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Life cycle assessment of storage systems: the case study of a sodium/nickel chloride battery

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ABSTRACT

This study assesses the energy and environmental impacts of sodium/nickel chloride batteries, one of the emerging battery technologies for energy storage and smart grids.

The analysis was conducted using the Life Cycle Assessment methodology according to the standards of the ISO 14040 series. The study system was one sodium/nickel cell battery providing electric storage for a photovoltaic system, and the manufacturing, operation, and end-of-life steps were analysed.

The results indicated that the operation step has the greatest energy impact (55–70% of the total), with the manufacturing step, particularly cell manufacturing, contributing the greatest environmental impact (>60% of the total).

This paper makes two original contributions: 1) it presents one of the first LCA analyses of sodium/nickel chloride batteries with the aim of identifying the energy and environmental impacts of this technology; 2) it provides a set of energy and environmental outcomes identifying the "hot spots" of the selected technology that must be carefully considered to upgrade the current efficiency and sustainability of electric storage device standards.

1. Introduction

European energy policy has three objectives: fighting climate change, limiting Europe's dependence on imported hydrocarbons, and providing secure and affordable energy to consumers (Commission of the European Communities, 2007a).

Electricity storage technologies play an important role in facilitating more secure, efficient and sustainable energy sources and forms of energy use (Naish et al., 2008) and in the development of the European power system by increasing the market share of renewable energy and distributed energy generation (European Commission, 2012a).

The European Commission stressed the importance of future research on electricity storage (Commission of the European Communities, 2007b; European Commission, 2012b). In particular, the development of electricity storage systems is included in the electricity grid initiative launched by the European Commission (Entsoe, 2010) and in a list of strategic energy technologies that need to be developed and given higher priority in future research (European Commission, 2012b).

Electrical energy storage is a priority due to the intermittent or variable nature of most forms of low carbon energy generation (Beccali et al., 2008), in contrast with the traditional fossil fuel dominated electricity network. Electrical energy storage offers the potential to store generated electricity and subsequently match supply with demand as required (Naish et al., 2008).

Electricity storage technologies will prepare the electricity grid at all voltage levels for the massive increase in small-scale decentralised and large-scale centralised renewable electricity (European Commission, 2010a) and can help to achieve more sustainable forms of goods production, energy use and mobility. Batteries allow for reductions in energy consumption and carbon dioxide emissions when used for partially and fully electrified vehicles, and represent a storage option for energy generated during off-peak periods by photovoltaic systems and wind turbines (Sullivan and Gaines, 2010; McManus, 2012).

The battery market is already large and has developed to serve mobile and stationary applications. The European and Middle Eastern electricity storage market is approaching 1 billion euro annually (Eurobat, 2012). Improving performance standards will make market demand relevant in the coming decades.

The sodium/nickel chloride battery or ZEBRA (Zero Emission Battery Research Activities) battery (Parkhided, 2006) is an

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Nomenclature

Ac	acidification
BMI	battery management interface
CV	coefficient of variation
DC	direct current
FE	freshwater eutrophication
GER	global energy requirement
FU	functional unit
GWP	global warming potential
HT	human toxicity
LCA	life cycle assessment
LU	land use
MDV	median value
ME	marine eutrophication
MV	medium value
NRE	non-renewable energy consumption
ODP	ozone depletion potential
POF	photochemical ozone formation
PV	photovoltaic panel
RE	renewable energy consumption
SD	standard deviation
TCB	thermo-compression-bonded
TE	terrestrial eutrophication
WRD	water resource depletion
ZEBRA	zero emission battery research activities

innovative energy storage system with applications in electric cars, vans, buses and hybrid vehicles, and marine technologies. Recently, ZEBRA batteries have been used as storage devices in electrical networks and power grids, as telecommunications back-up power, in direct current (DC) supply from photovoltaic and wind generators, and for load levelling (Manzoni et al., 2008; Sudworth, 2001).

The raw electrode materials for ZEBRA batteries are plain salt and nickel, in combination with a ceramic electrolyte and a molten salt. Batteries consist of individual cells enclosed in a thermally insulating package. During the cycling of the battery, internal resistive losses allow for an average operating temperature of 270 °C. When the battery stands idle for prolonged periods (exceeding 24 h), additional heating is required to keep the battery warm (Matheys et al., 2004). The characteristics of ZEBRA batteries are almost independent of ambient temperature, and there is effectively no lower temperature limit for battery operation. In addition, as ZEBRA batteries operate at an average temperature of 270 °C, their use at extremely cold or hot ambient temperatures does not lead to any detrimental effects. This is an advantage with respect to conventional battery systems such as lead-acid batteries, which require more elaborate thermal management at extreme temperatures to avoid reduced battery performance (Parkhided, 2006).

The assessment of the real advantages of using ZEBRA batteries for energy storage must include an analysis of the energy and environmental impacts during the life cycle of these systems.

Even if these batteries have no direct emissions during the operations step and are charged with electricity produced by renewable energy technologies, they cannot be considered totally clean. In fact, batteries consume energy and cause environmental impacts during their life cycle that cannot be neglected. The life cycle thinking approach allows the resource use (raw materials and energy) and environmental burdens related to the full life cycle of the technology to be taken into account (Beccali et al., 2012).

This paper applied the Life Cycle Assessment (LCA) methodology to assess the energy and environmental impacts related to the life cycle of ZEBRA batteries.

This paper makes two original contributions: 1) it presents one of the first applications of LCA to ZEBRA batteries with the aim of identifying the energy and environmental impacts of these technologies; 2) it provides a set of energy and environmental outcomes and identifies the "hot spots" of this technology that must be carefully considered to improve upon the current efficiency and sustainability of electric storage device standards.

2. LCA of batteries: state-of-the-art

To the authors' knowledge, the only LCA of sodium/nickel chloride batteries was carried out within the SUBAT project (Matheys et al., 2004, 2007, 2008; Van den Bossche et al., 2006). This project investigated the environmental impacts (expressed in eco-indicator points) of five different battery technologies used for electric vehicles, including lead-acid, nickel–cadmium, nickel–metal hydride, lithium-ion, and sodium/nickel chloride batteries. The authors selected as functional unit (FU) "a battery enabling the vehicle to cover a specific range (60 km) when driving up to 80% of the depth-of-discharge of the battery", and followed a "cradle to grave" approach, including the manufacturing of the battery, the operation (energy losses due to the battery mass and energy efficiency), and recycling. The results showed that for all studied systems, the manufacturing step has the greatest impact. The manufacturing of lead-acid battery has the highest impact (1091 eco-points), followed by nickel–metal hydride (945 eco-points), nickel–cadmium (861 eco-points), sodium/nickel chloride (368 eco-points), and lithium-ion batteries (361 eco-points). Considering the entire life-cycle and including the negative environmental impact of the recycling process, the nickel–cadmium battery has the highest impact (108 eco-points), followed by lead-acid (100 eco-points), nickel–metal hydride (97.7 eco-points), lithium-ion (55.2 eco-points), and sodium/nickel chloride batteries (46.5 eco-points).

Sullivan and Gaines (2010) presented an interesting literature review of LCA studies of batteries. The authors examined cradle-to-grave studies on lead-acid, nickel–cadmium, nickel–metal hydride, sodium–sulphur, and lithium-ion battery technologies. The results reveal considerable variation in the primary energy consumption for each battery technology due to location effects, dated and missing information, the compilation of data from numerous sources, the effects of different battery applications, and uncertain material requirements and manufacturing processes. The magnitude of primary energy consumption and greenhouse gas emissions increase in the following order: lead-acid (intermediate value: approximately 25 MJ/kg and 91 kg CO_{2eq}/kg), nickel–cadmium (intermediate value: approximately 100 MJ/kg and 240 kg CO_{2eq}/kg), lithium-ion (intermediate value: approximately 170 MJ/kg and 357 kg CO_{2eq}/kg), sodium–sulphur (intermediate value: approximately 180 MJ/kg and 566 kg CO_{2eq}/kg), and nickel–metal hydride (intermediate value: approximately 200 MJ/kg and 524 kg CO_{2eq}/kg).

Other LCA studies have been performed that were not included in the review by Sullivan and Gaines (Majeau-Bettez et al., 2011; Schexnayder et al., 2001;Samaras and Meisterling, 2008; Notter et al., 2010; Zackrisson et al., 2010; McManus, 2012). The results of these studies in terms of global warming potential (GWP), global primary energy requirement (GER) and non-renewable primary energy requirement (NRE) are provided in Table 1.