving a carbon reduction target of 80% by 2050 will mean a transition in the systems for producing, delivering and using energy that is not only low carbon, but also secure and affordable, thus resolving the energy policy '*trilemma*' [5]. A portfolio of energy options [5,6] will be required to meet this *trilemma*: energy demand reduction and energy efficiency improvements, carbon capture and storage (CCS) from fossil fuel power plants, and a switch to other low or zero carbon energy sources [various sorts of renewable energy technologies (including wind power, solar photovoltaic arrays, and bioenergy) or nuclear power]. Energy storage devices, such as batteries, will inevitably be required as a means of storing the power generated by 'intermittent' renewable energy sources, such as wind power. In addition, the possibility of introducing battery-powered electric vehicles to replace combustion engine vehicles has also been the subject of serious research effort over recent decades [7–10]. Earlier rechargeable batteries, such as the mature 'lead-acid' battery chemistry, were found to be too bulky and heavy to adequately fulfil either of these roles. Consequently, researchers began investigating alternative battery chemistries that might be more compact and lightweight.

1.2. Batteries as energy storage devices

An electrochemical cell (hereinafter referred to as simply a 'cell') is able to store energy by exploiting the chemical potential difference between its electrodes. A battery consists of a series of cells in series and or parallel. The main components of a cell are: a metal cathode (or negative electrode), a non-metal anode (or positive electrode), and an ionically conductive material (the 'electrolyte'). A cell generates an electric current during discharge by moving to a more stable state through a set of ionic chemical reactions that occur at the surfaces of the electrodes. Positive ions are formed at the negative electrode as metal atoms 'give up' at least one electron. They then flow towards the anode before reacting with this non-metal positive electrode. In order to maintain the principle of electro-neutrality there must also be a flow of electrons (and thus a current) from the cathode to the anode. This process continues until the negative electrode material is exhausted. Primary cells obviously become redundant at this life-cycle stage, whilst secondary (or 'rechargeable') cells can be recharged. The electrolyte is an essential component of an electrochemical cell, since it facilitates the chemical reactions whilst simultaneously preventing a short circuit. This is achieved by producing the electrolyte from a material that conducts ions, but not electrons, thus ensuring the electrons travel through the external circuit and deliver a current to the load [6,7].

'Advanced Rechargeable Battery Technologies' (ARBT) can be characterised as having higher cell voltages and higher energy densities compared to more mature technologies, such as Nickel–Cadmium (Ni–Cd). Research into this new breed of batteries only began 40 years ago [8–11]. One of the factors driving their recent development has been consumer demand for portable electronic equipment, such as mobile phones, mp3 players, tablets, and laptop computers [9,8,11,12,14]. In order to produce truly portable electronic devices, higher energy density batteries are required that are thus lighter and more compact. They constitute a significant proportion of the total mass and volume of such electronic devices.

In order to achieve higher energy densities, researchers have considered more reactive electrode materials, such as lithium and sodium, that exhibit higher electrode potentials and in turn higher cell voltages [13,15]. Higher cell voltages mean that fewer cells need to be joined in series to reach the desired battery voltage, which reduces the volume and mass of the battery and hence increases the energy density. Lithium and sodium are also considerably lighter than more traditional cathode materials, such as lead or cadmium, which further increases their energy density benefit. However, the highly reactive nature of lithium and sodium meant that conventional aqueous electrolytes could not be used. The main alternatives to aqueous electrolytes were a metal salt dissolved in an organic solvent, which gave rise to Li-Ion batteries, and a solid macromolecule or ceramic, which were the technologies that prompted the development Li-Ion Polymer [14] and 'ZEBRA' [13,15] batteries respectively (see Table 1). The latter term was derived from 'ZEolites applied to Battery Research Africa', which was a secretive collaborative project in the mid-1970s – during the 'apartheid' era – between the South African Council