Journal of Energy Storage 19 (2018) 213–225

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows

Silvia Bobba[a,b], Fabrice Mathieux[a,*], Fulvio Ardente[a], Gian Andrea Blengini[a,b], Maria Anna Cusenza[c], Andreas Podias[d], Andreas Pfrang[d]

[a] European Commission, Joint Research Centre (JRC), Directorate for Sustainable Resources, Land Resources Unit, Via E. Fermi 2749, 21027 Ispra, VA, Italy
[b] Politecnico di Torino, Department of Environment, Land and Infrastructure Engineering, Corso Duca degli Abruzzi, 24–10129 Torino, Italy
[c] Università degli Studi di Palermo, Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici (DEIM), viale delle Scienze, 90128 Palermo, Italy
[d] European Commission, Joint Research Centre (JRC), Directorate for Energy, Transport and Climate, Energy Storage Unit, Westerduinweg 3, 1755 LE Petten, The Netherlands

ARTICLE INFO

Keywords:
Environmental impact
Life Cycle Assessment (LCA)
Battery second-use
Reuse
Repurposing
Electric Vehicles (EVs)

ABSTRACT

After their first use in electric vehicles (EVs), the residual capacity of traction batteries can make them valuable in other applications. Although reusing EV batteries remains an undeveloped market, second-use applications of EV batteries are in line with circular economy principles and the waste management hierarchy. Although substantial environmental benefits are expected from reusing traction batteries, further efforts are needed in data collection, modelling the life-cycle stages and calculating impact indicators to propose a harmonized and adapted life-cycle assessment (LCA) method.

To properly assess the environmental benefits and drawbacks of using repurposed EV batteries in second-use applications, in this article an adapted LCA is proposed based on the comparison of different scenarios from a life-cycle perspective. The key issues for the selected life-cycle stages and the aspects and parameters to be assessed in the analysis are identified and discussed for each stage, including manufacturing, repurposing, reusing and recycling.

The proposed method is applied to a specific case study concerning the use of repurposed batteries to increase photovoltaic (PV) self-consumption in a given dwelling. Primary data on the dwelling's energy requirements and PV production were used to properly assess the energy flows in this specific repurposed scenario: both the literature search performed and the results obtained highlighted the relevance of modelling the system energy using real data, combining the characteristics of both the battery and its application. The LCA results confirmed that the environmental benefits of adopting repurposed batteries to increase PV self-consumption in a house occur under specific conditions and that the benefits are more or less considerable depending on the impact category assessed. Higher environmental benefits refer to impact categories dominated by the manufacturing and repurposing stages. Some of the most relevant parameters (e.g. residual capacity and allocation factor) were tested in a sensitivity analysis. The method can be used in other repurposing application cases if parameters for these cases can be determined by experimental tests, modelling or extracting data from the literature.

1. Introduction

A rapid increase in the worldwide stock of electric vehicles (EVs) is expected in the near future [1–3]. Lithium-ion (Li-ion) chemistry is recognized as the dominant battery technology available for EVs [4]. Therefore, an increased demand is expected for high-energy density traction Li-ion batteries. Due to the lifetime of batteries, this trend will inevitably lead to an increase of flows of waste batteries that need to be collected and treated [4,5] and to a substantial modification of the battery value chain (e.g. collection schemes and end-of-life treatment).

Although current experience is still very limited, once such used batteries are collected, recycling is presently the most common end-of-life (EoL) treatment for used EV batteries. However, a new EoL option concerning the reuse of such batteries is emerging worldwide. This is because the remaining capacity of the batteries after their use in EVs ranges from 60% to 80% of their initial capacity and it can be potentially exploited in sectors other than the automotive sector [6–8]. Recent studies and pilot projects state that extending the lifetime of EV

* Corresponding author.
E-mail address: fabrice.mathieux@ec.europa.eu (F. Mathieux).

https://doi.org/10.1016/j.est.2018.07.008
Received 31 January 2018; Received in revised form 14 June 2018; Accepted 9 July 2018

batteries by using them in other types of application can lead to various benefits, including economic, environmental and social. However, because of the novelty of the topic and the limited availability of data, more investigations are needed to confirm and quantify such benefits [6,9].

In Europe, the relevance of reuse as a waste management strategy to prevent wastage and contribute to the EU's jobs and social agenda has been acknowledged by both the waste management hierarchy, defined in 2008 by the Waste Framework Directive [10] and in 2015 by the European Commission's Circular Economy Action Plan [11]. The End-of-life vehicles (ELV) and the Batteries Directives [12,13] support the recycling of batteries after they have been used in EVs. However, several stakeholders currently support the inclusion of a "reuse" option in the EU Batteries Directive (e.g. the European Association for Advanced Rechargeable Batteries, the European Portable Battery Association, the Association of European Automotive and Industrial Battery Manufacturers), as shown, for instance, during a panel discussion at the 22nd International Congress for Battery Recycling (ICBR 2017). Moreover, in the framework of the Circular Economy Action Plan [11], the Innovation Deal concerning the reuse of EV batteries, recently launched by the European Commission[1] [14], demonstrates that legislators and innovators have increasing interest in this field.

A wide-ranging analysis of the scientific and technical literature suggests that the absence of a clear framework for the second use of EV batteries can result in imprecise or interchangeable terminology, such as "reuse", "repurpose" or "refurbish" [15–17]. However, some terminology proposals exist: for example, according to Ardente et al. [18], "reuse" implies that a product is being utilized for the purpose for which it was conceived, and "repurposing" refers to utilizing products in other, different applications (often referred to as "second-use" applications). Therefore, consistent with the aim of the study, in this paper "repurposed EV batteries" refer to EV batteries that, after their use in EVs, are tested and prepared for use for energy storage in a second-use application.

Existing international and European industrial activities, research and development (R&D) projects, and demonstration projects indicate that the second use of Li-ion batteries is of great interest to several actors in the value chain [19]. Nevertheless, several barriers were identified in different studies: 1) regulatory barriers, mainly relating to the absence of a clear framework for definition of battery reuse [20–25]; 2) technical barriers, related to the lack of data about battery performance and degradation [9,20]; 3) economic barriers, such as uncertainty with regard to economic returns and the market for EV batteries, and the absence of economic incentives [20–22,25–27], and 4) safety barriers, such as hazards and fire risks associated with removing and handling Li-ion batteries [9,25].

From a complementary economic perspective, several authors have studied the benefits of reusing EV batteries, especially in relation to decreases in EV costs as a result of longer battery service lives [9,28,29]. From a legal perspective, more efforts are required to provide "an adequate legal framework for second-life applications", for example in the forthcoming review of the Batteries Directive [30].

To support the EV second-use regulatory framework, the sustainability of extending the lifetime of EV batteries to second-use applications should be demonstrated. Thus, the three sustainable development pillars – economic, social and environmental – should be assessed[2], but only a few studies in the literature integrate an economic assessment with social and environmental aspects related to the second-use of batteries [31]. In the scientific literature, an increasing number of studies are available concerning environmental aspects; however, they show major differences in the environmental analysis methodology adopted (see Section 2).

In the context of the sustainability assessment, this paper contributes to developing a method for assessing the environmental impacts of adopting repurposed EV batteries for other applications. In particular, the method develops an indicator based on the life-cycle impacts of the system in which repurposed batteries are used, considering all of the value chain stages affecting second use.

In line with this goal, Section 2 summarizes some relevant results from the literature, identifying the key aspects of repurposed EV batteries and their use in the specific second-use applications that are considered in the assessment. Section 3 describes the proposed method, the specific scenarios used to develop it and the relevant analysis parameters. The method is then used to assess the performance of a repurposed EV battery in specific housing configurations (Section 4) for which the energy and the environmental aspects are discussed in detail.

2. Literature review on environmental assessment of reuse

Although the second use of batteries has been studied less often than recycling [32], environmental benefits are generally expected [6,9,32,33].

Several studies in the literature have estimated the environmental performances of the systems in which batteries have been used, based on a life-cycle approach. However, comparisons of these studies are difficult because of major differences in scope (e.g. different second-use applications and different product systems analysed), system boundaries (e.g. different life-cycle stages and different geographical boundaries), life-cycle inventory data used for the life-cycle stages (e.g. energy flow of the use stage, battery degradation patterns and expected battery lifetime), and impact assessment methods considered. Despite the efforts dedicated to developing a life-cycle assessment (LCA) in this area, guidelines or harmonized approaches do not yet exist [34]. This is a major barrier to identifying when the repurposing of EV batteries brings environmental benefits. The next paragraphs further analyse each of these diverging practices in the literature.

Repurposed Li-ion batteries could be used in several applications (e.g. utility operations, commercial and residential buildings) depending on their characteristics [35]. An analysis of recent European and international industrial activities, research and innovation projects and research studies, using repurposed EV batteries, revealed that the most frequently reviewed applications are those for integrating renewable energy into the grid. Examples are smoothing for renewable energy systems [27,29,36,37]; energy storage of a single wind turbine/photovoltaic (PV)/battery system [36]; off-grid PV vehicle charging system [38]; and diurnal energy shifting, allowing intermittent renewable energy sources to be used more widely (e.g. wind and solar) [39]. Other applications relate, for example, to transmission and distribution upgrade [6,40,41], regulation services [6,28,40] and supplemental reserves [26,33,36,39,42]. Depending on the type of second use being analysed, repurposed EV batteries for storage applications could substitute non-Li-ion batteries (e.g. lead-acid batteries) or other energy sources (e.g. fossil fuels) and support a shift to renewable energy [21,26,27,39].

The use phase of energy storage is generally recognized as extremely important [26,27], and consequently it is relevant to properly defining both the application in which the storage is used and the associated system boundaries. The lifetime of a battery should take into account battery degradation, which depends on both the battery's initial characteristics (e.g. first life, residual capacity, efficiency) and the specific second-use conditions (e.g. load profile, temperature). The lack of data in this field is reflected by the fact that, in other studies, the estimated life of a battery during its second use is based on

[1] "The Innovation Deal focuses on propulsion batteries and will assess whether existing EU legal provisions and the transposition to national or regional law hamper the use of batteries in a second-life application or otherwise discriminate any technology that might be necessary for second-life applications" [14].

[2] https://ec.europa.eu/environment/efe/content/long-term-vision-sustainable-future_en.