EVALUATION ON PERFORMANCE AND ENVIRONMENTAL IMPACTS OF THE REVIVED INDUSTRIAL LEAD-ACID BATTERIES

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ABSTRACT

In Malaysia, various types of batteries have evolved, as the energy revolution from internal combustion engines to electric motors continues to progress due to increased environmental awareness. The lead-acid battery is one of the preferred choices to run the electric motor for industrial applications, such as electric forklifts and golf carts. However, the problem with lead-acid batteries is that their performance degrades over time, as the internal resistance of the battery increases due to the presence of lead sulphates ($PbSO_4$) . Low-capacity batteries are recycled through the pyrometallurgical method contributing to carbon emissions ($kgCO_2e$). As an alternative, regeneration technology has been introduced to revive low-capacity batteries using high-current pulses of up to 450 A to dissolve lead sulphates on the plates. The results from the experimental work that has been conducted, this technology can enhance battery capacity up to 96% and can also improve battery longevity. Using the life-cycle assessment (LCA) method, this study evaluated the carbon footprints ($kgCO_2e$) of recycling and reviving lead-acid batteries. The carbon footprints ($kgCO_2e$) were evaluated gate-to-gate with a functional unit of 1,315 kg lead-acid batteries. The findings from SimaPro simulator software show that recycling a lead-acid battery generated 131% more carbon footprints ($kgCO_2e$) than from reviving it. Besides that, the process and environmental costs of both methods were compared using the environmental life-cycle costing (E-LCC) approach. The comparative results from the SimaPro simulator software show that reviving lead-acid batteries was 79% more economical than recycling them. Lastly, in response to environmental awareness, this study proposed a policy framework for lead-acid battery distribution and waste management to assist in handling the batteries.

ABSTRAK

Di Malaysia, pelbagai jenis bateri telah berkembang, kerana revolusi tenaga daripada enjin pembakaran dalaman kepada motor elektrik terus berkembang berikutan peningkatan kesedaran alam sekitar. Bateri asid plumbum ialah salah satu pilihan untuk menjalankan motor elektrik untuk aplikasi industri, seperti forklif elektrik dan kereta golf. Walau bagaimanapun, masalah dengan bateri asid plumbum ialah prestasinya merosot dari semasa ke semasa, kerana rintangan dalaman bateri meningkat disebabkan oleh kehadiran sulfat plumbum ($PbSO_4$) . Bateri berkapasiti rendah dikitar semula melalui kaedah *pyrometallurgical* yang menyumbang kepada pelepasan karbon ($kgCO_2e$). Sebagai alternatif, teknologi penjanaan semula telah diperkenalkan untuk menghidupkan semula bateri berkapasiti rendah menggunakan denyutan arus tinggi sehingga 450 A untuk melarutkan sulfat plumbum pada plat. Hasil daripada kerja-kerja eksperimen yang telah dijalankan, teknologi ini dapat meningkatkan kapasiti bateri sehingga 96% dan juga dapat meningkatkan jangka hayat bateri. Menggunakan kaedah penilaian kitaran hayat (LCA), kajian ini menilai jejak karbon ($kgCO_2e$) kitar semula dan menghidupkan semula bateri asid plumbum. Jejak kaki karbon ($kgCO_2e$) dinilai dari pintu ke pintu dengan unit berfungsi 1,315 kg bateri asid plumbum. Penemuan daripada perisian simulator SimaPro menunjukkan bahawa mengitar semula bateri asid plumbum menjana 131% lebih banyak jejak karbon ($kgCO_2e$) berbanding daripada menghidupkannya semula. Selain itu, proses dan kos persekitaran kedua-dua kaedah telah dibandingkan menggunakan pendekatan pengekosan kitaran hayat alam sekitar (E-LCC). Hasil perbandingan daripada perisian simulator SimaPro menunjukkan bahawa menghidupkan semula bateri asid plumbum adalah 79% lebih menjimatkan daripada mengitar semulanya. Akhir sekali, sebagai tindak balas kepada kesedaran alam sekitar, kajian ini mencadangkan rangka kerja dasar untuk pengedaran bateri asid plumbum dan pengurusan sisa untuk membantu dalam mengendalikan bateri asid plumbum.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	-	Ampere
Ah	-	Ampere Hour
ASEAN	-	Association of South-East Asian Nations
BOL	-	Beginning of Life
CC	-	Constant Current
CC-CV	-	Constant Current-Constant Voltage
CV	-	Constant Voltage
CH_4	-	Methane
CO_2	-	Carbon Dioxide
EOL	-	End of Life
E-LCC	-	Environmental Life-Cycle Costing
GHG	-	Greenhouse Gas
HFCs	-	Hydrofluorocarbons
H_2O	-	Water
H_2SO_4	-	Sulphuric Acid
I_{pulse}	-	Pulse Current
LCA	-	Life-Cycle Assessment
LCI	-	Life-Cycle Inventory
LCIA	-	Life-Cycle Impact Assessment
MATLAB	-	Matrix Laboratory
MCC	-	Multi-stage Constant Current
$MgSO_4$	-	Magnesium Sulphates
Na_2SO_4	-	Sodium Sulphates
N_2O	-	Nitrous Oxide
Pb	-	Lead Metal
PbO_2	-	Lead Oxide
$PbSO_4$	-	Lead Sulphate

PFCs	-	Perfluorocarbons
pt.	-	Point
$R_{internal}$	-	Internal Resistance
SF_6	-	Sulphur Hexafluoride
SG	-	Specific Gravity
SLI	-	Starting-Lighting-Ignition
SOC	-	State of Charge
V	-	Voltage
$V_{constant}$	-	Constant Voltage
wt.%	-	Percentage by weight

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CHAPTER 1

INTRODUCTION

1.1 Background of study

The global community has recently become concerned about an increase in carbon dioxide (CO_2) and other greenhouse effects on the climate. Human-caused greenhouse gas emissions, primarily from the combustion of fossil fuels for electricity generation, have increased the greenhouse effect and contributed to global warming [1]. Six greenhouse gases (GHGs) are involved in heat traps in the atmosphere, according to the Kyoto Protocol, which are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) [2]. Carbon footprints (kgCO_2e) is calculated by taking into account all GHG emissions throughout a product's life cycle and is expressed in CO_2 equivalent. The report from the International Energy Agency (2019) stated that the Association of South-East Asian Nations (ASEAN) contributed 5% of the total global carbon emissions (kgCO_2e), with Malaysia ranking fourth (236.6 MtCO_2e) in the ASEAN region, as shown in Figure 1.1.

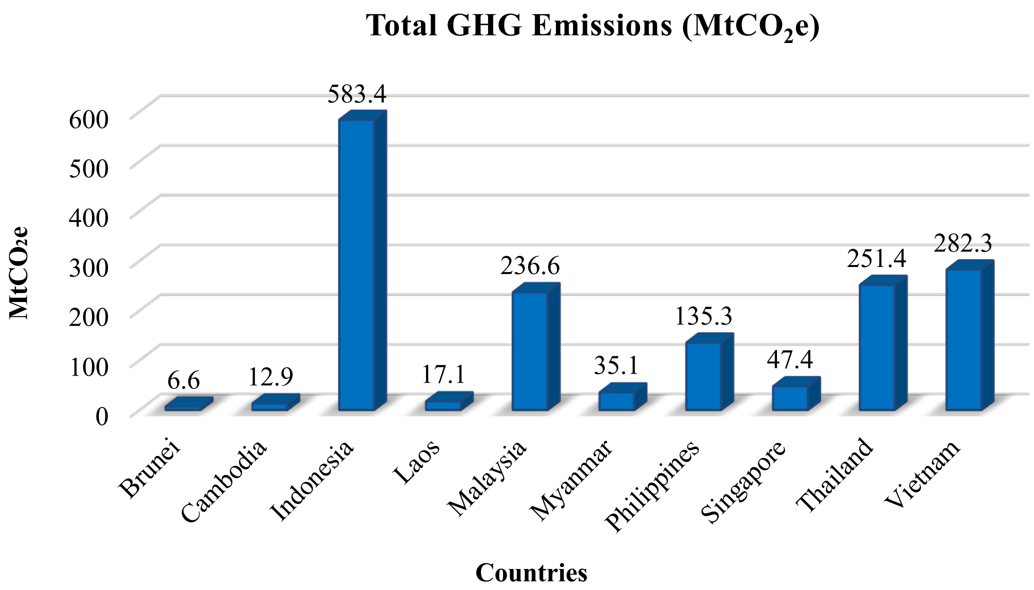

Figure 1.1: Total carbon footprints (kgCO_2e) of ASEAN countries [3]

The worldwide demand for energy storage devices is growing with various types of rechargeable batteries appearing in the market. The important characteristics of a rechargeable battery are that its charging and discharging, transform electric energy into chemical energy and back again into electric energy. The lead-acid battery is one of the first rechargeable batteries built for various applications in different industrial and non-industrial areas [4][5]. Generally, the lead-acid battery is composed of lead metal (Pb) as the negative plate and lead oxide (PbO_2) as the positive plate, both of which are immersed in an electrolyte of sulphuric acid (H_2SO_4) and water (H_2O) solution [6]. The primary raw materials in these batteries are lead metal, polypropylene polymer and sulphuric acid. Lead accounts for 60% of the total mass of a battery. Lead-acid batteries are widely used as a chemical power source around the world because of their stable voltage, safety, reliability, low cost, broad application range and high recycling rate [7].

However, the global expansion of the lead-acid battery industry has been linked to environmental and public health issues, particularly the emission of lead, which is classified as one of the top-heavy metal pollutants [7]. One of the major disadvantages of lead-acid batteries is the gradual loss of capacity caused by the build-up of lead sulphates on the plates, which increases the internal resistance of the battery [8][9]. When the batteries lose their effectiveness, they are classified as used lead-acid batteries, also known as hazardous waste [10]. Some of the materials in the used lead-acid batteries, are either being recycled to make a new battery or will be disposed. If lead-acid batteries are not disposed of properly, they will cause severe environmental pollution [11][12]. The greenhouse gases emitted during the recycling process contribute to global warming.

Numerous studies have been conducted over the years to improve the performance of lead-acid batteries, with the goal of increasing their life cycle and decreasing the number of batteries recycled. One alternative is the regeneration technology of applying high-current pulses with constant voltage to restore the capacity of lead-acid batteries [13]. The high-current pulses generate instantaneous heat to force electrons to move and a chemical reaction to occur. As a result, the lead sulphate attached to the plates break down and revert to the active electrolyte. The result is the plates' area being free of lead sulphates, and the battery capacity is restored and becomes sustainable.

The life-cycle assessment (LCA) approach is a benchmarking tool for assessing the environmental impact of products, processes, and services throughout their life cycle, from raw material collection to manufacturing, transportation, use, and disposal (cradle-to-grave) [14]. LCA is used to determine the environmental impact of the lead-acid battery manufacturing process over its entire life cycle, as well as the key factors driving the environmental impact. The application of LCA in the lead-acid battery industry can help to reduce pollution in the battery industry.

This research studied the effect of internal resistance on battery performance by studying the charging and discharging characteristics of lead-acid batteries with varying internal resistance conditions. The lead-acid battery block in MATLAB/Simulink was used in the simulations, and the internal resistance values were based on actual data from the industry. This research presents the concept and process of regeneration technology using high-power pulses ($V_{constant}$, I_{pulse}) as the alternative to revive lead-acid batteries. The performances of the batteries before and after the application of regeneration technology would be shown. Besides that, this study dealt with the environmental impacts of recycling and reviving lead-acid batteries using the pyrometallurgy and regeneration methods, respectively. LCA is used to identify the carbon footprints (kgCO_2e) for both methods. This study also evaluated the process and environmental costs of reviving and recycling lead-acid batteries using the E-LCC method. E-LCC was developed in order to be compatible with LCA and it evaluates costs incurred throughout a product's life cycle. Finally, this report also proposed a policy framework for waste battery management to assist in handling lead-acid battery disposal.

1.2 Problem statement

The concerning state of fossil depletion, combined with the growing awareness of deteriorating climatic conditions, has recently prompted the development of alternative energy technologies. The lead-acid battery technology is one of the most widely used and cost-effective electrochemical technologies, with a much more comprehensive range of applications [15]. However, the primary concern of lead-acid batteries is the increase in internal resistance caused by lead sulphates that accumulates on the batteries' plates during the discharging process, which contributes to the shorter lifespan of the batteries. As the charging and discharging process continues, the lead sulphates become thicker and cover the conductive area of the plates, resulting in capacity loss [9]. It is estimated that the majority of lead-acid batteries discarded each year suffer from lead plates clogged with lead sulphates. As millions of tonnes of spent batteries are discarded each year over the last two decades, battery recycling has become significant and imperative [16]. Recycling lead-acid batteries emits a significant amount of GHGs, which have impacts on both the environment and human health. Furthermore, low-capacity lead-acid batteries have an economic impact because there will be costs incurred for battery reproduction and remanufacturing.

Therefore, the formation of lead sulphates, which increases lead-acid batteries' internal resistance, was analysed in this research. The characteristics of charging and discharging the lead-acid batteries at various internal resistance values were investigated. In addition, the reviving of lead-acid batteries using high-power pulses ($V_{constant}$, I_{pulse}) would be analysed as one of the selective methods to break lead sulphates on the plates, thus prolonging the lifespan of the batteries. This study also employed LCA to compare the environmental impact in terms of carbon footprints ($kgCO_2e$) between conventional recycling and the process of reviving lead-acid batteries using regeneration technology. Finally, the process and environmental costs of recycling and reviving using regeneration technology was assessed using the E-LCC method.

1.3 Hypothesis

In this study, the recycling and reviving of lead-acid batteries were analysed and compared. If the application of regeneration technology with high-power pulses ($V_{constant}$, I_{pulse}) can decrease the number of recycled lead-acid batteries, then it can reduce the carbon footprints ($kgCO_2e$) that impacts the environment.

1.4 Aim

This study aimed to analyse the condition of lead-acid batteries after implementing the regeneration method using high-power pulses ($V_{constant}$, I_{pulse}). Moreover, the goals of this study were also to evaluate the environmental and economic impacts of recycling and reviving 1,315 kg lead-acid batteries using LCA and E-LCC approaches. Lastly, a policy framework would be proposed for managing lead-acid batteries, with the aim of reducing the number of disposed lead-acid batteries.

1.5 Objectives

This research work embarked on the following objectives:

I. To observe and evaluate lead-acid batteries' condition based on significant parameters before and after the reviving process through regeneration technology.

II. To assess the carbon footprints ($kgCO_2e$) from the processes of recycling and reviving lead-acid batteries through pyrometallurgy and regeneration, respectively, using the LCA approach.

III. To evaluate the process and environmental costs of recycling and reviving lead-acid batteries using the E-LCC method.

1.6 Scope of study

The scopes of the research are as follows:

I. Analysing the performance of lead-acid battery during charging and discharging based on the following parameters and conditions:
   i. The battery was limited to 48 V/775 Ah lead-acid battery.
   ii. Internal resistance values for the simulations were referred from industry data (Renewcell (M) Sdn Bhd), which were 0.0011 Ω, 0.0049 Ω and 0.0153 Ω.
   iii. The simulations used the MATLAB/Simulink simulator software.
   iv. The charging of the lead-acid battery used the constant current – constant voltage (CC-CV) method.
   v. The discharging of the lead-acid battery used controlled voltage source as constant load.
   vi. The focus was on evaluating the values of the state of charge (SOC), voltage, current, charging power and power capacity of the batteries.

II. Analysing the performance of lead-acid batteries before and after the reviving process based on the following parameters and conditions:
   i. The charging process used the RNC 48100 battery charger.
   ii. The discharging process, also known as the capacity test, used the RCL 4830 battery discharger.
   iii. For measuring specific gravity (SG) the ISBA-5218-A battery analyser refractometer was used.
   iv. The regeneration process used MacBatec Midi Regenerator.
   v. The focus was on evaluating the values of voltage, capacity, discharge time and SG of the batteries.

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APPENDIX I

LIST OF PUBLICATION

1) **Ibrahim, N.S.M**, Ponniran, A., Rahman, R.A., Martín, M., Yassin, A.M., Eahambram, A., & Aziz, M.H. (2020). Parameters Observation of Restoration Capacity of Industrial Lead-acid Battery Using High Current Pulses. International Journal of Parallel, Emergent and Distributed Systems, 11, 1596.

APPENDIX J

VITA

The author was born on 25 July 1995, in Jerantut, Pahang, Malaysia. She completed her secondary education at Sekolah Agama Menengah Tinggi Tengku Ampuan Rahimah (SAMTTAR) and Sekolah Agama Menengah Bestari (SAMBEST), Selangor, Malaysia. After her secondary education, she earned admission into the matriculation programme at Johor Technical Matriculation College (KMTJ) in Pontian, Johor. After completing the matriculation programme, she continued to pursue her undergraduate studies at one of the premier local technical universities, Universiti Tun Hussein Onn Malaysia (UTHM), located in Batu Pahat, Johor. She graduated with a bachelor's degree in Electrical Engineering with Honours in 2019. After completing her degree, she applied to join the university as a Graduate Research Assistant (GRA) in the Department of Electrical Power, under the Faculty of Electrical and Electronic Engineering (FKEE). Currently she is in her final year to complete her master's degree. Her current research topics are related to lead-acid batteries, which involved the de-sulphate method, LCA and E-LCC.