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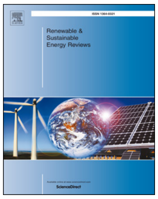

The lithium-ion battery: State of the art and future perspectives

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ABSTRACT

Lithium-ion batteries play an important role in the life quality of modern society as the dominant technology for use in portable electronic devices such as mobile phones, tablets and laptops. Beyond this application lithium-ion batteries are the preferred option for the emerging electric vehicle sector, while still underexploited in power supply systems, especially in combination with photovoltaics and wind power. As a technological component, lithium-ion batteries present huge global potential towards energy sustainability and substantial reductions in carbon emissions. A detailed review is presented herein on the state of the art and future perspectives of Li-ion batteries with emphasis on this potential.

1. Introduction

Lithium-ion (Li-ion) batteries are well known power components of portable electronic devices such as smart phones, tablets and laptops. Nevertheless, these batteries can play a much bigger role in our modern society, most specifically as a key component in the development towards energy sustainability. In combination with the electricity grid, Li-ion batteries could support the integration of high shares of photovoltaic (PV) and wind energy in the power mix by providing storage capacity and ancillary services. Thereby, an electricity mix with a small carbon footprint is the healthy basis for the large implementation of electric vehicles (EV), where Li-ion batteries are the technology of choice. Li-ion batteries also have huge potential for use in off-grid power supply systems, especially in combination with solar home systems (SHS), to provide reliable access to electricity in developing regions. The current state of the art of the Li-ion battery is presented herein, along with its future perspectives with emphasis on the connection between Li-ion batteries and energy sustainability. Thereby, the objective of this work is not only to provide a comprehensive review, but also to emphasize the required actions to be able to exploit the full potential of Li-ion batteries as a key component in the shift from depletable to sustainable resources.

Recent scientific literature includes a comprehensive updated review on energy storage technologies by Gallo et al. [1] and the description of energy storage systems including features, advantages, environmental impacts and applications by Sevket Guney and Tepe [2]. The Li-ion battery technology is discussed in several scientific papers and books; for instance Pistoia details the advances and applications [3], while Warner focuses on the battery-pack design [4], and Światowska and Barboux tackle the different Li-ion battery chemistries with consideration of resource extraction and recycling [5]. Besides taking into consideration recent developments in the field of Li-ion batteries, this manuscript is different from previous works on the topic in its structure and focus, as described next.

A comprehensive review of the state of the art requires detailing the different Li-ion battery chemistries and their key properties. Comparison with other electric energy storage (EES) technologies is relevant, especially with commercially available competitors. This contrast allows to understand the advantages of Li-ion batteries within the broader EES context and how these translate into implementation and market shares. This understanding also reflects on the comparison between the different Li-ion battery chemistries. Thereby, detailing the applications of Li-ion batteries is highly relevant. Of course, there is a big number of applications, but the most relevant ones in terms of market share are portable electronic devices and road-transport, while there is a relevant untapped potential for use in power supply systems. These three applications are the focus of this review. Although the use of Li-ion batteries in portable electronic devices is not related to

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Abbreviations: BMS, Battery management system; CAES, Compressed air energy storage; DoD, Depth of discharge; EES, Electric energy storage; EV, Electric vehicle; GHG, Greenhouse gases; HEV, Hybrid electric vehicle; ICEV, Internal combustion engine vehicle; Li-ion, Lithium-ion; LCA, Life cycle assessment; LCO, Lithium cobalt oxide; LED, Light emitting diode; LFP, Lithium iron phosphate; LMO, Lithium manganese oxide; LTO, Lithium titanate; NCA, Lithium nickel cobalt aluminum oxide; NiCd, Nickel-cadmium; NiMH, Nickel metal hydride; NMC, Lithium nickel manganese cobalt oxide; O&M, Operation and maintenance; PHEV, Plug-in hybrid electric vehicle; PHS, Pumped hydro storage; PV, Photovoltaic; R&D, Research and development; SEI, Solid electrolyte interphase; SHS, Solar home system; SOC, State of charge; SOH, State of health; V2G, Vehicle to grid

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renewable energy and sustainability, data provided herein is relevant for an overall comprehensive review. Proper detailing of the state of the art requires also a briefing on the Li-ion battery industry to summarize the manufacturing process from raw materials to battery cells and packs. Thereby, a closer analysis of potentially critical materials, especially cobalt and lithium, is carried out. Also a briefing on the environmental impact of Li-ion batteries on a life cycle basis is provided. Overall, a state of the art that tackles these mentioned aspects allows for drawing conclusions on future perspectives for Li-ion battery technology. Key issues include how the Li-ion battery market will grow in the different applications and overall, what market shares can be expected for the different chemistries, how this could affect the availability of critical materials, how battery costs are expected to evolve, and which technological improvements are foreseeable. Finally, the potential role of Li-ion batteries in reducing carbon emissions and contributing to energy sustainability is emphasized. There are two major areas addressed herein; i) the use in power supply systems to support the integration of renewable energy sources, and ii) the electrification of road-transport. Most importantly, the required efforts, decisions and practices to exploit this Li-ion battery potential towards energy sustainability are highlighted.

Section 2 provides a brief overview of EES with a short comparison between the Li-ion battery and the closely competing battery technologies. Section 3 highlights the different Li-ion battery chemistries currently commercially available and details the cell key components. Section 4 provides an overview of the Li-ion battery industry, most specifically in terms of the value chain from raw materials to the application. Section 5 details the key properties of the commercially available Li-ion battery chemistries with emphasis on the specific energy and power, durability and safety. An understanding of the strengths and weaknesses of each chemistry provides the basis for identifying usage potentials. Section 6 is dedicated to the Li-ion battery applications, with focus on three major areas: portable electronic devices, road-transport and power supply systems. Although this section initially considers the current commercial state and use, it also takes into account future potentials. Section 7 highlights the Li-ion battery market trends and estimates the demand growth until 2030. A demand breakdown in the different major applications is provided. The implications of this market growth are highlighted, such as the expected cost reductions following the learning curve as well as the market shares of the different Li-ion chemistries. Section 8 provides a summary of the raw materials required to sustain the Li-ion battery industry in line with its expected market growth, and discusses the most critical elements; lithium and cobalt. The need for far reaching battery recovery and recycling schemes is emphasized and the role recycled materials could play is highlighted. Section 9 discusses the life cycle carbon emissions of the Li-ion battery and highlights the path towards properly exploiting this technology in favor of the environment. Finally, Section 10 provides a summary of the key factors and required practices that connect the Li-ion battery with energy sustainability.

2. Overview on electric energy storage

EES systems convert electric power to another form of energy for storage, and then reconvert to electricity when required. EES can also be carried out directly, as in capacitors; these, however, have limited applications due to low specific energy. Energy conversion can be accomplished in many ways; mechanical, thermal, electrochemical, etc. Consequently, there is a long list of EES technologies, of which some are already commercial, while others are still in the research and development (R&D) or demonstration stages. An example of systems that use mechanical energy are pumped hydro storage (PHS), and flywheels. An example of a thermal system is the cryogenic energy storage. Thermal systems are generally characterized by a low round-trip efficiency, due to the low conversion efficiency from thermal energy back to electric power as imposed by the second law of thermodynamics. This results as a very limiting factor for thermal systems on the application level. The widest diversity of EES technologies is to be found in electrochemical systems, which include lead-acid, lithium-ion, nickel-cadmium, nickel metal hydride, sodium-sulphur, vanadium redox, zinc-bromine, nickel-hydrogen, nickel-zinc, molten salt and metal-air batteries, among others. Some batteries operate at ambient temperature, while others, such as molten salt and sodium-sulphur, operate at high temperatures. Another categorization regards solid state batteries and flow batteries, such as vanadium redox and zinc-bromine. Flow batteries are akin to fuel cells. At a commercial level, currently the most relevant rechargeable batteries are lead-acid, Li-ion, nickel metal hydride (NiMH) and nickel-cadmium (NiCd). Table 1 provides a summary of the strengths and weaknesses of these batteries. Further information on lead-acid batteries can be found in [6–8]. The reader is directed to [9–11] and [12] for more details on NiMH and NiCd batteries, respectively.

Several applications require EES, including power supply systems, portable electric and electronic devices, transportation systems, space applications, etc. Each of these applications has different segments; for instance, power supply systems could refer to grid-connected systems, but also to off-grid systems. Grid-connected EES units could be installed as centralized or distributed units. Diverse requirements result from this. Each EES technology has its own performance characteristics that make it more or less suitable for a specific application. Such key properties include energy density, specific energy, specific power, round-trip efficiency, self-discharge rate, calendar and cycle lives, full charge and discharge times, initial cost, O&M requirements and safety. It should also be highlighted that while some EES systems are strictly stationary, others are adaptable to mobile applications. Furthermore, some technologies can be produced as small size units, while others have limited adaptability to that.

PHS is currently the dominating EES technology connected to the electricity grid. PHS is a very mature technology for this use, especially because hydropower has been widely implemented for power generation for over a century. PHS plants have very long calendar lives and satisfactory round-trip efficiencies, while their low energy density is not a setback in this application. Compressed Air Energy Storage (CAES) is still under demonstration for grid-connected uses. There are currently two commercial CAES plants worldwide: one in Germany and the other in the USA, with a total capacity of 400 MW, while a third plant is under development in the UK. The installed capacity of flywheels and super-capacitors is currently insignificant; although there is a recent commissioning of a MW scale plant in the USA, flywheels are still unpopular, and super-capacitors are still at an early stage of adoption. Interest in batteries for grid-connected uses is on the rise; for instance, there are approximately 25,000 domestic installations in Germany in conjunction with PV systems with a total storage capacity of 160 MWh [14]. Further details on EES for stationary applications can be found in [15–18].

While stationary power supply systems have minor EES requirements regarding specific energy and power, these characteristics become a priority in portable electric and electronic devices and in electric mobility. Fig. 1 provides a comparison of different EES technologies and emphasizes the overall advantage of the Li-ion battery in this aspect. Altogether, rechargeable batteries dominate portable and mobile EES applications, and the technologies listed in Table 1 present the highest market shares. Other technologies, such as fuel cells, are expected to represent a growing market already in the near future [14].

3. Li-ion battery chemistries

Of all metals available for battery chemistry, lithium is considered to be the most promising. Apart of being widely available and non-toxic, it is very light and electropositive. This fundamental advantage over other chemistries allows lithium-based batteries to have higher potential for energy storage. Nevertheless, lithium is highly reactive, so