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ScienceDirect

Energy Procedia 99 (2016) 229 – 234

Energy Procedia

10th International Renewable Energy Storage Conference, IRES 2016, 15-17 March 2016, Düsseldorf, Germany

Recycling of Battery Technologies – Ecological Impact Analysis Using Life Cycle Assessment (LCA)

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Abstract

By the means of life cycle assessment (LCA), the ecological impact of recycling and reuse of materials of three battery technologies was analyzed: lead acid, lithium-ion and vanadium redox flow. Reuse of materials is considered through a cradle to cradle method, meaning the materials which can be reused count as a credit in the LCA. It is shown that the recycling and reuse by a good integrated recycling process lower the ecological impact by up to 49%. Some materials are highly influential. By substitution of these, the ecological impact can be lowered significantly.

Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy

Keywords: storage; battery; LCA; PbA; Li-Ion; VRF; cradle to cradle

1. Introduction

With a growing market for battery technologies, recycling processes become increasingly important. The current literature on the environmental impact of batteries focuses on comparison of different storage systems. Recycling has not been analyzed in this discussion so far [1, 2]. Therefore in this paper the influence of using recycled materials for different battery technologies on the battery system's environmental impact is analyzed.

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Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy
doi:10.1016/j.egypro.2016.10.113

2. Life Cycle Assesment

A life cycle assessment (LCA) is used to analyze the ecological impact of the recycling of three battery technologies. The LCA follows the standards of ISO 14040 [3] and ISO 14044 [4] and was conducted in Umberto NXT LCA [5]. The data to calculate the emissions was derived from the Ecoinvent v3 database [6].

2.1. Goal and Scope Definition

The aim of recycling is primarily the reuse of resources and hence avoiding new extraction. For modelling the reuse, the cradle to cradle method is used. The recycled material is counted as a credit in the primary material phase.The considered battery systems are lead acid battery (PbA), lithium-ion battery (Li-Ion) and vanadium redox flow battery (VRF). A four-person household with a PV storage system is used as a reference case. It is assumed that the storage system has a usable capacity of 4 kWh with 5 kW power and is operated with 200 cycles per year [7, 8]. The assessment period is set as 20 years. Replacement of the battery after reaching the maximum amount of life cycles is considered in the LCA. The functional unit is 1 useable kWh of capacity (kWh_{uc}). The functional unit considers the system lifetime (t) as well as the annual cycles (C_{year}) of the battery. Data sets for material demand and recycling of PbA and Li-Ion battery are retrieved from literature sources. Dataset of VRF battery was derived from unpublished research at Fraunhofer ISE. The ReCiPe 2008 impact model [9] was used in the Life Cycle Impact Assessment (LCIA). By using this method, the impacts are characterized and weighted in ecological points. The more ecological points a product has, the worse is its ecological impact.

2.2. Life Cycle Inventory Analysis (LCI)

In the Life Cycle Inventory Analysis (LCI) material production, energy requirement, energy loss during use phase as well as the transport of the battery from manufacturer to user and from user to recycling stage are summarized for later use in the LCA. The material composition of each battery type is listed in Fehler! Verweisquelle konnte nicht gefunden werden. to Fehler! Verweisquelle konnte nicht gefunden werden. in Appendix A. The LCI is conducted based on the battery weight, which is calculated by the useable capacity and the energy density. The battery characteristics are listed in Fehler! Verweisquelle konnte nicht gefunden werden..

Table 1. Battery Characteristics

	PbA	Li-Ion	VRF
depth of discharge [%]	50 [10]	85 [10]	100 [11]
efficiency	0.9 [12]	0.9 [12]	0.9 [11]
energy density [Wh/kg]	25 [11]	150 [11]	25 [11]
life cycles	2,000 [11]	5,000 [10]	>10,000 [11]
calendar lifetime	10 [11]	20 [11]	20 [11]

It is assumed that the battery is replaced if the maximum number of life cycles is exceeded. In the analyzed case, PbA has to be replaced once while the Li-Ion battery and the VRF are not replaced during the assessment period due to a large number of life cycles. In order to analyze the effect of recycling, the avoided material manufacturing is modelled separately in two scenarios: a best-practice-scenario (1) and a current-practice-scenario (2). In the first scenario the maximum amount of technically reusable resources is considered. The second scenario represents the current state of technology of reusing materials in battery production. Assuming that battery recycling and battery production is a closed loop, every recyclable material will be used as a recycled material in the production phase. The current-practice scenario of PbA battery is similar to the best-practice-scenario: 58% of the materials are reusable, particularly lead and sulfuric acid, while today 57% are actually reused. Li-Ion materials are reusable by 62%, but only 49% are currently being reused. Lithium is not reused due to economic reasons [2]. VRF is not as widely used as Li-Ion and PbA, therefore the recycling process is not yet well-developed. Hence in the current practice scenario recycling will not be considered. Due to the high amount of plastic that is not recyclable, reusable materials have a share of only around 18% of the VRF battery.

2.3. Life Cycle Impact Assesment (LCIA) and Interpretation

The impact categories were modelled using the ReCiPe2008 method [9]. In this method the results of 18 impact categories are converted to ecological points. Particularly the following impact categories have a high influence on the results: climate change, depletion of mineral resources and fossil fuel resources, particular matter formation, human toxicity and agricultural land occupation. Fig. 1 shows the sum of ecological points per kWh storage capacity seperated by the different life cycle phases. The ecological points of the recycling phase include the environmental impact of waste management such as recycling, waste incineration or landfilling. The hatched area demonstrates the saved ecological points by the reuse of materials which otherwise would have been caused in the extraction of primary material. Without any reuse of the materials, the ecological impact of primary material would be larger.

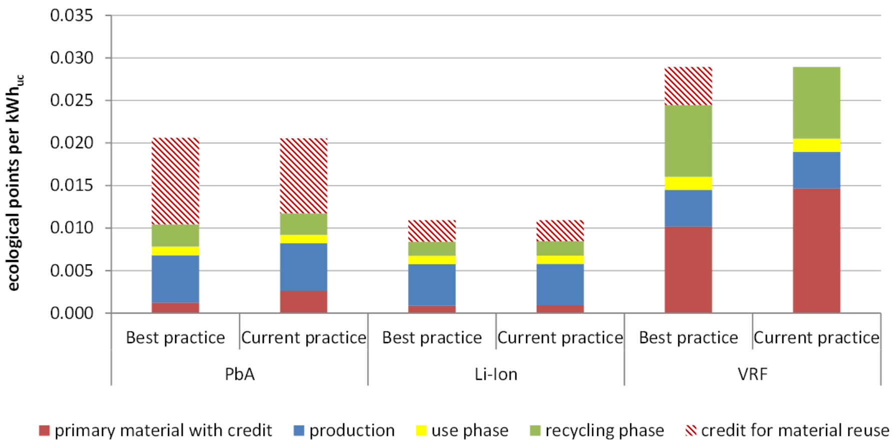

Fig. 1 Ecological Impact of the analyzed battery technologies by lifecycle phase

As can be seen in Fig. 1, the use of recycled materials reduces the ecological points of the PbA battery up to 49% in the best-practice-scenario. The recycling of lead has the greatest effect in reducing the ecological points, especially in terms of metal depletion and human toxicity obtained from recycling. By using the best-practice-scenario instead of the current-state scenario a reduction of 12% of the ecological points can be achieved.

The reuse of materials in the Li-Ion battery decreases the ecological points by 23% in both scenarios. Iron is the most relevant material in this case. The results show only a small difference (less than 1 percentage point) of ecological points for Li-Ion batteries between best-practice-scenario and current-state-scenario. Lithium is not recycled in the current-state-scenario. As a result, the recycling and reuse of lithium has a small ecological impact.

Reuse of materials decreases the ecological points of VRF batteries by only 16%. This is due to the fact that VRF have a high proportion of plastic materials. The recycling of these materials is more complicated and related to higher costs and therefore currently not applied.

Beside the recycling aspect of the materials, the ecological impact of the primary materials was analyzed. Fig. 2 shows the share of materials on material consumption and their effects in ecological points.

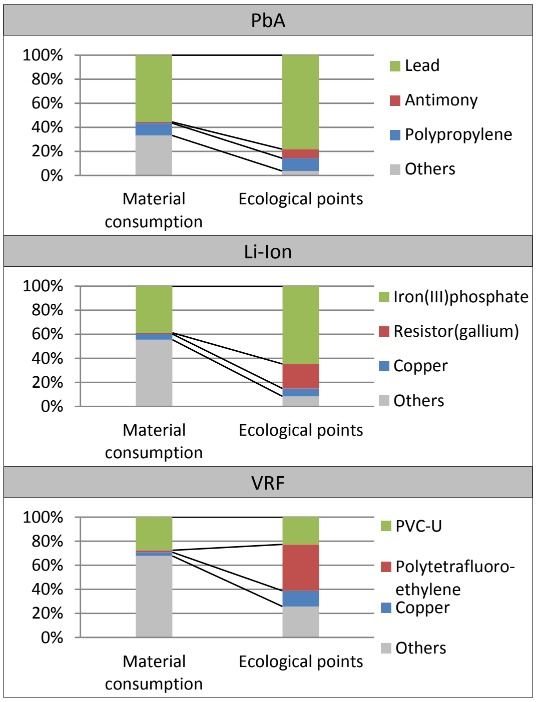

Fig. 2 Share of material in consumption and ecological impact for the analyzed battery technologies.

As can be seen in Fig. 2, the ecological impact of each battery technology is driven by one or two materials mainly. Especially antimony in PbA, gallium in Li-Ion and polytetrafluoroethylene in VRF have a higher share on the ecological impact relative to their shares in the battery's material. Apart from the high potential of recycling there is a potential to reduce the environmental impact by replacing these materials with other materials which have a lower environmental impact.

3. Conclusion and Outlook

The analysis shows that the recycling of lead-acid batteries is very important as the ecological impact can thereby be decreased by almost 50%. The Li-Ion battery has the lowest ecological impact among the analyzed battery technologies. Yet, its ecological impact can still be decreased by more than 20%. For both lead batteries and Li-Ion batteries, state-of-the-art recycling and reuse is close to best-practice. For VRF batteries with a lower market share there is no established recycling process up to date. To capture the potential of a 16% ecological impact reduction, the establishment of a recycling process is therefore highly recommended. It was also shown that few materials which are only used in small portions can have a significant influence on the ecological impact of the battery system. Reduction or substitution of gallium in the Li-Ion battery or polytetrafluoroethylene in VRF should be in the focus of further research in order to continue decreasing the ecological impact of the storage technologies.

Acknowledgments

This work has been financially supported by the state of Baden-Wuerttemberg as part of the Baden Wuerttemberg Research Program Securing a Sustainable Living Environment (BWPLUS).

Appendix A

Table 2. Material composition of Lead Acid Battery [13,14]

Material	Share of battery weight [%]
Lead	25
Lead oxides	35
Polypropylene	10
Sulfuric acid	10
Water	16
Glass	2
Antimony	1

Table 3. Material composition of Li-Ion battery [13,15]

Material	Share of battery weight [%]
Graphite	18
Carbon black	0.005
Cooper	5
Styrene butadiene latex	1
$LiFePO_4$	44
Iron (III) phosphate	42
Lithium carbonate (Li_2CO_3)	10
Carbon	0.009
Carbon dioxid into air	9
Aluminium foil	2
Carbon black	3
Styrene butadiene latex	4
Polypropylene	1
Aluminium foil	1
Dimethoxyethane	16
Lithium salt (Lithium chloride)	3
Resistor (gallium)	1
Polypropylene	1
Polyethylene	0.009

Table 4. Material composition of VanadiumRedox Flow Battery

Material	Share of battery weight [%]
Vanadium	5.31
Sulfuric acid	8.16

Water	28.16
PVC-U	27.47
Aluminium	5.47
Cooper	3.19
Polytetrafluoroethylene	1.45
Graphite	0.52
Stainless steel	1.07
Polyethylene	1.46
Polypropylene	14.99
PVC-U	0.05
Stainless steel	2.71
Polyphenylene sulfide	0.01

Table 5. Energy demand for battery production [16]

Battery Technology	Energy demand [MJ/Wh]
PbA	0.42
Li-Ion	1.20
VRF	0.74

References

[1] Spanos, C., Turney, D. E., and Fthenakis, V. 2015. Life-cycle analysis of flow-assisted nickel zinc-, manganese dioxide-, and valve-regulated lead-acid batteries designed for demand-charge reduction. *Renewable and Sustainable Energy Reviews* 43, 478–494.

[2] Sullivan, J. and Gaines, L. 2012. Status of life cycle inventories for batteries. *Energy Conversion and Management* 58, 134–148.

[3] DIN Deutsches Institut für Normung e.V. 2009. *Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen* 13.020.10, Berlin 13.020.10, 14040.

[4] DIN Deutsches Institut für Normung e.V. 2006. *Umweltmanagment-Ökobilanz- Anforderungen und Anleitungen* 13.020.10, Berlin 13.020.10, DIN EN ISO 14044.

[5] ESU. 2015. *ecoinvent Datenbestand*. http://www.esu-services.ch/de/daten/ecoinvent/. Accessed 15 October 2015.

[6] *Umberto NXT LCA*. ifu Institut für Umweltinformatik Hamburg GmbH, Hamburg.

[7] BSW-Solar. 2013. Informationen zur Förderung von Solarstrom-Speicher. Informationspapier des BSW-Solar, Stand 30.08.2013.

[8] Lorenz, C. and Schröder, G. *Wirtschaftlichkeit Batteriespeicher*. *Berechnung der Speicherkosten und Darstellung der Wirtschaftlichkeit ausgewählter Batteriespeichersysteme*. Leipziger Institut für Energie GmbH, Leipzig.

[9] Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. D., Strujis, J., and van Zelm, R. 2013. *ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*.

[10] Carmen eV. 2015. *Unterscheidungsmerkmale Akkumulatoren*. http://www.carmen-ev.de/sonne-wind-co/stromspeicher/batterien/646-unterscheidungsmerkmale-von-akkumulatoren. Accessed 2 October 2015.

[11] Sauer, D. U., Lunz, B., and Magnor, D. 2013. *Marktanreizprogramm für dezentrale Speicher insbesondere für PV-Strom*. Institut für Stromrichtertechnik und Elektrische Antriebe iSEA RWTH Aachen, Berlin.

[12] Fuhs, M. 2014. Zwei Jahre Speichermarkt. Produktübersicht. *pvmagazine*, 2, 39–56.

[13] Jülch, V., Telsnig, T., Schulz, M., Hartmann, N., Thomsen, J., Eltrop, L., and Schlegel, T. 2015. A holistic comparative analysis of different storage systems using levelized cost of storage and life cycle indicators. *Energy Procedia* 73, 18–28.

[14] Sullivan, J. and Gaines, L. 2010. *A Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs*. Argonne National Laboratory, Illinois.

[15] Zackrisson, M., Avellán, L., and Orlenius, J. 2010. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues. *Journal of Cleaner Production* 18, 15, 1519–1529.

[16] Rydh, C. J. and Sandén, B. A. 2005. Energy analysis of batteries in photovoltaic systems. Part I: Performance and energy requirements. *Energy Conversion and Management* 46, 11-12, 1957–1979.