LIFE CYCLE ASSESSMENT OF VEHICLE BATTERIES

Miss Chuleekorn Sawettavong

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นางสาวชุลีกร เศวตวงษ์

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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By	Miss Chuleekorn Sawettavong
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Thesis Advisor	Associate Professor Prasert Pavasant, Ph.D.

Accepted by the Graduate School, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

……………………………………………………Dean of the Graduate School

(Associate Professor Amorn Petsom, Ph.D.)

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(Assistant Professor Chantra Tongcumpou, Ph.D.)

……………………………………………………Thesis Advisor

(Associate Professor Prasert Pavasant, Ph.D.)

……………………………………………………Examiner

(Assistant Professor Chanathip Pharino, Ph.D.)

……………………………………………………Examiner

(Premrudee Kanchanapiya, Ph.D.)

……………………………………………………External Examiner

(Punjaporn Weschayanwiwat, Ph.D.)

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งานวิจัยนี้ทำการประเมินวัฏจักรชีวิตของแบตเตอรี่รถยนต์ 3 ชนิด ได้แก่ ชนิดไม่เติมน้ำกลั่น ชนิดลูกผสม และชนิดเติมน้ำกลั่น การประเมินผลกระทบทางสิ่งแวดล้อม 5 ประภท ได้แก่ ภาวะโลกร้อน ภาวะความเป็นกรด การลดลงของโอโซน การปลดปล่อยโลหะ และการใช้พลังงาน โดยกำหนดให้การคำนวณปริมาณการปลดปล่อยก๊าซเรือนกระจก ก๊าซต่างๆ โลหะ และการใช้พลังงาน ตลอดวัฏจักรชีวิตของแบตเตอรี่รถยนต์คือ แบตเตอรี่รถยนต์ 1 ลูก (12 โวลต์) ที่ความจุไฟฟ้าไม่ต่ำกว่า 75 แอมแปร์-ชั่วโมง สำหรับรถกระบะที่มีอายุการใช้งาน 4 ปี ในกรณีทั่วไปแบตเตอรี่รถยนต์ชนิดไม่เติมน้ำกลั่น ชนิดลูกผสม และชนิดเติมน้ำกลั่น ปลดปล่อยก๊าซเรือนกระจก 62.3 83.4 และ 119 กิโลกรัมคาร์บอนไดออกไซด์เทียบเท่าตามลำดับ ปลดปล่อยก๊าซซัลเฟอร์ไดออกไซด์ 0.961 1.21 และ 1.66 กิโลกรัมซัลเฟอร์ไดออกไซด์เทียบเท่าตามลำดับ แบตเตอรี่รถยนต์ชนิดชนิดไม่เติมน้ำกลั่นปลดปล่อยก๊าซคลอโรฟลูออโรคาร์บอน 4.35E-06 ตามด้วย 5.67E-06 และ 7.99E-06 กิโลกรัมคลอโรฟลูออโรคาร์บอนเทียบเท่าสำหรับชนิดลูกผสมและชนิดเติมน้ำกลั่นตามลำดับ ปลดปล่อยโลหะ 4.54E-02 (ชนิดไม่เติมน้ำกลั่น), 5.66E-02 (ชนิดลูกผสม), และ 7.44E-02 (ชนิดเติมน้ำกลั่น) กิโลกรัมตะกั่วเทียบเท่าตามลำดับ ค่าพลังงานความร้อนต่ำ 1,072 เมกะจูล สำหรับแบตเตอรี่รถยนต์ชนิดไม่เติมน้ำกลั่น 1,462 เมกะจูลสำหรับชนิดลูกผสมและ 2,116 เมกะจูล สำหรับแบตเตอรี่ชนิดเติมน้ำกลั่น ซึ่งจะเห็นได้ว่าแบตเตอรี่ชนิดเติมน้ำกลั่นส่งผลต่อสิ่งแวดล้อมมากกว่าชนิดลูกผสมและไม่เติมน้ำกลั่นอย่างมีนัยสำคัญตามลำดับ โดยขั้นการได้มาซึ่งวัตถุดิบและขั้นการจัดการของเสียเป็น 2 สาเหตุสำคัญที่ส่งผลกระทบทางสิ่งแวดล้อมทุกประเภท ตะกั่วเป็นวัตถุดิบหลักที่ทำให้มีการปลดปล่อยก๊าซเรือนกระจก ก๊าซต่างๆ โลหะ และการใช้พลังงานในขั้นของการได้มาซึ่งวัตถุดิบ ส่วนขั้นการกำจัดของเสียนั้นโซเดียมไฮดรอกไซด์ที่ใช้สำหรับสะเทินกรดซัลฟิวริกให้เป็นกลางก่อนปล่อยสู่แหล่งน้ำเป็นสาเหตุหลักที่ส่งผลกระทบทางสิ่งแวดล้อม งานวิจัยนี้ได้เสนอแนวทางในการลดผลกระทบทางสิ่งแวดล้อม 2 วิธี ได้แก่ 1) การรีไซเคิลแบตเตอรี่ที่ถูกนำกลับของแบตเตอรี่ที่ใช้แล้ว 2) การเปลี่ยนวัตถุดิบโดยใช้แคลเซียมไฮดรอกไซด์ในการสะเทินกรดแทนโซเดียมไฮดรอกไซด์ งานวิจัยนี้ชี้ให้เห็นว่าการรีไซเคิลแบตเตอรี่ที่ใช้แล้วและถูกนำกลับมาในเปอร์เซนต์ที่เพิ่มขึ้น (จากปกติ 75% เป็น 100%) พบว่าทางเลือกในการลดผลกระทบทางสิ่งแวดล้อมแบ่งเป็น 3 กรณี ได้แก่ ทางเลือก A (75% ของแบตเตอรี่ที่ใช้แล้วถูกนำกลับมารีไซเคิล แคลเซียมไฮดรอกไซด์เป็นสารเคมีที่ใช้ในการบำบัดเบื้องต้น) ทางเลือก B (100% ของแบตเตอรี่ที่ใช้แล้วถูกนำกลับมารีไซเคิล โซเดียมไฮดรอกไซด์) และทางเลือก C (100% ของแบตเตอรี่ที่ใช้แล้วถูกนำกลับมารีไซเคิล บำบัดโดยแคลเซียมไฮดรอกไซด์) ซึ่งทางเลือก C มีประสิทธิภาพในการลดผลกระทบทางสิ่งแวดล้อมมากที่สุด ทางเลือก A ดีเป็นลำดับที่สองสำหรับด้านภาวะโลกร้อน การลดลงของโอโซน และการใช้พลังงาน ขณะที่ทางเลือก B มีประสิทธิภาพดีเป็นลำดับที่สองสำหรับภาวะความเป็นกรดและการใช้พลังงาน การวิเคราะห์ทางเศรษฐศาสตร์พบว่าแบตเตอรี่ชนิดไม่เติมน้ำกลั่นมีผลกระทบทางสิ่งแวดล้อมน้อยกว่าแบตเตอรี่ชนิดลูกผสมและชนิดเติมน้ำกลั่นสำหรับกรณีที่ซื้อแบตเตอรี่ลูกใหม่ กรณีที่นำแบตเตอรี่ลูกเก่าขายคืนและซื้อแบตเตอรี่ลูกใหม่พบว่าแบตเตอรี่ชนิดลูกผสมดีกว่าแบตเตอรี่ทั้งสองชนิดที่เหลือ

สาขาวิชา การจัดการสิ่งแวดล้อม	ลายมือชื่อนิสิต ....
ปีการศึกษา 2556	ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ....

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KEYWORDS: LIFE CYCLE ASSESSMENT / VEHICLE BATTERIES / LEAD ACID BATTERY / ENVIRONMENTAL IMPACT

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This study evaluated environmental impacts throughout the life cycle of the three types of vehicle batteries which were maintenance free, hybrid, and conventional batteries. Five environmental impacts were evaluated, i.e. global warming potential, acidification, ozone depletion, heavy metal emission and energy resource consumption. Functional unit was one unit of battery (12V) with the capacity of not less than 75 Ampere-hour (Ah) for pickup trucks with a life time of 4 years. The result showed that, without recycling scheme, the maintenance free, hybrid, and conventional batteries emitted GHGs gas 62.3, 83.4, and 119 kgCO_2eq and sulfur dioxide 0.961, 1.21, and 1.66 kgSO_2eq, respectively. The maintenance free battery released 4.35E-06 following by 5.67E-06, and 7.99E-06 kgCFC_{11}eq by hybrid, and conventional batteries, respectively. The emission of heavy metal was from lead accounted for 4.54E-02 (maintenance free), 5.66E-02 (hybrid), and 7.44E-02 (conventional) kgPbeq. All batteries consumed energy throughout their lives, i.e. 1,072 MJ LHV for maintenance free, 1,462 MJ LHV for hybrid, and 2,116 MJ LHV for the conventional battery. The conventional battery affected the environment more significantly than the hybrid and maintenance free, respectively. The raw material acquisition stage and waste management stage were two main causes for the environmental impacts. The acquisition of lead resulted in a large quantity of gas being emitted, while sodium hydroxide used to neutralize sulfuric acid could pose some serious effect on the water course. This study proposed two options to reduce the environmental impacts: 1) Recycling materials from collected spent batteries, and 2) Replacement of sodium hydroxide (NaOH) with calcium hydroxide ($Ca(OH)_2$). Each environmental mitigating option could be further classified into three scenarios, i.e. Option A (75% collection, $Ca(OH)_2$ as pretreatment chemical), Option B (100% collection, NaOH), Option C (100% collection, $Ca(OH)_2$ as pretreatment chemical). In general, Option C provided the highest potential of reducing most of environmental impacts. Option A gave the second best when focused mainly on global warming potential, ozone depletion, and energy resource consumption whereas Option B provided the second best performance when acidification and energy resource consumption. In part of economic analysis, maintenance free battery was better than hybrid and conventional batteries in terms of environmental consideration for purchase a new battery option. Turning in an old battery and purchasing a new one option was better for hybrid battery than the other two.

Field of Study: Environmental Management Student's Signature ....

Academic Year: 2013 Advisor's Signature ....

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CHAPTER I

INTRODUCTION

1.1 Rationale

It is undoubted that Asia has become increasingly important both in terms of a market and the base of the world's major automotive manufacturers and many major car makers have moved their production bases to this part of the world. In 2011, Thailand was the major automotive industry, and was the 15th major industry of the world's manufacturers [1]. Due to this reason, several other auto-parts industry has also been expanded. Battery industry is one of the major developments with an average annual production of approximately 8.6 million batteries (both for domestic and export) [2]. To date, most vehicle batteries are a lead-acid type which contains acid (sulfuric acid) and some heavy metals, e.g. lead, which are considered hazardous. Inappropriate management of used lead-acid batteries could mean a release of such hazardous components to environment, e.g. an improper release of sulfuric acid which leads to corrosion problems, or illegal smelting of recycled lead which could release harmful gas, and this affects both environment and human health. The acute toxic effects of lead are headache, fatigue, and muscle pain. The long-term effects are on nervous system and brain, convulsions, memory loss, effects on kidneys, and congenital anomalies [3]. Proper management of batteries, however, covers not only proper end-of-life treatment, but also includes a decent manufacturing of batteries and its peripherals, along with the transportation of parts and batteries [4, 5].

Up to now, there are only a few studies on the environmental impact of vehicle batteries. Clearly there is a need to conduct such a study as this is not only for the sake of battery product alone, but it is also important for the evaluation of environmental impact of end-of-life vehicles as a whole which needs to be constituted of various components including batteries. This study, hence, aimed to evaluate environmental impacts throughout the life cycle of three types of vehicle batteries, i.e. maintenance free, hybrid, and conventional batteries. The study was applied for a case in Thailand and the evaluation was based on the criteria set out in life cycle assessment (LCA) tool. All raw materials extraction and processing, transportation, production, distribution/retail, consumer use and waste management (recycling, disposal, landfill) throughout the life cycle of vehicle batteries were identified and analyzed. There were two critical activities designed to accomplish in this evaluation. First, the mid-point impacts were employed as environmental indicators including: (i) global warming potential, (ii) acidification, (iii) ozone depletion, (iv) heavy metal emission, and (v) energy resource consumption. Second, hot spots from batteries were identified along with the potential options to improve the environmental performance of the vehicle batteries.

1.2 Objectives

- To evaluate environmental impacts throughout the life cycle of the three types of vehicle batteries, i.e. maintenance free, hybrid, and conventional batteries
- To investigate potential options that help lessen the impacts from three types of vehicle batteries

1.3 Scopes of the research

- Time period data for life cycle assessment of vehicle battery products: January 2010 to December 2010 (12 months)
- Products: Three types of vehicle battery were investigated, i.e. maintenance free battery (Battery A), hybrid battery (Battery B), and conventional batteries (Battery C) were investigated.
- Evaluated environmental impacts: (i) global warming, (ii) acidification, (iii) ozone depletion, (iv) heavy metal emission, and (v) energy resource consumption
- Functional unit: One unit of battery (12V) with the capacity of not less than 75 Ampere-hour (Ah) for a pickup truck with a life time of 4 years
- System boundary: The boundary of the assessment was based on the cradle to grave basis including, the raw material acquisition, transportation, production, energy flows, distribution/retail, customer use, and waste management/recycling.
- Sources of evaluated data: A vehicle battery production is composed of inputs and outputs from two sources, i.e. primary sources and secondary sources. The primary sources included data on material use, combustion process, transportation, energy flows, waste management or recycling in the production. The secondary sources included emission factors (E.F.) reported in international LCI databases and the carbon footprint guideline of Thailand (September 2011) [6], IPCC 2007 Guidelines for National Greenhouse Gas, and Thailand Greenhouse Gas Management Organization (TGO).
- Case study: Siam Furukawa, Co., Ltd is the vehicle battery producer that has been helpfully giving inputs and outputs on mass and energy flows.

1.4 Expected outcomes

- To understand the impacts from the use of vehicle batteries
- To compare the environmental impacts from each type of vehicle batteries, i.e. Battery A, Battery B, and Battery C
- To propose potential options to improve the environmental performance of vehicle batteries

CHAPTER II

THEORIES AND LITERATURE REVIEWS

2.1 Life cycle assessment

A life-cycle assessment (LCA) is a technique to quantify the environmental impacts of a product system throughout its life cycle from cradle-to-grave, i.e. starting from raw material acquisition, materials processing, manufacture, distribution, consumer use, repair and maintenance, and disposal or recycling (Waste management) [7], as shown in Figure 2-1.

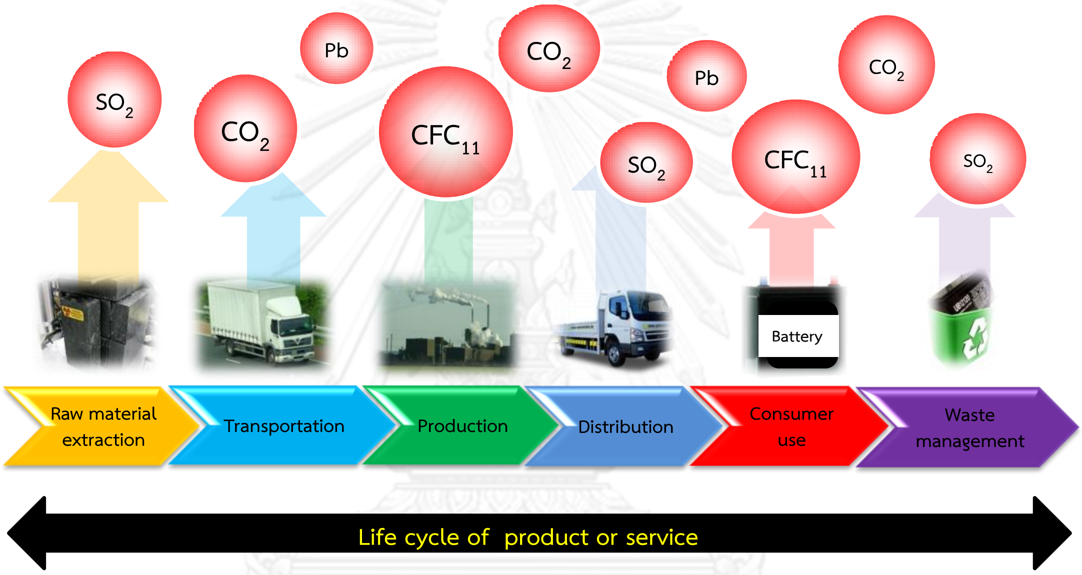


Figure 2-1 Life cycle assessment of product or service [8]

The essence of life cycle assessment includes the examination, identification, and evaluation of the relevant environmental implications of a material, process, product, or systems that create environmental concerns. The life cycle assessment is an objective process to evaluate the environmental burdens, and it composes of a product, process, or activity with identified and quantified energy and material usages, and environmental releases. The entire life cycle of the product, process or activity, encompassing extracting and processing raw materials is included in the assessment, such as; manufacturing, transportation, and distribution; use/re-use/maintenance; recycling; and final disposal [9]. The formal structure of LCA contains four stages: goal and scope definition, inventory analysis, impact analysis, and each stage mentioned have to be followed by interpretation of results [9]. The concept of the life-cycle methodology is pictured in Figure 2-2.

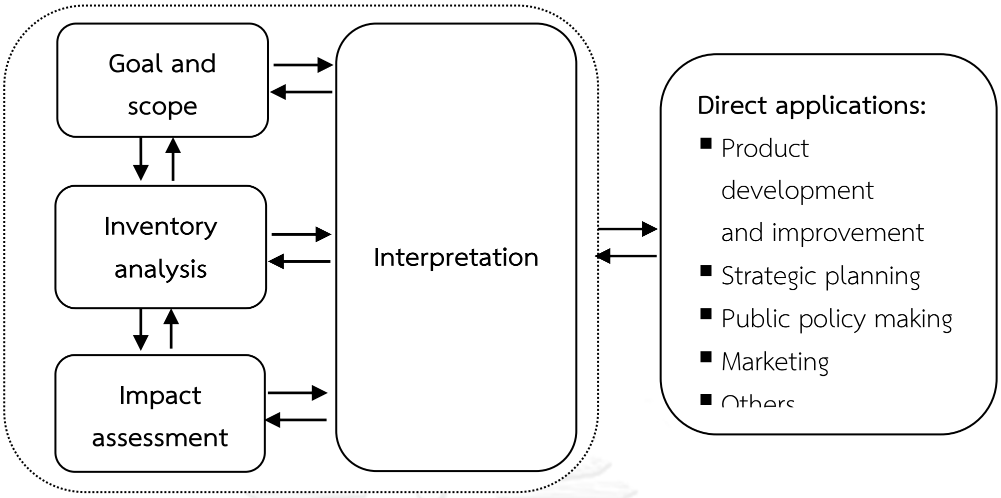


Figure 2-2 Life cycle assessment principles and framework [10]

The definition of formal structure of LCA [8]:

- Goal and scope definition: Identifying the target of the study such as the reasons and boundary of the study, the target group which is contacted for primary data, the type of target product, the functional unit, the environmental impact categories, hypothesis, limitation and expected results.
- Life cycle inventory analysis: Establishing a flow chart of the product life cycle with all the environmental inflows and outflows.
- Life cycle impact assessment: Understanding the environmental relevance of all the inflows and outflows.
- The interpretation: Analyzing the results and evaluate environmental impacts and adjust the potential options to improve the environmental performance.

2.2 Environmental Impacts

Environmental impacts are the consequences of the use of products or services which could affect human health or environmental integrity, including the risks imposed on the ecological conditions. Depending on the nature of the activities, the impacts could be grouped into several categories such as global warming potential, ozone depletion, acidification, eutrophication, carcinogens, heavy metal emission, winter smog, summer smog, pesticides, solid waste, and energy resources consumption, etc. Normally, lead-acid batteries require high level of energy in the production process, and they contain heavy metals which could affect the ecosystems if unintentionally released to the environment. This study focused mainly on five common environmental impacts i.e. global warming potential, acidification, ozone depletion, heavy metal emission, and energy resource consumption.

- Global Warming: This is the phenomenon that the average temperature of the earth increases. The main cause for this global warming problem is the increasing amount of Greenhouse Gases (GHGs) mainly by human's activities, such as energy consumption, the development and expansion of the industry, transportation, deforestation, including the destruction of natural resources and environment in many ways. As a result, temperatures and sea levels are going to rise annually [11]. Global warming impacts are considered worldwide, e.g. severe weather conditions, natural disasters, floods, earthquakes, severe storms, etc [12].
- Acidification: Acid rain is one of the pollutions occurred from the burning of fossil fuels, such as oil, coal, gas etc. Carbon dioxide or sulfur dioxide released to the atmosphere can combine with the rain and becomes carbonic acid or sulfuric acid [13].
- Ozone depletion: This describes the potential destruction of the ozone layer in the upper atmosphere as a result of human's activities. Its cause is the substances used widely as refrigerants (Chlorine Monoxide) and the evaporator (Chlorofluorocarbons) or CFC compounds used in many industries [14]. CFCs react with UV rays, free chlorine atoms occur and destroy ozone gas, decreasing the stratospheric ozone layer.
- Heavy metal release: Heavy metals are metals with a density greater than 5 g/cc; for example, lead, cadmium, mercury, cobalt, tin, copper, etc. These can accumulate in environment in all phases, i.e. soil, water, and air.
- Energy resource utilization: Degradation of the environment is often caused by human activities. Therefore, human try to seek new energy resources to meet their endless demand, this depletes the natural resources drastically.

2.3 Vehicle batteries [15]

A vehicle battery is the equipment that can change the stored chemical energy into electric energy. In Babylonian era, there has been using battery since last 500 B.C. However, current car batteries were invented by scientists 200 years ago. It can be divided into 4 kinds: for example,

- A primary battery is the battery that if it is used, it is not recharged again. There are many kinds of batteries, i.e. alkaline batteries, lithium batteries, etc. Many kinds and sizes of batteries are used for radios, watches, and clocks. Once these batteries loss all energy, they become hazardous wastes.

- A secondary battery is the battery that although it losses all energy, it is recharged again; for example, a car battery, a mobile battery, and a laptop battery, etc.
- A mechanical battery is the battery that although it losses all energy, it is recharged again by changing the negative electrode terminal of the used battery, this makes recharge rapidly, such as aluminium-air battery.
- A mixing battery is the battery that has mixed with the fuel cell, an electrode is gas and the other is itself, such as Zinc-bromine battery.

At the present, both primary and secondary batteries are popular, and most of them are based on lead which is considered toxic. There are 4 other kinds of batteries, which might replace the lead-acid battery, such as

- Nickel-Cadmium battery (NiCd): this kind of battery is more expensive than lead-acid battery, but it can be recharged many times and have long lifetime.
- Sodium-Sulfur battery (NaS): this kind of battery has low density of energy, cost, and it is used well at 350 °C.
- Zinc-Bromine battery (ZnBr): this kind of battery gives high voltage, cheap, and long lifetime. It is appropriate for the sky trains; however, a leaking of the stored charges and toxic bromine gas are its problems.
- Vanadium-Redox battery (Vanadium-Redox): this kind of battery can charge immediately by changing electrolyte, it has long lifetime, low leakage rate of charge, the high density of energy, and it is easy to use. Although vanadium is toxic to living organisms, it is safe if kept in a standard container. However, the upscale of this battery is still undergone current development and therefore its application is still very limited.

2.3.1 A secondary battery (Vehicle battery or lead-acid battery) [15]

A lead-acid battery has evolved for long time about 100 years. There are many ways to classify a lead-acid battery as mentioned below:

- A conventional battery: This kind of battery has a lot of vapor loss rate over a lifetime. The electrode plates are made of lead-antimony (Lead Antimony) both positive and negative plates which make them high heat resistance, high acid resistance, and high charge resistance (high internal resistance). However, it has disadvantages in terms of having a fast self-discharge. The charge will be compressed slowly, because of its high internal resistance. The current flow is slow, the heat from charging occurs significantly. Therefore, the result is a loss of acid quickly, and a battery is charged overload easily.

- A low maintenance battery (Hybrid battery): This kind of battery has been improved for solving the main problem of a conventional battery by changing the kind of negative plates to be lead calcium, but positive plates still are lead antimony. This is to reduce the vapor loss rate over a lifetime. Therefore, the properties of battery are reducing less charge, losing less acid vapor, reducing less overcharge, recharging charges faster.
- A maintenance free battery: This kind of battery is improved to respond to the behavior of users who have no time for car maintenance. Both positive plates and negative plates are lead calcium or lead silver. A maintenance free battery can be classified into 3 kinds:

Flood: it is appropriate to use in tropical countries, because acid is still liquid, so it has high heat resistance and can be divided into two types. The first type, non-seal lead acid battery, the soft acid still leaks and corrodes the car, and due to this acid loss, the battery must be still filled with water, but less than the hybrid battery. The second type, seal lead acid battery, it can protect the leakage of acid and keep the amount of acid as long as it can be. Therefore, it protects the corrosion of the car well. The production of these kinds of battery must control the quality of plates, they are produced by rolling and pressing with high density (Expansion Grid Technology). Moreover, the quality of lead has to be only pure lead to ensure high resistance.

Gel: the acid inside battery is transmuted to be gel to reduce the leakage of acid from battery. However, this battery cannot be compared with the lead acid in terms of efficiency, therefore it is not used as car battery.

Absorbent Glass Matt; AGM Technology (dry battery): this kind of battery is improved from gel battery that makes the battery have high quality and gives the energy more than the normal battery; moreover, it uses fiber glass as the special materials. These are insulators that obstruct between positive plates and negative plates, and these fiber glasses can absorb all of acid to be inside the battery. Therefore, there is not any the leakage of the acid from the battery. However, this type of battery still has the same limitations as the gel battery, which are the temperature for working is not over 55°C, and if keep using it with over temperature for long time, the lifetime of battery is shorter than it should be. Figure 2-3 displays the components of car battery can be described as follows [16]:

1) Pole is the bar of lead that extends out of the cover, such as positive and negative poles, there are symbols that can be noticed certainly.

2) Negative plate is the lead plate that has the main component, which is pore to store electricity as well as positive plate.

3) Separators & Glass mat are made of insulating material; for example, synthesis paper, rubber, plastic. The liquid spread all parts of the plates and separates between positive and negative plates for protection of short circuit.

4) Positive plate, there is dark brown lead peroxide that is the part for storing electric charges. The good positive plate should have many pores to affect acid has the good reaction.

5) Vent plug can release heat and gas that occurs while the battery is used. It is made from strong rubber or plastic, like the cover and container of battery.

6) Indicator sign is used to check the level of acid and capacity of electricity of a battery.

7) Container & Lid are made from rubber or plastic that acts as insulators, and helps resist to coolness and heat, and absorption of the high acid. There are rubbers at the bottom of container to protect an electric short-circuit when lead dross falls down to the bottom of the container.

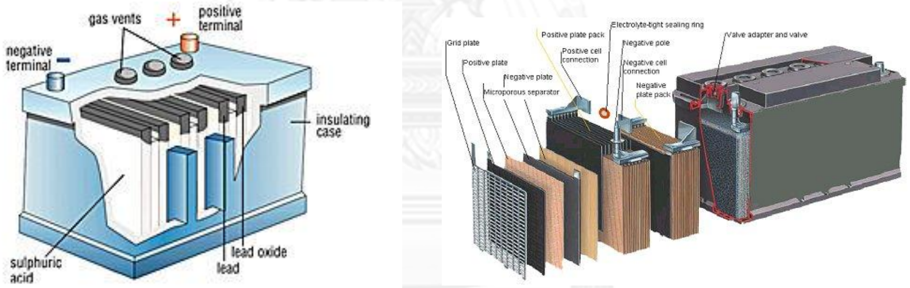
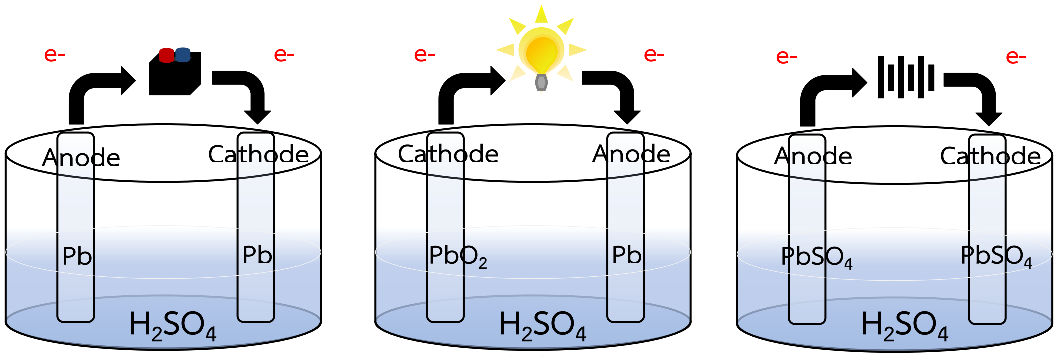


Figure 2-3 Components of lead battery collect electricity [17]

2.3.2 How do vehicle batteries work? [18]

When two different metals such as positive and negative plates are dipped into electric solution (Sulfuric acid), they become battery that give 2.1 voltages per a cell, the electric energy by chemical reaction between two metals, and electricity occurs in electric solution because of the complete circuit; for example, the light in front of a car connects to a battery. There are three components for the work of car batteries, such as

1. Lead dioxide (PbO_2) on positive plate
2. Sponger lead (Pb) on negative plate
3. Sulfuric acid (H_2SO_4) or electric solution.



(1) Charging for the first time **(2)** Distribute electricity **(3)** Next charging

Figure 2-4 Lead electric cells [18]

Lead electric cells compose of electrodes that are lead plates, dilute sulfuric acid as electrolyte when it is the first time for charging. The plates connected to the positive pole of battery (Anode is oxidized to be lead (II) ions), as shown in Equation (2.1).

$$Pb(s) \longrightarrow Pb^{2+}(aq) + 2e^{-} \tag{2.1}$$

When it is added with oxygen, it becomes lead (IV) oxide, as shown in Equation (2.2).

$$Pb^{2+}(aq) + O_2(g) \longrightarrow PbO_2(s) \tag{2.2}$$

Therefore, at an anode (positive pole), the plates will be changed to be lead (IV) oxide. The electricity and distribution can be occurred by the different poles, following Equation (2.3) and (2.4).

Anode - positive pole : $Pb(s) + SO_4^{2-}(aq) \longrightarrow PbSO_4(s) + 2e^{-}$ (2.3)

Cathode - negative pole : $PbO_2(s) + SO_4^{2-}(aq) + 4H^{+}(aq) + 2e^{-} \longrightarrow PbSO_4(s) + 2H_2O(l)$ (2.4)

Electrons will flow from anode (positive pole) though the circuit to cathode (negative pole), from the Equation (2.4), it can be noticed that the product is $PbSO_4(s)$. Therefore, when the battery is used for a certain time period, its voltage will keep decreasing until become zero. Because both of the electrodes are the same poles, there is not the difference of them.

The reactions of cells can reverse and the battery can be recharged. In this case lead (II) sulfate at the negative pole will become lead. The other pole lead (II) sulfate will be lead (IV) oxide, as shown in Equation (2.5) and (2.6).

Anode - positive pole : $PbSO_4(s) + 2H_2O(l) \longrightarrow PbSO_2(s) + SO_4^{2-}(aq) + 4H^{+}(aq) + 2e^{-}$ (2.5)

Cathode - negative pole: $PbSO_4(s) + 2e^{-} \longrightarrow Pb(s) + SO_4^{2-}(aq)$ (2.6)

From these reactions, they distribute electricity, and the intensity of acid will keep decreasing from the specific gravity of about 1.25 to 1.30 on the temperature in that time. Whenever the specific gravity falls below 1.20 at the room temperature, the battery should be recharged.

2.4 Production of vehicle batteries [16]

The main processes of vehicle battery production are:

2.4.1 Oxide and grid processing production: Oxide and grid processing production, lead oxide is produced from pure lead. Oxide that is pasted on grid plates can be produced by mixing water, acid and other chemicals. This step includes:

1) Oxide production

Lead oxide is the material that is pasted on the surface of grid plates, which is produced with Ball Mill process or Barton-Like oxide, pictured in Figure 2-5.

2) Paste Mixing

Lead oxide, water, and other chemicals are added into furnace to transform to be paste mixing particles in this process.

3) Grid production and parts casting

Grid production and parts casting compose of continuous casting and strip casting. Both of them will be sent to mold for extrusion of grid (plate) or other parts, illustrated in Figure 2-6.

2.4.2 Plate Processing: Paste mixing particles are pasted on grids. Pasted pates are cured in the ovens before being sent for assembly, as shown in Figure 2-7 to 2-8.

2.4.3 Formation: Formation or dry charging is the important process for the maintenance free battery, the first step is taking plates with their cases (containers) into yanks and connected by lead poles. Plates are formed (or charged) inside tanks, as shown in Figure 2-9.

Figure 2-5 Lead furnace with barton process [19]

Figure 2-6 Grid machine producer [19]

Figure 2-7 Grid machine producers [19]

Figure 2-8 Pasting machine producers [19]

Figure 2-9 Batteries being charted by wet charging [19]

2.4.4 Assembly of battery: The important parts, i.e. pasted plates, separators, cases (containers), and covers are assembled in this process. The assembly is composed of:

1) Stacking
After the plates have been cured for removing the moisture, they are stacked with switching between positive and negative plates by the machines and labors follows Figure 2-10.
2) Stacking cells with group burning
After cells or plates have been stacked and put into the cases (containers), each cell is connected to each other, as displayed in Figure 2-11.

Figure 2-10 Stacking machine with manual system [19]

Figure 2-11 Stacking machine [19]

3) Intercell welding and post burning

After the plates have been stacked, next step is connecting cells with heat follows Figure 2-12.

Figure 2-12 Machine used for connecting cells with heat [19]

2.5 Toxic and danger of batteries [15]

Toxic and danger of batteries is from chemical substances used to make battery, such as lead, manganese, cadmium, nickel, mercury and chemicals used in the reaction, i.e. sulfuric acid etc. If these chemical substances are not managed appropriately, the contamination to ground, surface water, atmosphere occurs, then the large amount of expansion to the plants and animals happens. Effects of inappropriate battery are as follows.

1) The causes of acute illness or chronic due to exposure to toxic chemicals or toxic residues of used batteries. It is usually found in workers at a flashlight and batteries factory, or solid waste collection workers. All these toxins can enter the body by inhalation of dust and vapor, eating contaminated foods, and they are also absorbed through the skin as well.

2) The causes of contamination of soil, groundwater and surface water as a source of water nearby household consumer, then it infiltrates the soil and pass through the plants and other creatures.

3) The causes of air pollution and the spread of chemical vapor. On the other hand, dust from waste incineration with waste battery campsites is released to the atmosphere. The workers collect garbage, villagers who dig the garbage and people living around the waste disposal facility breathe the pollution into their bodies.

2.6 Literature reviews

A report by MTEC and TEI (2008) [16] provided an LCA case study for the EcoDesign of vehicle batteries to compare environmental impacts between 2 types of battery, which were maintenance free and conventional batteries. In addition, propose methods to decrease energy consumption and environmental impacts. The study covered the environmental impacts throughout the life cycle of the vehicle batteries production, i.e. raw material, production process, usage, transportation (domestic) and waste management. A functional unit was one unit of battery (12V) with the capacity of about 80-90 Ampere-hour (Ah) for a pickup truck with a life time of 2 years. Global warming: The study resulted that hot spots of both types of vehicle batteries were from the customer use stage (54 kgCO_2eq) and the main cause was fuel at 22.13 liters throughout 2 years. Raw material acquisition was the second hotspot, and the maintenance free battery was half of the conventional battery. The last stage for greenhouse gas emission was the production stage. Acidification: This impact was proved that the hotspot was taken place at the raw material stage. The highest amount of sulfur dioxide was released, focused on the lead, polypropylene, and polyethylene production. The second hotspot from the customer use stage (fuel), following the production stage. Ozone depletion: The production stage affected this impact mostly because the electricity and sodium hydroxide production emitted CFC and HCFC. The customer use and the raw material acquisition released CFC_{11}eq lesser than the production stage, respectively. Heavy metal emission: The highest heavy metal was emitted by customer use stage and fuel was the major origin, followed by the raw material acquisition and production stage, respectively. Energy resource consumption: The trend of hotspot in this impact was similar to global warming.

Tulyakorn (2000) [20] studied the coagulation of wastewater from a battery's lead recycling industry. Lead (Pb) removal and total dissolved solids (TDS) from the wastewater, sodium hydroxide (NaOH) and calcium hydroxide ($Ca(OH)_2$) were used to adjust the pH of the waste prior to coagulation. Epofloc was used as a coagulant, whilst coagulant aids were Creafloc C-130, Kurifloc PA-331 or Kurifloc C-0320S. The study was devided into 2 parts: a) Determination of the characteristic and b) Determination of the optimum canditions by mixing NaOH/$Ca(OH)_2$ coagulant/ coagulant aids for the reduction of Pb and TDS from the wastewater. The cost for each option was then compared.

The results showed that TDS was better reduced by $Ca(OH)_2$ than by NaOH. However, the performance were not significant by different with Pb. Kurifloc C-0320S and Kurifloc PA-331 were better than other coagulant or coagulant aid used in the study. The costs of chemicals in the coagulation process, and pH adjustment were compared. The process using NaOH and Kurifloc C-0320S costed about 2.31 Baht/m^3 , while the process using $Ca(OH)_2$ and Kurifloc C-0320S costed only about 0.59 Baht/m^3.

Wechagarn (2007) [3] studied the environmental management of lead-acid type used car batteries in Thailand. The result, it was useful to investigate on how to manage the hazardous components and recover the situation. The recycling of batter was studied in terms of storing, gathering, separating the components, waste treatment, and the cost of each process. Lead melting factories did not get profit much enough to be concerning about the environmental conserving. The waste treatment cost about 93.794 Baht per kg. of lead, but the factories got profit about 11.206 Baht per kg. of lead without waste treatment. Therefore, it needs to be encouraged the excess cost by the government, with added to the new battery price. Lead melting factory, as the place that toxic is generated, should be located and controlled on the cooperation of the government and private organization. In addition, the location of lead melting factory and used battery warehouse should be investigated in order to minimize the recycling process.

Sullivan and Gaines (2010) [21] studied the cradle-to-gate life-cycle inventory of five kinds of batteries, i.e. lead-acid, nickel-cadmium, nickel-metal hydride, sodium-sulfur, and lithium-ion battery. Primary data was collected at the production of battery constituent materials and battery manufacture and assembly. Life-cycle production data for many battery materials are used, though some need to be updated. For the remaining battery materials, data throughout lifecycle either are nonexistent or, in some cases, in need for updating. Although processes from battery production are well presented, the amount of energy and material flows is missing. However, lead-acid batteries have the lowest production energy, CO_2 emissions, and criteria pollutant emissions.

Rydh and Karlstrom (2002) [22] studied a life cycle assessment of recycling portable nickel–cadmium (NiCd) batteries in Sweden. The study was identified life cycle activities by two cases, i.e. 1) the different recycling rates and 2) the different time boundaries of metal emissions from landfilled. The primary energy (65%) is used in the battery production, whilst 32% is used in the raw material production, excluding the user phase. Landfill and incineration are the major places that originates metal emissions, are responsible for 96-98%. However, the distance for the collection of batteries does not impact to energy use and emissions. The primary energy use can be saved 16% when recycled nickel and cadmium instead of virgin metals in part of battery manufacture. In addition, Less primary energy 46 and 75 % are taken placed when recycled cadmium and nickel metal, compared with extraction and refining. NiCd batteries are recycled closed to 100%, considering an environmental perspective.

Salomone et al. (2005) [23] applied Life Cycle Assessment (LCA) methodology to show an eco-balance of a recycling plant that treats spent lead-acid batteries. Pyrometallurgical treatmentwas was used to obtain lead from spent batteries by the recycling plant. The potential environmental impacts arising from the recycling plant's operations were evaluated by the application of LCA methodology (ISO 14040 series). Hence, net emissions of greenhouse gases and other major environmental consequences were identified the hot spots inside the recycling plant. The study highlights stages of a recycling plant for spent lead-acid batteries, which environmental improvements are appropriate to achieve between a business, providing a basis for suggestions to minimize the environmental impact of its production phases, improving process and company performance in environmental terms.

Rydh (1999) [24], the vanadium redox battery (vanadium battery) and the lead-acid battery for use in stationary were studied the environmental impact by an LCA tool. The vanadium battery had less environmental impact than the lead-acid one. The vanadium battery had more net energy storage efficiency than the other one, due to long cycle-life, good performance of resource and recycling ability of it.

Frost (1999) [25] investigated the developments in lead-acid batteries in lead producer’s perspective. Present progress is being improved in many aspects of materials, design and construction for lead–acid batteries. This work is taken placed by the auspices of the Advanced Lead–Acid Battery Consortium (ALABC). These developments will be applied in commercial products, and that there will be cross-fertilization between the emerging electric vehicle (EV) battery technology and the starting, lighting and ignition (SLI) battery. Some of the possible replacements in materials, design and construction had an impact on the recovery, recycling, smelting and refining of lead–acid batteries. Some of the possible developments are presented and their possible impacts are debated. It is likely that negative effects may be minimized if developments of battery are considered from other perspectives, largely based on the overall life-cycle, as early in the design phase of new products as possible. Three strategies for minimizing undesirable effects are supported: 1) improved communication between car manufacturers, battery manufacturers and lead producers 2) a life-cycle analysis identifies and optimizes all attributes of the product 3) coordinated action need to make up issues important to the industry.

A lot of researches were studied many types of battery about environmental impacts by LCA tool, recycling of a battery and improvement of products. Some of the similar studies above that were analyzed by LCA are compared in Table 2-1.

Table 2-1 Some studies of Life Cycle Assessment for batteries

Authors/ Articles	Year/ Country	Types of battery	Aims and scopes	Conclusions	Methods to decrease environmental impacts
A report by MTEC & TEI "LCA – Eco-Design : Batteries." [16]	2008/ Thailand	**Lead-acid**	- To make up a study of LCA from a battery product. - To develop Eco-Design of a battery product - To expose the new knowledge for public - FU was established for a battery has long life for 2 years a battery. - Two types of batteries, i.e. maintenance free and conventional battery were the representations. - Five environmental impacts were studied, such as, global warming, ozone depletion, acidification, heavy metal, and energy resource.	- All impacts demonstrated that usage stage affects to in energy use, GHGs emission, and metal emission. The main origin was from fuel of the engine. - The maintenance free battery had less environmental impacts the other. - The maintenance free battery impacted ozone depletion for the lest (44.4%), heavy metal, global warming and energy resource accounted for 59.1, 54.1, 70.8, and 71.8, respectively.	- There were three methods for the development, i.e. 1) The development of production, 2) Design of a battery product, 3) Strategy of marketing and supporting the eco-product.

Table 2-1 Some studies of Life Cycle Assessment for batteries (cont.)

Authors/ Articles	Year/ Country	Types of battery	Aims and scopes	Conclusions	Methods to decrease environmental impacts
Sullivan and Gaines “Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs.” [21]	2010/ Sweden	**Lead-acid, Sodium-nickel, Nickel-Cadmium, Nickel-Metal hydride, Lithium-Ion**	- To review the literature on battery life-cycle assessments with a focus on CTG energy, GHG, and criteria emissions - LCA considered based on cradle to gate in this study.	- Lead-acid had the lowest production energy and criteria pollutant emission from the five batteries reviewed. NiCd was next lowest. - There was need for more information to be used to analyze.	**-** The reduced environmental burdens of production was from using recycled materials

Table 2-1 Some studies of Life Cycle Assessment for batteries (cont.)

Authors/ Articles	Year/ Country	Types of battery	Aims and scopes	Conclusions	Methods to decrease environmental impacts
Salomone et al. "Environment Assessment, An Eco-balance of a Recycling Plant for Spent (Lead-Acid Batteries)." [23]	2005/ Italy	**Lead-acid**	- To assess the potential environmental impacts from the recycling of spent lead-acid batteries Pyrometallurgical treatment was used for recycling. - FU was formed of a tonne of recycled lead delivered to the battery manufacture site. - The net emissions of greenhouse gases, and other major environmental consequences could be evaluated in three processes, such as crushing, neutralization, smelting and refining, plus transport and waste treatment.	- The smelting stage contributed all impacts most, followed by refining, and improvement options.	- The research identified hot spots in which environmental improvements are achievable by a business, improvement (to minimize the impacts of production phases), and company performance in environmental terms.

Table 2-1 Some studies of Life Cycle Assessment for batteries (cont.)

Authors/ Articles	Year/ Country	Types of battery	Aims and scopes	Conclusions	Methods to decrease environmental impacts
			- Seven environmental impacts were evaluated, i.e. climate change, fossil fuel depletion, ozone depletion, human toxicity, waste disposal, acid deposition, and eutrophication.		

Table 2-1 Some studies of Life Cycle Assessment for batteries (cont.)

Authors/ Articles	Year/ Country	Types of battery	Aims and scopes	Conclusions	Methods to decrease environmental impacts
Rydh "Environmental assessment of vanadium redox and lead-acid batteries for stationary energy store." [24]	1999/ Sweden	**Vanadium redox & Lead-acid**	- To assess and compare between vanadium redox and lead-acid batteries by LCA tool. - Five environmental impacts were evaluated such as, global warming potential, photo-oxidant formation, acidification, eutrophication and resources. - FU was defined as an electricity storage system with a power rating of 50 kW, a storage capacity of 450 kWh and an average delivery of 150 kWh electrical energy per day for 20 years.	- The environmental impact of the vanadium battery was lower than the lead-acid one. - Because of long cycle-life, good performance of resource and recycling ability of the vanadium battery, the net storage efficiency of vanadium battery was greater than the lead-acid.	- The energy requirements for the production and recycling phase were responsible for 2.9-3.5 times more for the lead-acid than the vanadium battery - The results showed net energy efficiency of the lead-acid and vanadium redox batteries were 0.68 and 0.72, respectively.

CHAPTER III

PROBLEM DESIGNATION AND SYSTEM INVENTORY

This chapter illustrates the methods and procedures for the assessment in this research, as revealed in Figure 3-1. The three types of vehicle batteries are the selected representations for this evaluation, such as (i) maintenance free battery (Battery A), (ii) hybrid battery (Battery B), and (iii) conventional battery (Battery C).

3.1 Research plan

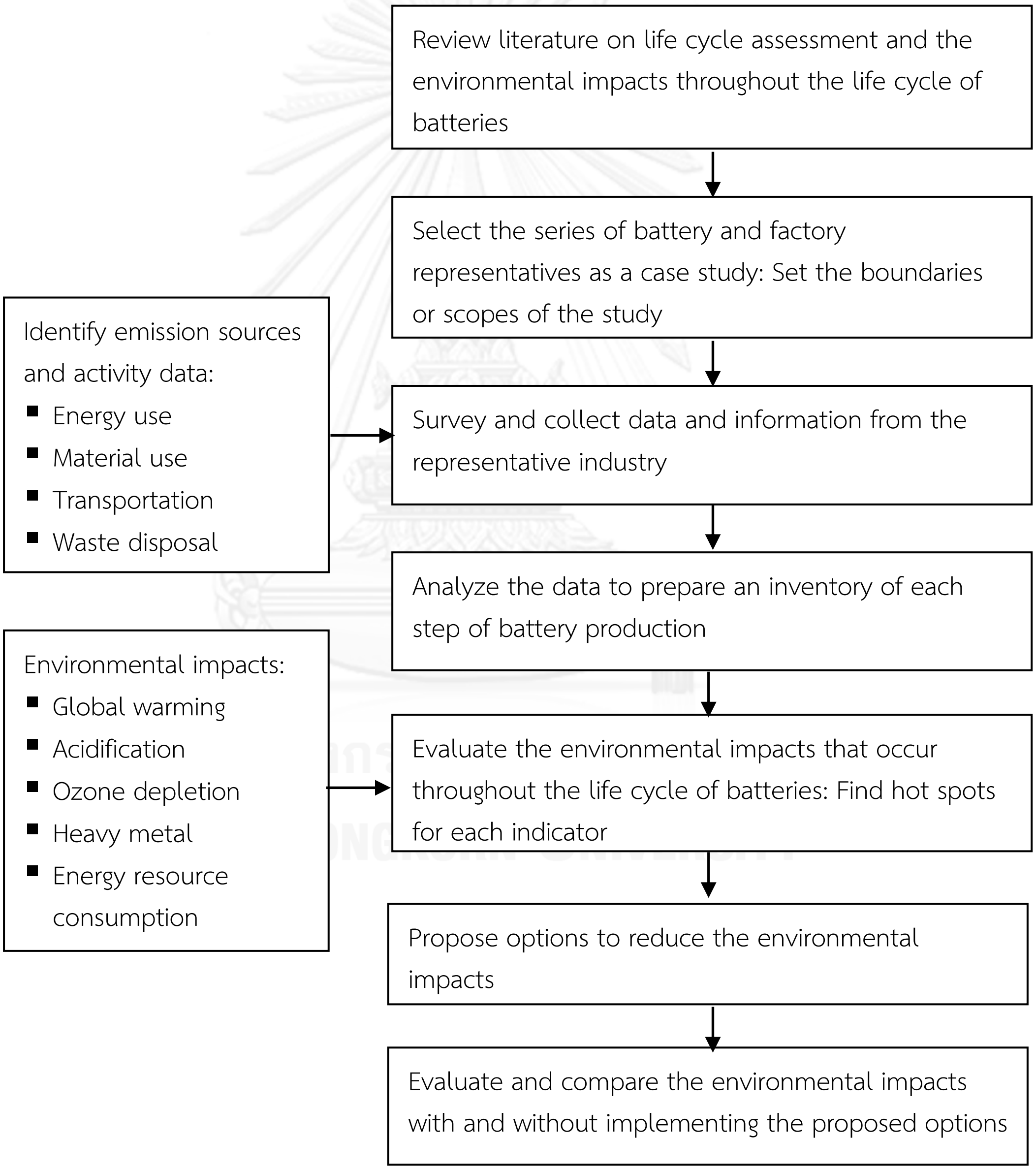


Figure 3-1 Hierarchical activities for this research

3.2 Goal and scope definition

3.2.1 Setting objectives

The main objective of this research is to evaluate five environmental impacts, i.e. global warming potential, acidification, ozone depletion, heavy metal emission, and energy resource consumption throughout the life cycle of the vehicle batteries. The sub objectives are to investigate hot spots and to investigate potential options that help lessen the impacts from three types of vehicle batteries; moreover, to compare five environmental impacts among three types of vehicle batteries.

3.2.2 Defining the functional unit

The functional unit of battery is set at one unit of battery (12V) with the capacity not less than 75 Ampere-hour (Ah) for pickup trucks and a life time of 4 years. Although each battery has slightly different current capacities, i.e. maintenance free (115 Ah), hybrid (100 Ah), and conventional (75 Ah), they are considered to deliver the same function to the pickup trucks (for typical use). The product specification of these batteries is given in Table 3-1.

Table 3-1 Product specification of three types of vehicle batteries in this study

Models		*Battery A*	*Battery B*	*Battery C*
Battery capacity (Ah)(C-20)		115	100	75
Outside dimension of a battery (mm.)	Length	304	304	304
	Width	171	171	171
	High	201	201	201
	High to pole	225	225	225
Pole location		Right	Right	Right
Type of pole		Large	Large	Large
Life time		4	3	2

3.2.3 Setting boundaries

The assessment boundary of the three types of vehicle batteries is based on the cradle to grave basis, including: raw materials extraction and processing; transportation; production; distribution/retail; consumer use; and waste management (recycling, pretreatment, landfill). The life cycle of vehicle batteries is divided into two main parts. The first part includes raw material acquisition, energy, resource production, usage, battery reclamation, and waste management, whereas the second part focuses in more detail on the production of vehicle battery in the industry as this involves several process steps, i.e. grid casting, pasting, assembly, (Jar) formation, and packing as illustrated in Figures 3-2.

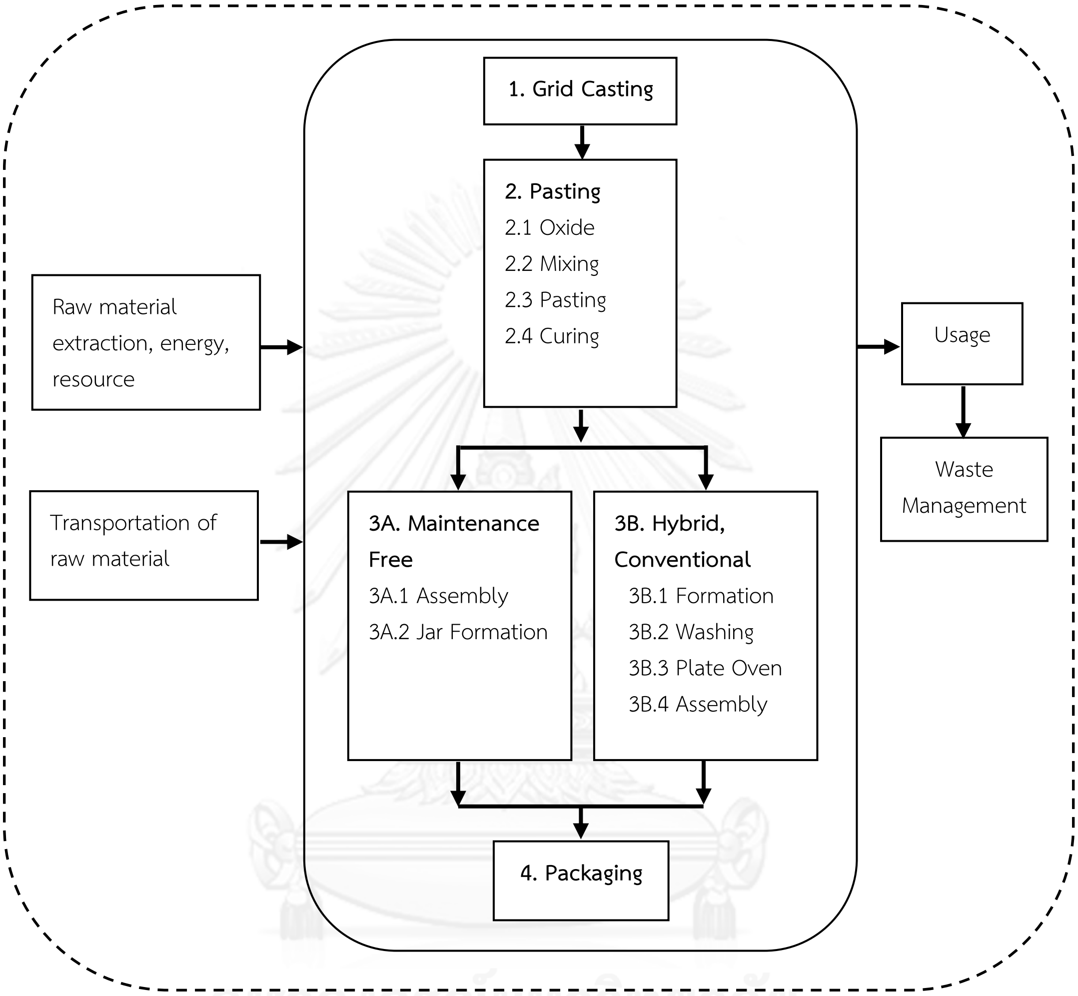


Figure 3-2 Boundary for consideration in this work

3.2.4 Building a process map

The process map diagrams of three types of vehicle batteries were built as follows (Figures 3-3 to 3-5).

1) Raw material acquisition: The data of raw materials as the main components of vehicle batteries was collected from one of the battery industries in the central region of Thailand. First, the objective industry was contacted in order to understand the production process. Then, a series of battery products was selected where primary data was collected (the amount of raw material, used energy, utilities,

transportation, distribution) for the evaluation of life cycle assessment of vehicle batteries.

2) Transportation of raw material: The data of transportation for raw materials i.e. the amount of lead, sulfuric acid, containers, covers, vent plugs, separators, and carton (components of a battery), which were collected. The estimation of emission was from the summation delivering trip and returning trip.

3) Production process: Five environmental impacts from the production process were derived from the amount of energy and utilities used in the production process such as electricity, natural gas, water supply, soft water, and deionized water. The amount of energy and utilities used were allocated by the main component of vehicle battery, i.e. lead (mass allocation). There were two main production processes for vehicle batteries. The processes of maintenance free batteries includes grid casting, pasting (oxide, mixing, pasting, and curing), assembly, Jar formation, and packing; otherwise, the process for hybrid and conventional batteries includes grid casting, pasting (oxide, mixing, pasting, and curing), formation, washing, plate oven, assembly, and packing. The amount of waste (dross) released the production process was low; therefore, the waste was not included for the evaluation.

4) Distribution/retail: All types of vehicle batteries were distributed to all regions in Thailand i.e. north, south, east, west, north-east, and the central region of Thailand (this work did not include the transport between retailers and consumers). Two types of vehicles were employed to transport battery products, i.e. 4-wheel trucks with a carrying capacity of 7 tons, and 6-wheel trucks with 8.5 tons capacity. The average distance was estimated from the distance between the distributors and the distribution site and retailer of each part of Thailand. The weights of each type battery product are listed following the order from maintenance free, hybrid, and conventional batteries as 23.6, 15.8, and 14.3 kg per unit, respectively.

5) Consumer use: The use of battery was based on a general use of pick-up trucks with the following assumptions. The truck was assumed to run 100 km per day, and the distilled water was consumed at the rate of 40 grams per 1,000 kilometers for all types of battery.

6) Waste Management: This stage is the important component of this study, composed of three main parts, i.e. interpretation, hotspot analysis and option proposition, and option evaluation. The first part (interpretation) focused on non-recycling case where the whole spent batteries were not recycled. Therefore all components such as lead, polypropylene, polyethylene, polycarbonate and carton

were sent to landfill, except sulfuric acid that was neutralized by sodium hydroxide (NaOH) before sending to landfill.

This basic case scenario was analyzed and hotspots were identified for each indicator (environmental impact). It will be elucidated in Section 4.2 that the two major hotspots were at the extraction of lead and the wastewater treatment. Hence, two options were proposed to reduce the impacts, i.e. 1) recycling material option and 2) chemical replacement option.

3.3 Life cycle inventories (LCI)

This stage consists of primary data in each stage of life cycle of vehicle batteries, i.e. raw materials energy used production processes, and types of vehicle for transportation. Raw material acquisition stage is established the components of three types of vehicle batteries (Battery A, Battery B, and Battery C), respectively in Table 3-2.

3.3.1 Separation of life cycle of vehicle batteries

The data of the battery industry was collected for a primary data; however, some data was from Thai and national data base (Literature reviews).

3.3.2 Bill of Material (BOM)

The comparison among three types of the representations needed to analyze, other than the difference of processes of production, their materials were compared their bills of materials (BOM), LCI was shown in Table 3-3.

3.3.3 Inventory of transportation

Transportation stage displayed the amount of components for vehicle batteries, distance, and type of vehicle in Table 3-4.

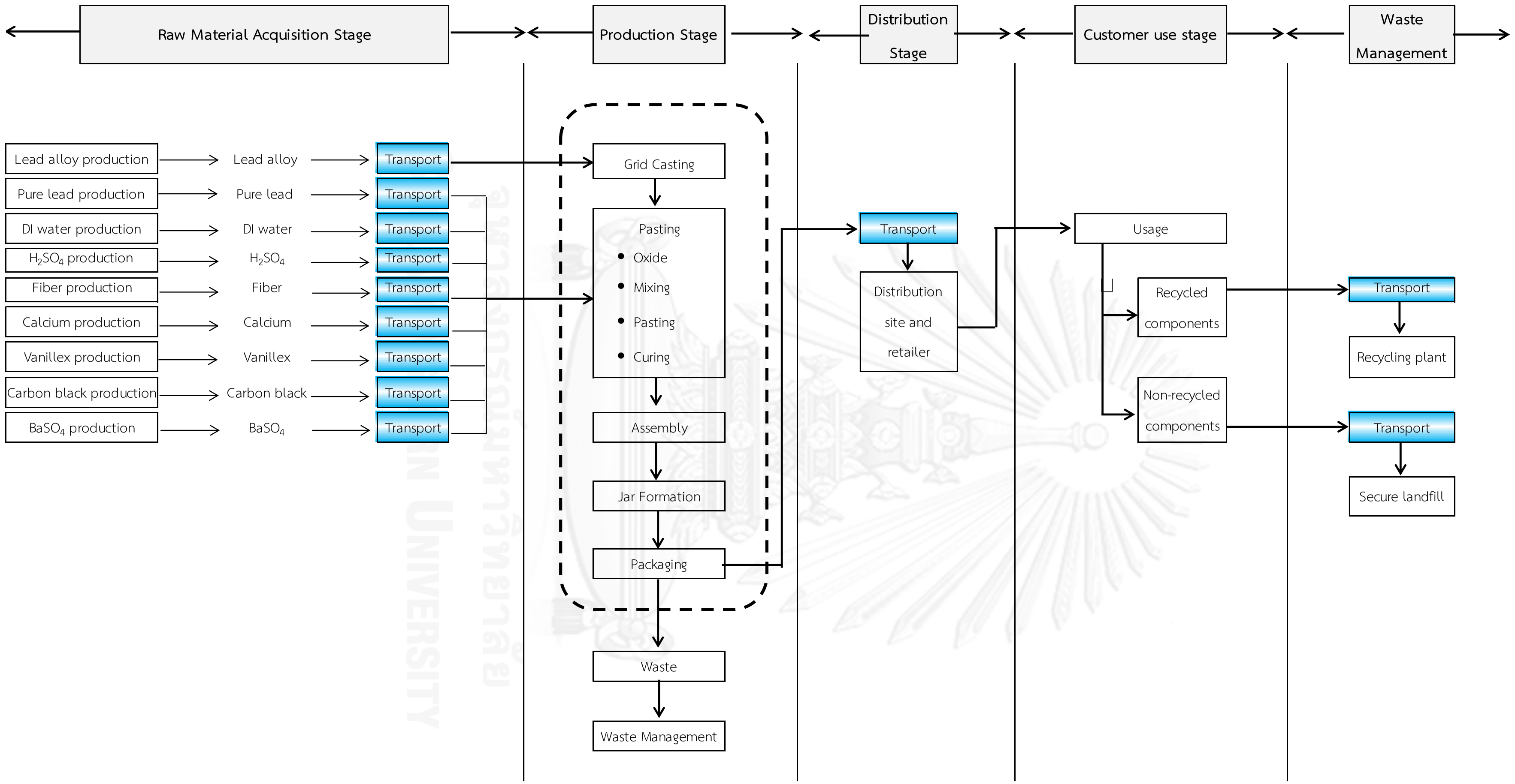


Figure 3-3 Life cycle flow chart of maintenance free battery (Battery A)

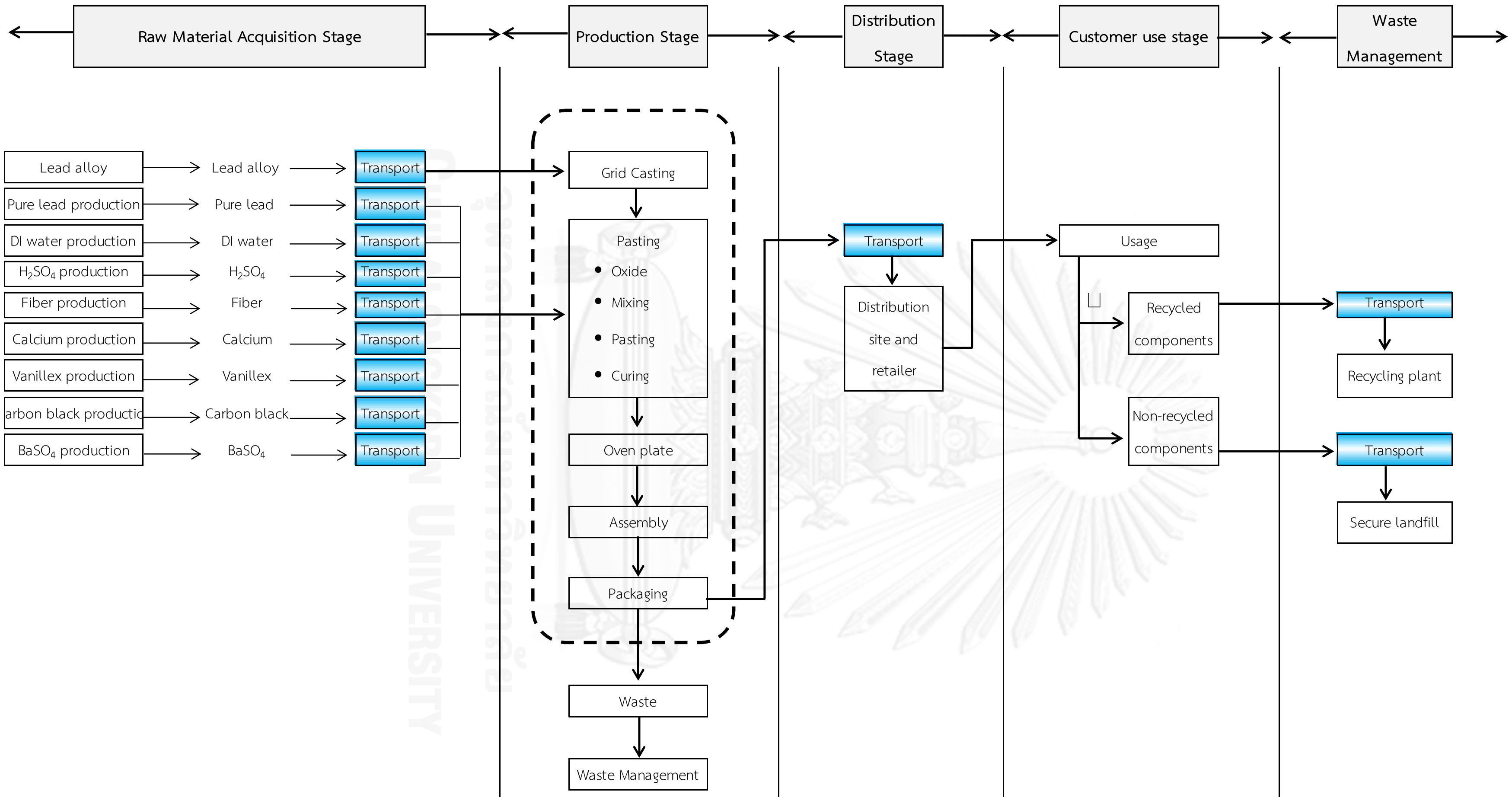


Figure 3-4 Life cycle flow chart of hybrid battery (Battery B)

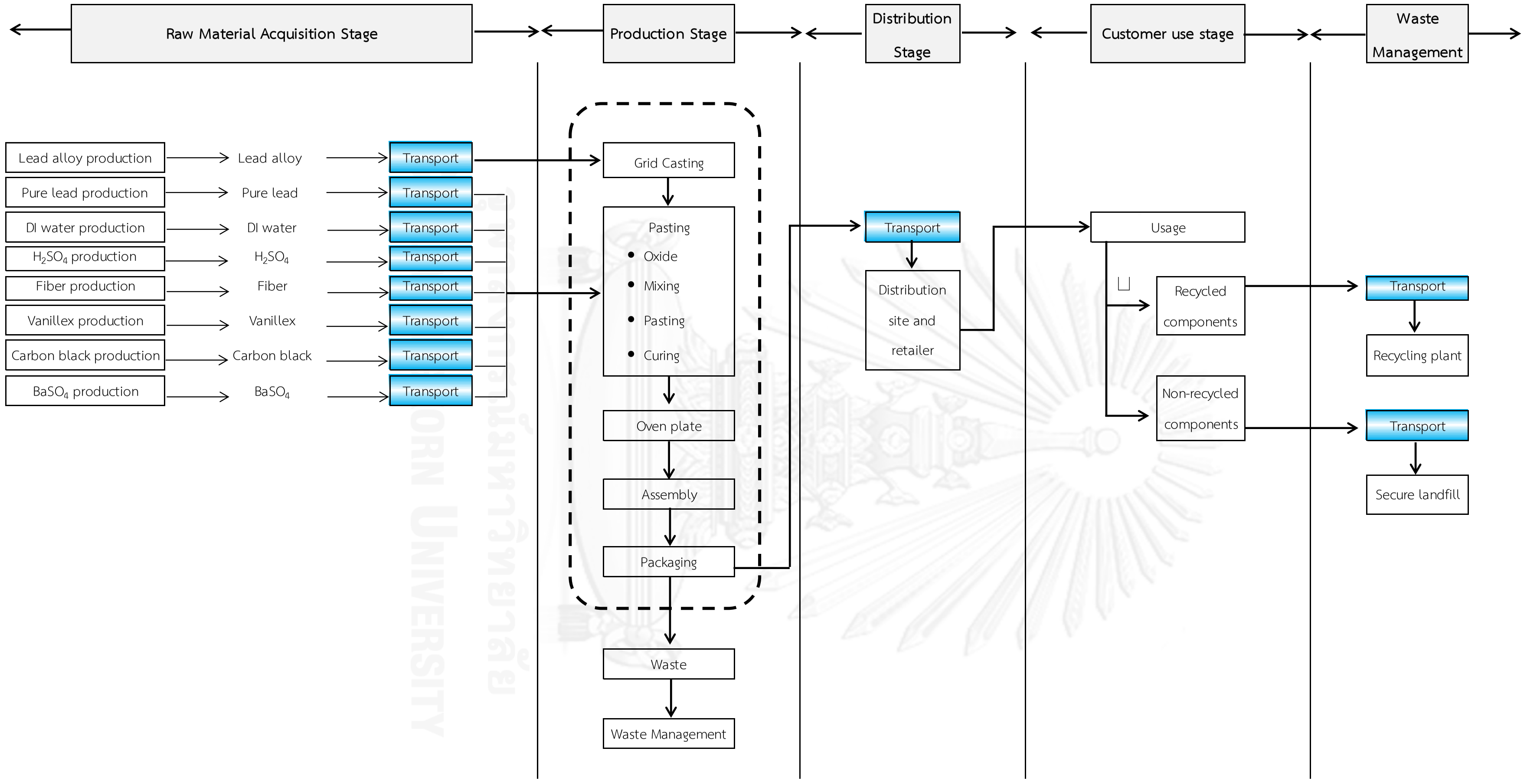


Figure 3-5 Life cycle flow chart of conventional battery (Battery C)

3.3.4 Inventory of utilities

The evaluation of environmental impacts required information on the amounts of all utilities used in the production stage of the three batteries. This included: electricity, natural gas, supply water, soft water, and DI water. At the end, allocation based on the quantity of lead in each battery was applied in the estimation of the inventory. The resulting inventory is illustrated in Figures 3-6 to 3-8.

Table 3-2 Sources of data all phases (Stages) throughout LCA of vehicle batteries

Phases	Inventories	Sources of data
Raw material acquisition	Extracted lead	Data from the factory
	Recycling lead	Goedkoop et al. (2010)
	Polypropylene	Data from the factory
	Recycling polypropylene	Weigel (2011)
	Polyethylene	Data from the factory
	Recycling polyethylene	Weigel (2011)
	Polycarbonate	Data from the factory
	Indicator sign	Data from the factory
	Sulfuric Acid	Data from the factory
	Carton	Data from the factory
	Recycling carton	Goedkoop et al. (2010)
	Natural gas	Data from the factory
Transportation	Lead	Data from the factory
	Containers	Data from the factory
	Covers	Data from the factory
	Vent plugs	Data from the factory
	Separators	Data from the factory
	Indicator sign	Data from the factory
	Sulfuric Acid	Data from the factory
	Carton	Data from the factory

Table 3-2 Sources of data all phases (Stages) throughout LCA of vehicle batteries (cont.)

Phases	Inventories	Sources of data
	Natural gas	Data from the factory
Production	Electricity	Data from the factory
	Natural gas	Data from the factory
	Supply water	Data from the factory
	Soft water	Data from the factory
	DI water	Data from the factory
Distribution	North (4 Wheels)	Data from the factory
	North (6 Wheels)	Data from the factory
	South (6 Wheels)	Data from the factory
	East (4 Wheels)	Data from the factory
	East (6 Wheels)	Data from the factory
	West (4 Wheels)	Data from the factory
	West (6 Wheels)	Data from the factory
	Center (4 Wheels)	Data from the factory
	Center (6 Wheels)	Data from the factory
	Northeast (4 Wheels)	Data from the factory
	Northeast (6 Wheels)	Data from the factory
Customer use	DI water	Data from the factory
Waste management	Battery Management	Salomone et al. (2005)

Table 3-3 Bill of materials for all types of batteries (1 FU)

No.	Raw materials	Weight of components (g)			Recycling material	Source
		Battery A	*Battery B*	*Battery C*		
1	Positive terminal	126	213	275	√	Local
2	Negative terminal	126	213	275	√	Local
3	Positive plates	7,203	9,137	11,953	√	Local
	Lead alloy	N/A	N/A	N/A		
	Pure lead	N/A	N/A	N/A		
	DI water	N/A	N/A	N/A		
	H_2SO_4	N/A	N/A	N/A		
	Fiber	N/A	N/A	N/A		
	Calcium	N/A	-	-		
	Vanillex	N/A	N/A	-		
	Carbon black	N/A	N/A	N/A		
	$BaSO_4$	N/A	N/A	N/A		
4	Negative plates	6,971	8,216	10,637	√	Local
	Lead alloy	N/A	N/A	N/A		
	Pure lead	N/A	N/A	N/A		
	DI water	N/A	N/A	N/A		
	H_2SO_4	N/A	N/A	N/A		
	Fiber	N/A	N/A	N/A		
	Calcium	N/A	N/A	-		
	Vanillex	N/A	N/A	-		
	Carbon black	N/A	N/A	N/A		
	$BaSO_4$	N/A	N/A	N/A		
5	Cut-out and Cell connectors	738	984	1,476	√	Local Local
6	Container	765	1,145	1,718	√	Local
7	Cover	423	298	723	√	Local
8	Vent plug	15.6	41.6	57.6	√	Local
9	Separators	297	563	919	×	Local
10	Indicator sign	8	10.7	16	×	Local
11	Sulfuric acid	6,678	8,167	13,500	×	Local
12	Carton	230	307	460	√	Local
	Total	**23,587**	**29,295**	**42,010**		

Table 3-4 Amount of components and types of vehicles for transportation

No.	Components	Unit	Quantity			Distance (km)	Types of vehicles in each environmental impacts	
			Battery A	*Battery B*	*Battery C*			
1	Lead	ton	3.25E-03	4.02E-03	5.27E-03	65.3	Transport, lorry 10 wheels 16 tons, runs in normal conditions	a
							Transport, lorry 16-32 t EURO3 RER S 16 tons	b
		ton	4.74E-03	5.86E-03	7.69E-03	134	Transport, lorry 10 wheels 16 tons, runs in rough conditions	a
							Transport, lorry 16-32 t EURO3 RER S 16 tons	b
		ton	2.98E-03	3.69E-03	4.83E-03	61.5	Transport, trailer, 10 wheels, 16 tons, runs in normal conditions	a
							Transport, lorry 16-32 t EURO3 RER S 16 tons	b
		ton	4.11E-03	5.08E-03	6.67E-03	40.6	Transport, trailer, 10 wheels, 16 tons, runs in rough conditions	a
							Transport, lorry 16-32 t EURO3 RER S 16 tons	b
		ton	9.33E-05	1.15E-04	1.51E-04	1.85	Transport, trailer more, 18 wheels, 32 tons, runs in normal conditions	a
							Transport, lorry more 32 t EURO3 RER S 32 tons	b
2	Container (PP)	ton	7.65E-04	1.15E-03	1.72E-03	135	Transport, lorry 6 wheels 11 tons, runs in normal conditions	a
							Transport, lorry 16-32 t EURO3 RER S 11 tons	b
3	Cover (PP)	ton	4.23E-04	2.98E-04	7.23E-04	135	Transport, trailer, 4 wheels, 1.5 tons, runs in normal conditions	a
							Transport, lorry 3.5-7.5 t EURO3 RER S 1.5 tons	b
4	Vent plug (PP)	ton	1.56E-05	4.16E-05	5.76E-05	100	Transport, trailer, 4 wheels, 1.5 tons, runs in normal conditions	a
							Transport, lorry 3.5-7.5 t EURO3 RER S 1.5 tons	b
5	Separator (PE)	ton	2.97E-04	5.63E-04	9.19E-04	100	Transport, lorry 6 wheels 11 tons, runs in normal conditions	a
							Transport, lorry 16-32 t EURO3 RER S 11 tons	b

Table 3-4 Amount of components and types of vehicles for transportation (cont.)

No.	Components	Unit	Quantity			Distance (km)	Types of vehicles in each environmental impacts	
			Battery A	*Battery B*	*Battery C*			
6	Indicator sign (PC)	ton	8.00E-06	1.07E-05	1.60E-05	700	Transport, lorry more, 22 wheels 32 tons, runs in normal conditions	a
							Transport, lorry 3.5-7.5 t EURO3 RER S 1.5 tons	b
7	Sulfuric Acid	ton	6.68E-03	8.17E-03	1.35E-02	300	Transport, trailer, 10 wheels, 16 tons, runs in normal conditions	a
							Transport, lorry 16-32 t EURO3 RER S 16 tons	b
8	Carton	ton	2.30E-04	3.07E-04	4.60E-04	120	Transport, lorry 4 wheels 7 tons, runs in normal conditions	a
							Transport, lorry 3.5-7.5 t EURO3 RER S 7 tons	b
9	Natural gasr	ton	7.57E-04	1.57E-03	3.10E-03	236	Transport, natural gas, pipeline, long distance RER S	b

Remarks: a for evaluation of global warming potential

b for evaluation of acidification, ozone depletion, heavy metal emission, and energy resource consumption

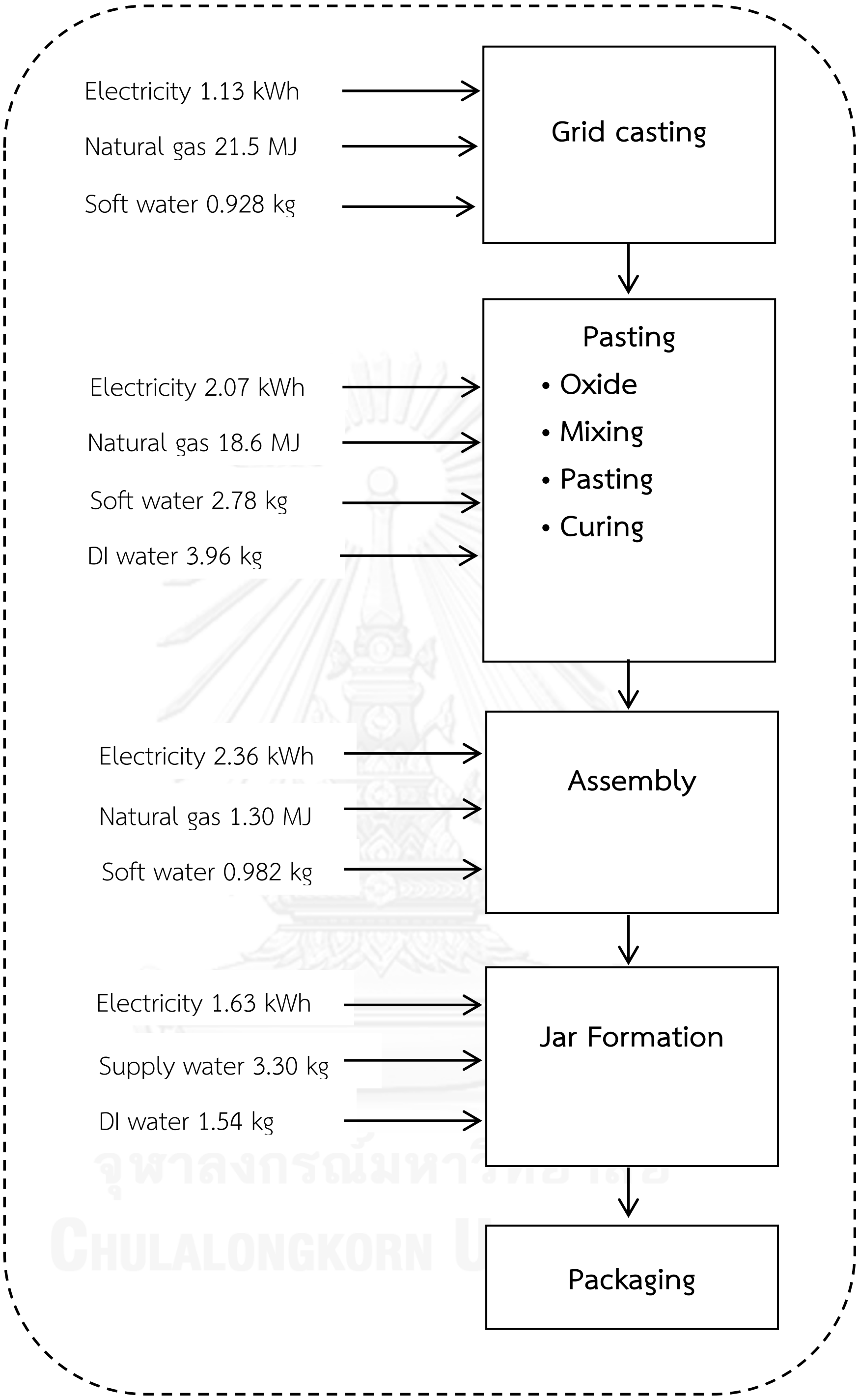


Figure 3-6 Inventory of utilities used in maintenance free batteries (Battery A) production

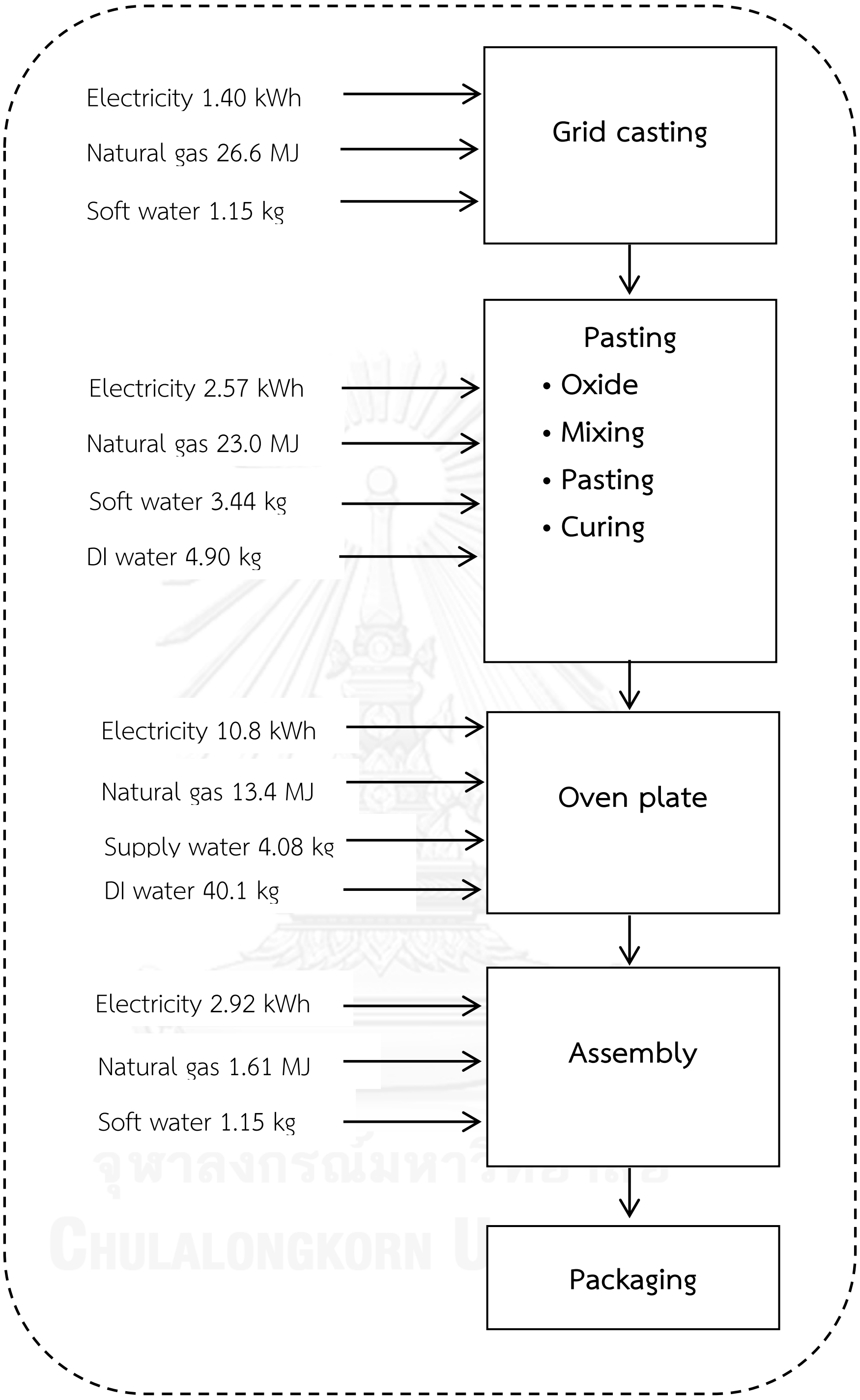


Figure 3-7 Inventory of utilities used in hybrid batteries (Battery B) production

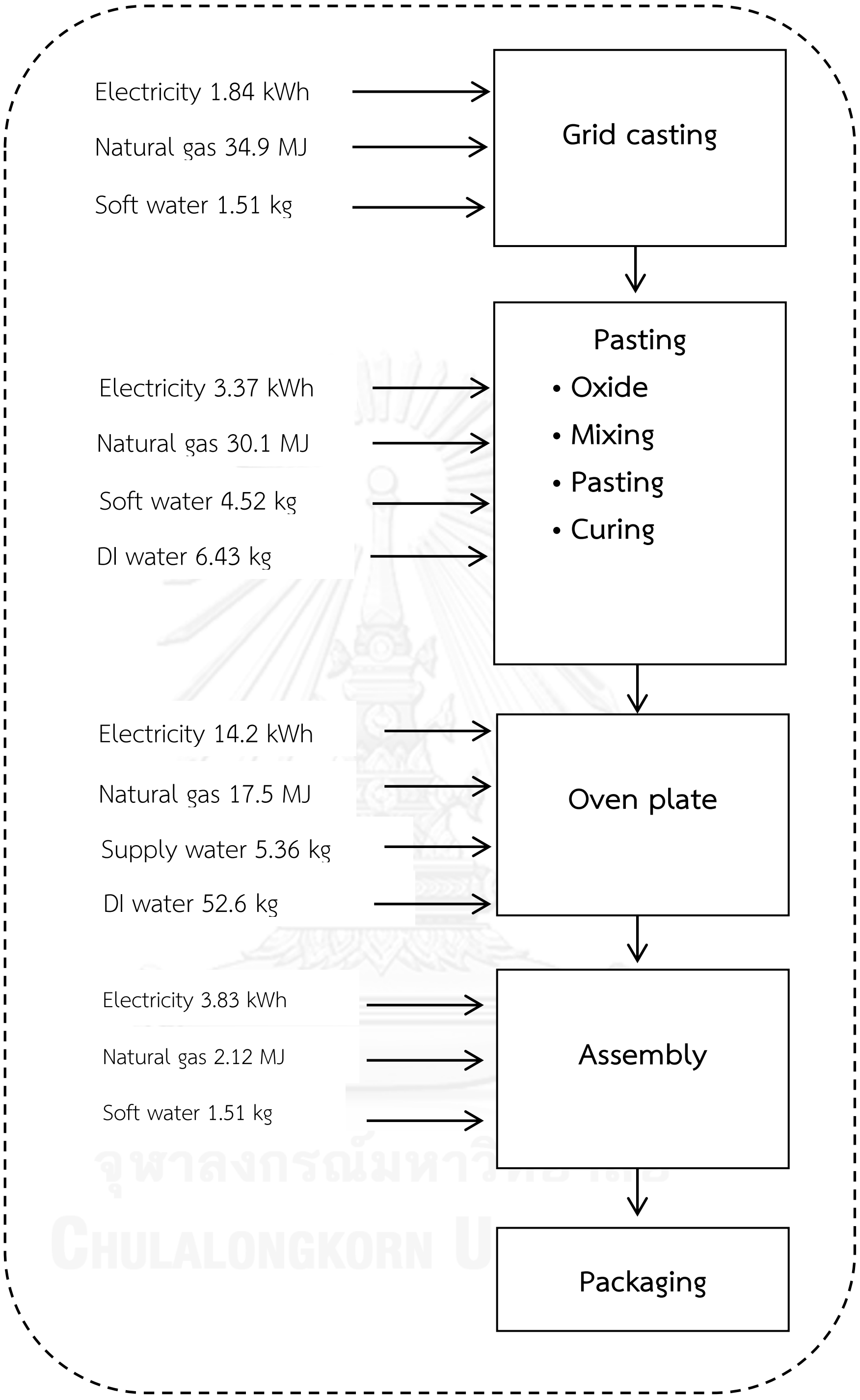


Figure 3-8 Inventory of utilities used in conventional batteries (Battery C) production

3.3.5 Inventory of distribution

Disrtribution stage requires the inventory regarding the amount of components for vehicle batteries, distance, and type of vehicle in Tables 3-6.

3.3.6 Consumer use

The use of battery was based on the following assumptions.

- The vehicle ran 100 km per day.
- Distilled water was consumed at the rate of 40 grams per 1,000 kilometers.
- Maintenance free battery (Battery A) did not need distilled water due to the small evaporation rate throughout its life (4 years).
- Hybrid battery (Battery B) required fresh distilled water at every 6 months throughout its life 3 years).
- Conventional battery (Battery C) needed to be added with fresh distilled water at every 3 months throughout its life (2 years). Specific assumptions for each type of battery are provided in Table 3-5

Table 3-5 Amount of distilled water consumed throughout life cycle of each type of battery products

Type of battery	Life time (years)	Distilled water (kg)	1 Functional Unit (years)	Distilled water (kg)
Battery A	4	-	4	-
Battery B	3	4.32	4	5.76
Battery C	2	2.88	4	5.76

3.3.7 Waste management

Environmental impacts are evaluated throughout the life cycle of batteries, i.e. global warming potential, acidification, ozone depletion, heavy metal emission, and energy resource consumption. The analysis of the non-recycling case identified the hot spots for each indicator.

Table 3-6 Distribution of three types of vehicles for distribution

No.	Components	Unit	Quantity			Distance	Types of vehicles in each environmental impacts	
			Battery A	*Battery B*	*Battery C*			
1	North, 4 wheels	ton	9.44E-04	8.43E-04	1.14E-03	700	Transport, lorry, 4 wheels, 7 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 7 tons	a b
	North, 6 wheels	ton	1.42E-03	1.26E-03	1.72E-03	700	Transport, lorry, 6 wheels, 8.5 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 8.5 tons	a b
2	South, 6 wheels	ton	2.36E-03	4.21E-03	5.72E-03	1,000	Transport, lorry, 6 wheels, 8.5 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 8.5 tons	a b
3	East, 4 wheels	ton	1.89E-03	1.69E-03	2.29E-03	200	Transport, lorry, 4 wheels, 7 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 7 tons	a b
	East, 6 wheels	ton	4.72E-04	4.21E-04	5.72E-04	200	Transport, lorry, 6 wheels, 8.5 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 8.5 tons	a b
4	West, 4 wheels	ton	6.37E-03	1.90E-03	2.57E-03	200	Transport, lorry, 4 wheels, 7 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 7 tons	a b
	West, 6 wheels	ton	7.08E-04	2.11E-04	2.86E-04	200	Transport, lorry, 6 wheels, 8.5 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 8.5 tons	a b
5	Center, 4 wheels	ton	6.37E-03	5.69E-03	7.72E-03	100	Transport, lorry, 4 wheels, 7 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 7 tons	a b
	Center, 6 wheels	ton	7.08E-04	6.32E-04	8.58E-04	100	Transport, lorry, 6 wheels, 8.5 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 8.5 tons	a b
6	Northeast, 4 wheels	ton	1.65E-03	2.95E-03	4.00E-03	700	Transport, lorry, 4 wheels, 7 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 7 tons	a b
	Northeast, 6 wheels	ton	7.08E-04	1.26E-03	1.72E-03	700	Transport, lorry, 6 wheels, 8.5 tons, runs in rough conditions Transport, lorry 3.5-7.5 t EURO3 RER S 8.5 tons	a b

Remarks: a - for the evaluation of global warming potential

b - for the evaluation of acidification, ozone depletion, heavy metal emission, and energy resource consumption

3.4 Calculation of five environmental impacts

The secondary data for this evaluation was based on some reliable databases especially those used in the Eco-indicator 95 V2.06 method from SimaPro7.3.3, data from IPCC 2006 Guidelines for National Greenhouse Gas Inventories [26], and also Thailand Greenhouse Gas Management Organization (Public Organization).

3.4.1 Global warming (kgCO2eq.):

Greenhouse gas emissions are estimated using associated inventory data per a fuctional unit of product multiplied with associate emission factors (EF_i) (as shown in Equation 3.1).

$$\boxed{GHG_{Emission} = \Sigma[\text{Inventory data}_i \times EF_i]} \qquad (3.1)$$

$GHG_{Emission}$ = Amount of greenhouse gas emissions ($kgCO_2eq.$)
Inventory data = Amount of raw materials, energy used (unit)
EF = Greenhouse gas emission factors of raw materials, energy used ($kgCO_2eq./unit$)
i = Type of raw materials or energy used

3.4.2 Acidification ($kgSO_2eq.$):

The atmosphere acidification ($kgSO_2eq.$) is estimated using inventory data per a fuctional unit of product multiplied by corresponding emission factors (EF_i) (as shown in Equation 3.2).

$$\boxed{SO_{2Emission\ .} = \Sigma[\text{Inventory data}_i \times EF_i]} \qquad (3.2)$$

$SO_{2emission}$ = Amount of sulfur dioxide gas emissions or atmospheric acidification ($kgSO_2eq.$)
Inventory data = Amount of raw materials, energy used (unit)
EF_i = Sulfur dioxide gas emission factor of raw materials, energy used ($kgSO_2eq./unit$)
i = Type of raw materials or energy used

3.4.3 Ozone depletion (kgCFC$_{11}$eq.):

The destruction of the ozone layer (in kgCFC$_{11}$eq) is estimated using associated inventory data per a fuctional unit of product multiplied by the emission factors (EF$_i$) (as shown in Equation 3.3).

$$\boxed{CFC_{11Emission} = \Sigma[\text{Inventory data}_i \times EF_i]} \quad (3.3)$$

CFC$_{11Emission}$ = Amount of CFC$_{11}$gas emissions or the destruction of the ozone layer (kgCFC$_{11}$eq.)
Inventory data$_i$= Amount of raw materials, energy used (unit)
EF$_i$ = CFC$_{11}$ gas emission factor of raw materials, energy used (kgCFC$_{11}$eq./unit)
i = Type of raw materials or energy used

3.4.4 Heavy metal (kgPbeq.):

Heavy metals are contaminated into several types of media, i.e. soil, water, air (in the unit of kgPbeq.). This can be obtained by multiplying the inventory data per a fuctional unit of product by emission factors (EF$_i$) (as shown in Equation 3.4).

$$\boxed{Pbeq. = \Sigma[\text{Inventory data}_i \times EF_i]} \quad (3.4)$$

Pb eq. = Amount of lead gas emissions (kgPbeq.)
Inventory data = Amount of raw materials, energy used (unit)
EF = Lead gas emission factor of raw materials, energy used (kgPbeq./unit)
i = Type of raw materials or energy used

3.4.5 Energy resources consumption (MJ LHV):

Energy resources are defined as anything that can be used as a source of energy i.e. oil, natural gas, and coal (MJ LHV). The inventory data per a fuctional unit of product is multiplied by emission factors (EFi) (as shown in Equation 3.5) to give such indicator.

$$\boxed{\text{Total energy} = \Sigma[\text{Energy usage amount}_i \times EF_i]} \quad (3.5)$$

Total energy = Total amount of used energy (MJ LHV)
Energy usage amount = Amount of used energy (unit)
EF_i = Energy resource emission factor of used energy (MJ LHV/unit)
i = Type of used energy

3.4.6 Transportation of raw material:

The data of transportation of raw materials i.e. the amount of lead, sulfuric acid, containers, covers, vent plugs, separators, indicator signs, and carton (components of a battery), which are collected. The estimates of emission from the summation of delivering and returning trips, are obtained from Equations (3.6) and (3.7), respectively.

Delivering trip (Full load):

$$\boxed{\text{Emission}_{FL}\,(a) = \begin{matrix}\text{Weight of}\\ \text{material (ton)}\end{matrix} \times \begin{matrix}\text{Distance}\\ \text{(km)}\end{matrix} \times \begin{matrix}\text{E.F.}_{FL}\text{ of}\\ \text{vehicle (a)}\end{matrix}} \tag{3.6}$$

Emission_{FL} = Emission of environmental impacts ($kgCO_2eq.$, $kgSO_2eq.$, $kgCFC_{11}eq.$, kgPbeq., MJ LHV)
a = Type of environmental impacts (Global warming, Acidification, Ozone depletion, Heavy metal emission, Energy resource consumption)
Weight of material = Weight of material (tonne)
Distance = Distance between suppliers to the factory/ the factory to dealer (kilometer)
E.F._{FL} of vehicle = Emission factor of each type of vehicles [($kgCO_2eq.$, $kgSO_2eq.$, $kgCFC_{11}eq.$, kgPbeq., MJ LHV)]/(tonne*(kilometer))

Returning trip (No load):

$$\text{Emission}_{NL}\text{ (a)} = \text{Weight of material (ton)} \times \text{Distance (km)} \times \text{E.F.}_{NL}\text{ of vehicle (a)} \,/\, \text{Load of vehicle} \tag{3.7}$$

Emission_{NL} = Emission of environmental impacts ($kgCO_2eq.$, $kgSO_2eq.$, $kgCFC_{11}eq.$, kgPbeq., MJ LHV)
a = Type of environmental impacts (Global warming, Acidification, Ozone depletion, Heavy metal emission, Energy resource consumption)
Weight of material = Weight of material (tonne)
Distance = Distance between suppliers to the factory/ the factory to dealer (kilometer)
E.F._{NL} of vehicle = Emission factor of each type of vehicles [($kgCO_2eq.$, $kgSO_2eq.$, $kgCFC_{11}eq.$, kgPbeq., MJ LHV)]/(kilometer)
Load of vehicle = Total load of vehicle (tonne)

CHAPTER IV

RESULTS INTERPRETATION AND OPTION ANALYSIS

LCI was collected in last chapter under the scope of the study. In this chapter, associated environmental impacts are classified, grouped, and compared among the three types of batteries. Hot spots were identified and potential options for decreasing the environmental impacts were proposed. Five environmental impacts were assessed throughout life cycle of vehicle batteries, i.e. global warming potential, acidification, ozone depletion, heavy metal emission, and energy resource consumption according to Eco-indicator 95 V2.06 (Europe e), the criteria set out in midpoint impacts. Figure 4-1 displays the research boundary of this study.

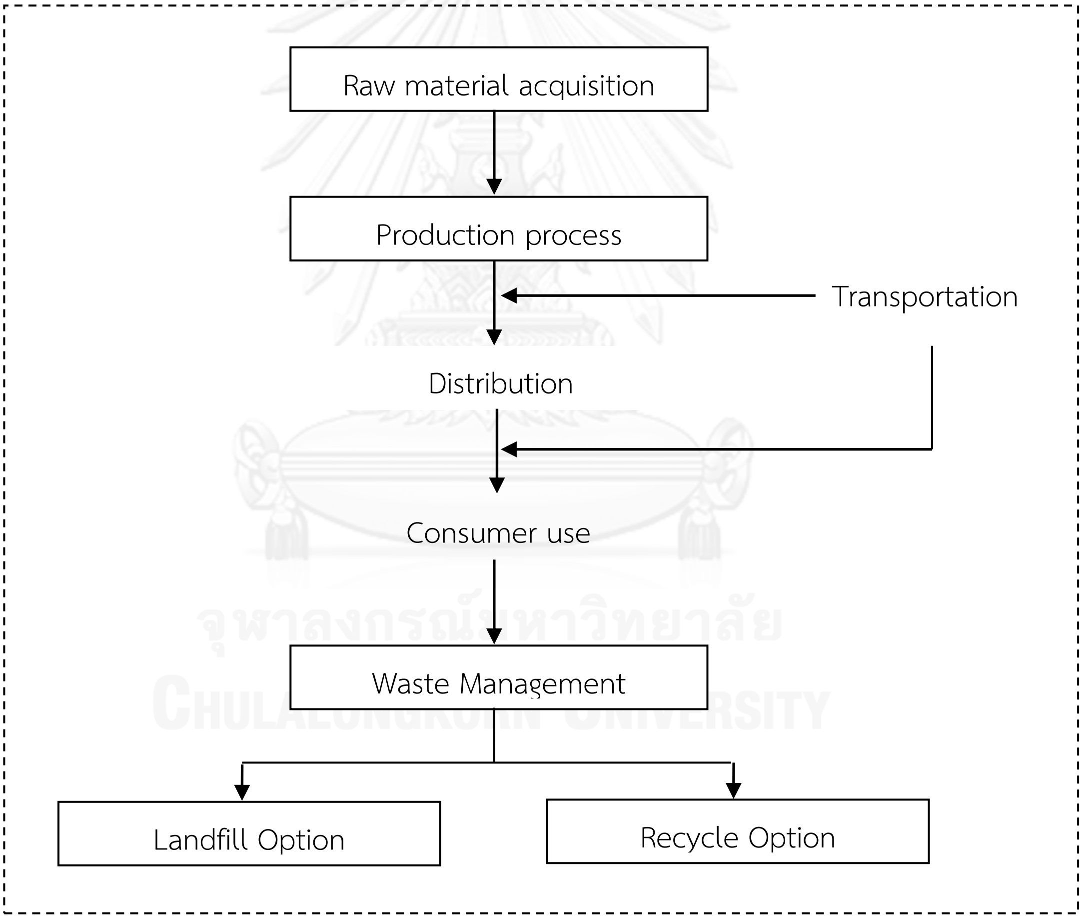


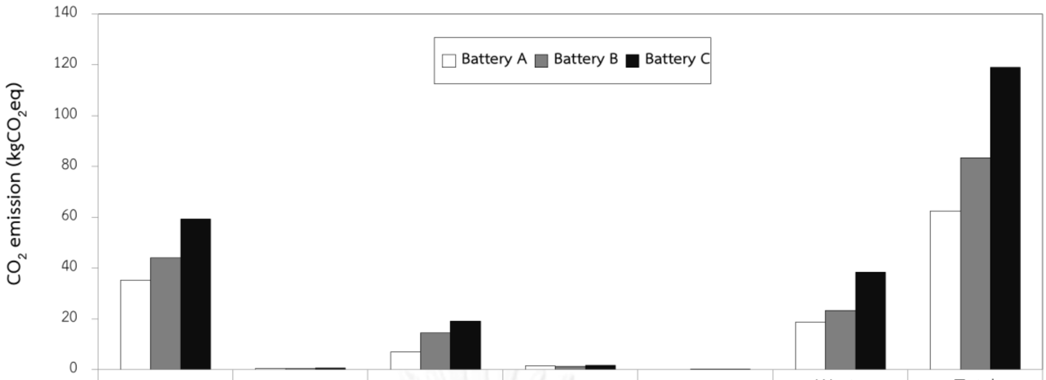
Figure 4-1 Research boundary

4.1 Interpretation

In this section, all stages throughout life cycle of the representations were analyzed. It was assumed here that the used batteries could not be recycled, therefore, all components of used batteries were sent to landfill. First, global warming potential was evaluated, and all carbon footprints are illustrated in Figure 4-2. The highest greenhouse gas was released by Battery C at 119 kgCO_2eq, followed by Battery B and Battery A, that released 83.4 and 62.3 kgCO_2eq, respectively. The hotspots were taken from the raw material acquisition stage which accounted for 49.9-56.5% of all stages (Figure 4-3), within which the extracted lead was responsible for 85.4-88.7%. The second hot spots were the waste management stage which generated 27.9-32.2% of all emission throughout their life cycles, as shown in Figure 4-3. The treatment of sulfuric acid was needed before emitting the waste water to the environment, and the sodium hydroxide used in this neutralization process was the major CO_2 emitter (74.9-76.8% from all material in this stage). As the Battery C contained more lead and acidic solution, this correspondingly led to a higher emission of GHGs from lead production and sodium hydroxide used in neutralization.

Figure 4-4 displays that the highest sulfur dioxide emission was from Battery C at 1.66 kgSO_2eq followed by Battery B (1.21 kgSO_2eq), and Battery A (0.961 kgSO_2eq). Batteries had the same hotspot at the raw material acquisition stage that accounted for 84.3-87.0% from the overall emission (Figure 4-5), where the extracted lead used for casting process was the main origin for sulfur dioxide emission (85.3-88.0% of all materials). The waste management stage was the second hotspot which was responsible for another 6.96-8.36% (Figure 4-5), with the sodium hydroxide (neutralization process) being the major emitter (97.8-98.1%).

In terms of ozone layer depletion (CFC_{11}eq), Figure 4-6 reveals that Battery C emitted the highest amount of CFC_{11}eq (7.99E-06 kgCFC_{11}eq), followed by Battery B (5.67E-06 kgCFC_{11}eq) and Battery A (4.35E-06 kgCFC_{11}eq). This shared similar trend with the global warming and acidification impacts with the major hot spot from the raw material acquisition stage (lead extraction) followed by the waste management stage (use of NaOH). Quantitative measures of this impact are illustrated in Figure 4-6 and Figure 4-7.



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Total (kgCO2eq)
☐ Battery A	35.2	0.322	6.82	1.44	0.000000	18.6	62.3
▨ Battery B	44.0	0.390	14.6	1.23	0.000149	23.3	83.4
■ Battery C	59.3	0.602	19.1	1.67	0.000149	38.3	119

Figure 4-2 Carbon dioxide emission throughout life cycle of three types of vehicle battery

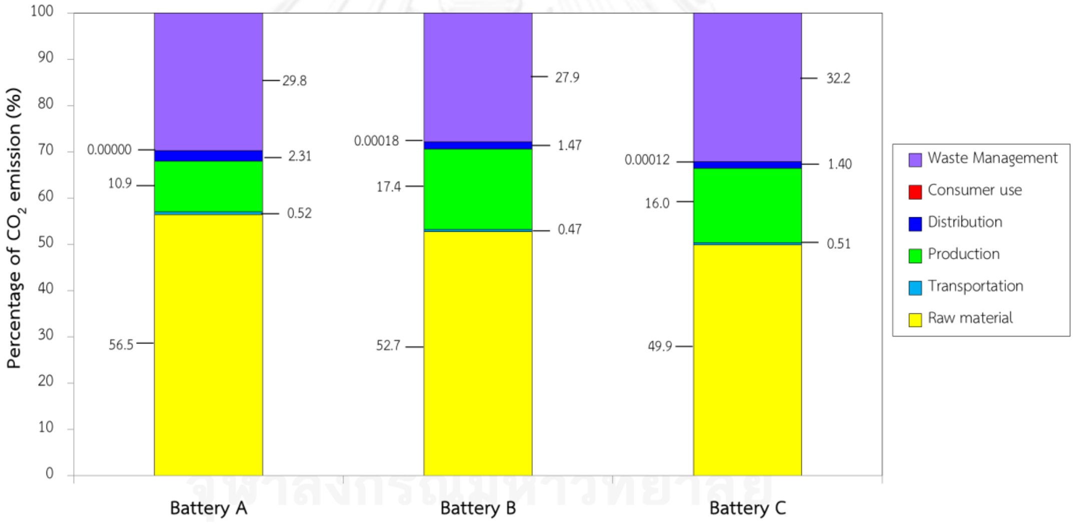
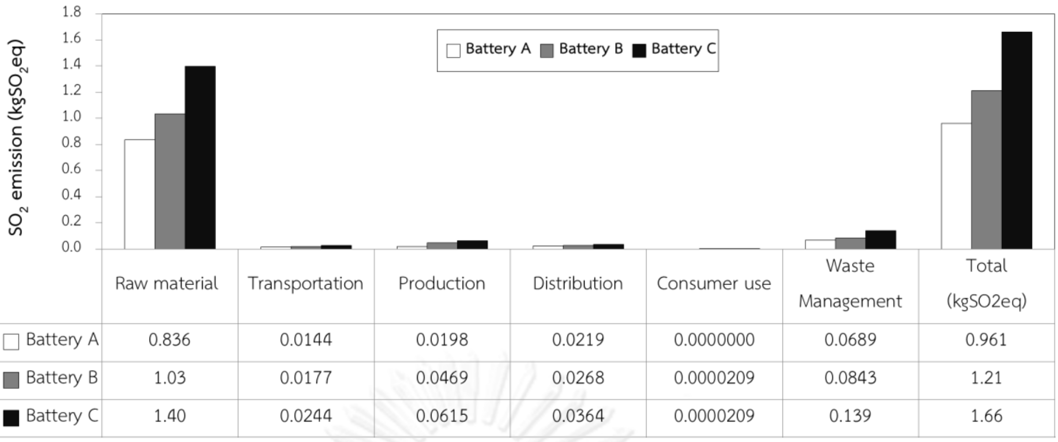


Figure 4-3 Distribution of carbon dioxide emission throughout life cycle of three types of vehicle battery



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Total (kgSO2eq)
☐ Battery A	0.836	0.0144	0.0198	0.0219	0.0000000	0.0689	0.961
▨ Battery B	1.03	0.0177	0.0469	0.0268	0.0000209	0.0843	1.21
■ Battery C	1.40	0.0244	0.0615	0.0364	0.0000209	0.139	1.66

Figure 4-4 Sulfur dioxide emission throughout life cycle of three types of vehicle battery

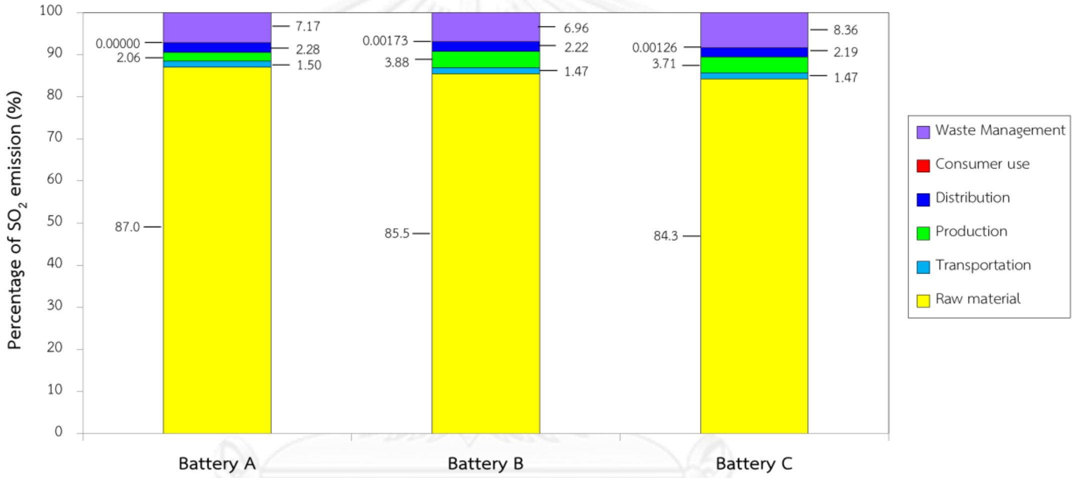
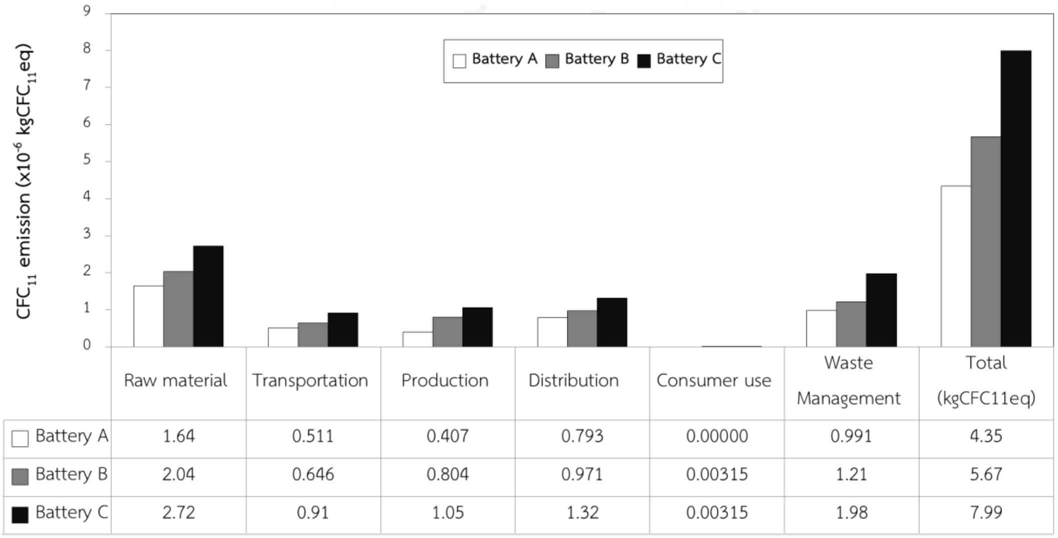


Figure 4-5 Distribution of sulfur dioxide emission throughout life cycle of three types of vehicle battery



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Total (kgCFC11eq)
☐ Battery A	1.64	0.511	0.407	0.793	0.00000	0.991	4.35
▨ Battery B	2.04	0.646	0.804	0.971	0.00315	1.21	5.67
■ Battery C	2.72	0.91	1.05	1.32	0.00315	1.98	7.99

Figure 4-6 CFC$_{11}$ emission throughout life cycle of three types of vehicle battery

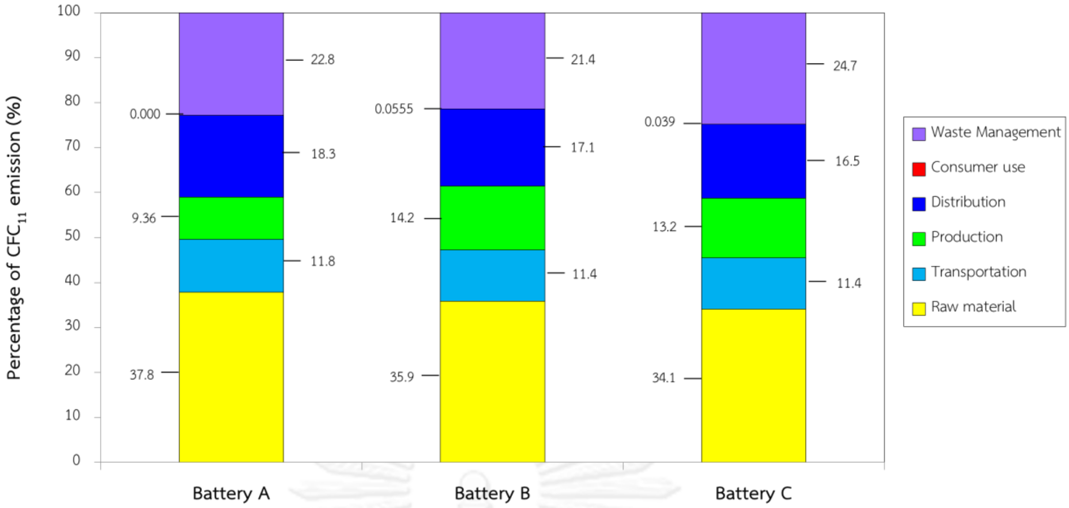
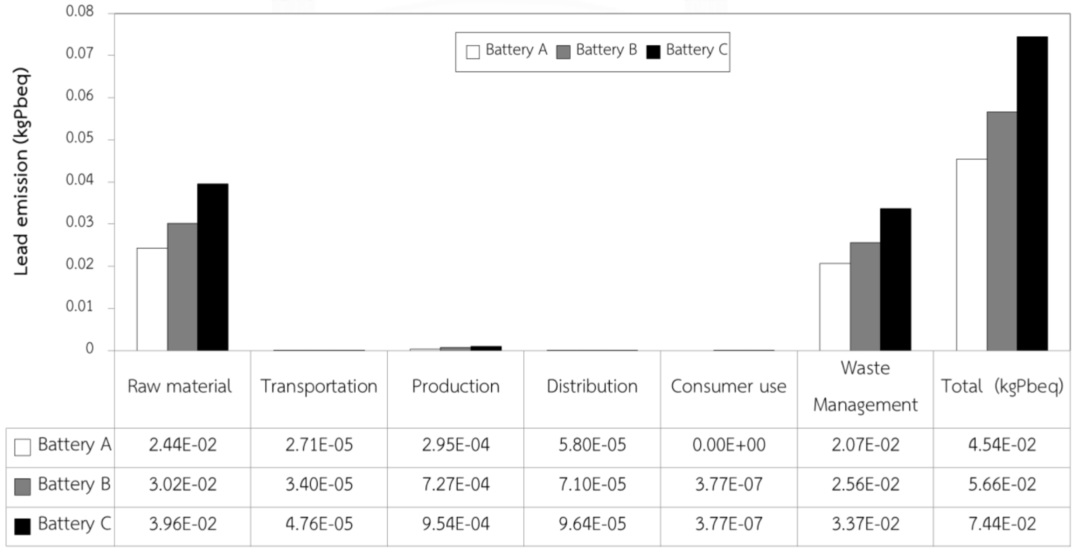


Figure 4-7 Distribution of CFC_{11} emission throughout life cycle of three types of vehicle battery

The fourth impact is revealed in Figure 4-8 (heavy metal emission). Battery C released lead emission more than Battery B and Battery A, i.e. 7.44E-02 kgPbeq for Battery C, 5.66E-02 kgPbeq for Battery B and 4.54E-02 kgPbeq for Battery A. The raw material acquisition stage was still the main hot spot responsible for 53.2-53.6% of the overall emission (Figure 4-9), where the extracted lead accounted for 99.3-99.5% of the emission from this stage. (Figure 4-9) also demonstrates that the second hot spot was the waste management particularly the landfill of lead which covered 45.2-45.5%. In contrast, heavy metal emission was different from other impacts because only the extracted lead was still the main sources of lead emission in both the raw material acquisition and waste management stage at 98.0-99.5%.



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Total (kgPbeq)
☐ Battery A	2.44E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	2.07E-02	4.54E-02
■ Battery B	3.02E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	2.56E-02	5.66E-02
■ Battery C	3.96E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	3.37E-02	7.44E-02

Figure 4-8 Lead emission throughout life cycle of three types of vehicle battery

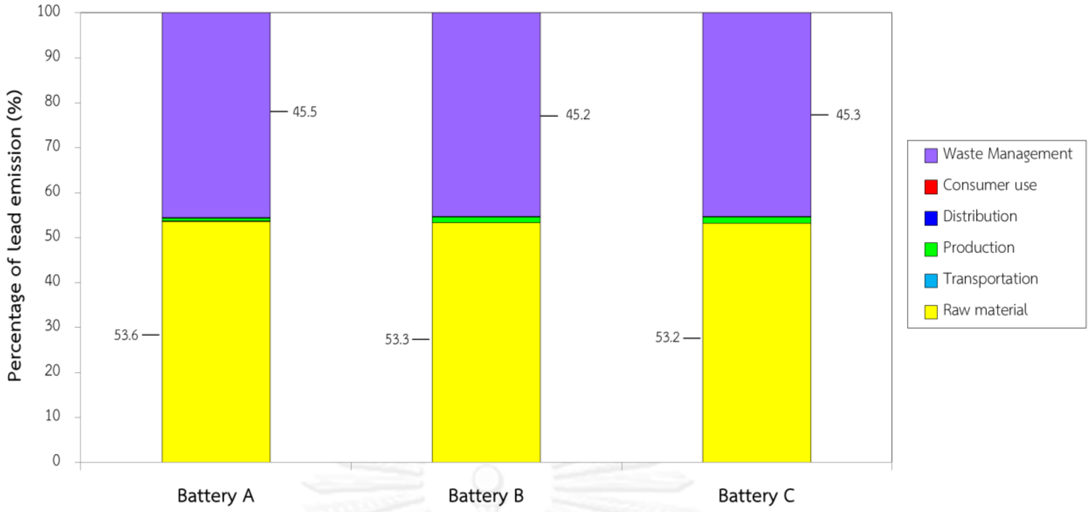
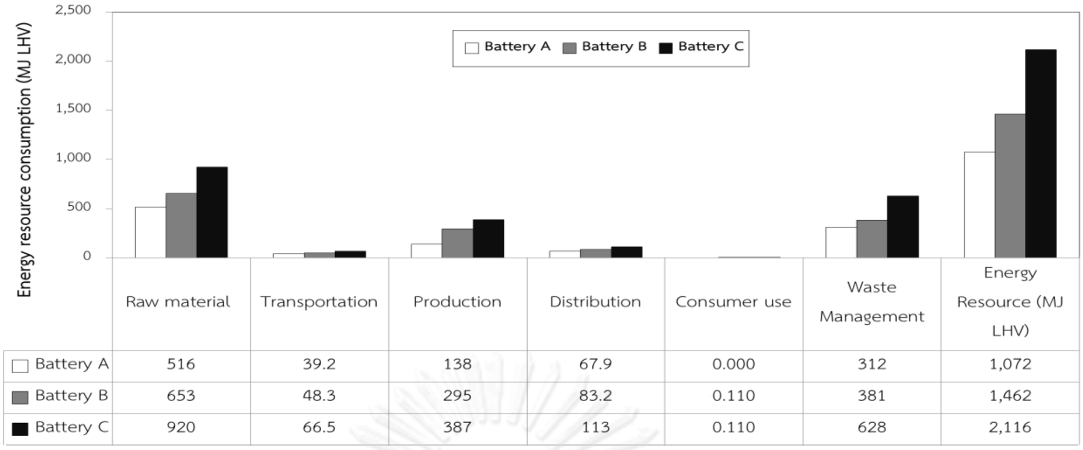


Figure 4-9 Distribution of lead emission throughout life cycle of three types of vehicle battery

Lastly, energy resources consumption is in Figure 4-10. Battery C consumed the highest amount of energy at 2,116 MJ LHV; whilst Battery B and Battery A accounted for 1,462 and 1,072 MJ LHV, respectively. All types of vehicle batteries required the highest amount of energy at the raw material acquisition stage, due particularly which was responsible for 43.5-48.1% of all stages (Figure 4-11), and the extracted lead was the main origin for energy consumption calculated for 67.1-73.7% of all material in this stage. The second hot spot (waste management) for this impact category shared 26.1-29.7 of the overall impact as demonstrated in Figure 4-11. Most energy was consumed at the neutralization of sulfuric acid which accounted for 97.8-98.1% from this stage.



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Energy Resource (MJ LHV)
☐ Battery A	516	39.2	138	67.9	0.000	312	1,072
▨ Battery B	653	48.3	295	83.2	0.110	381	1,462
■ Battery C	920	66.5	387	113	0.110	628	2,116

Figure 4-10 Energy resource consumption throughout life cycle of three types of vehicle battery

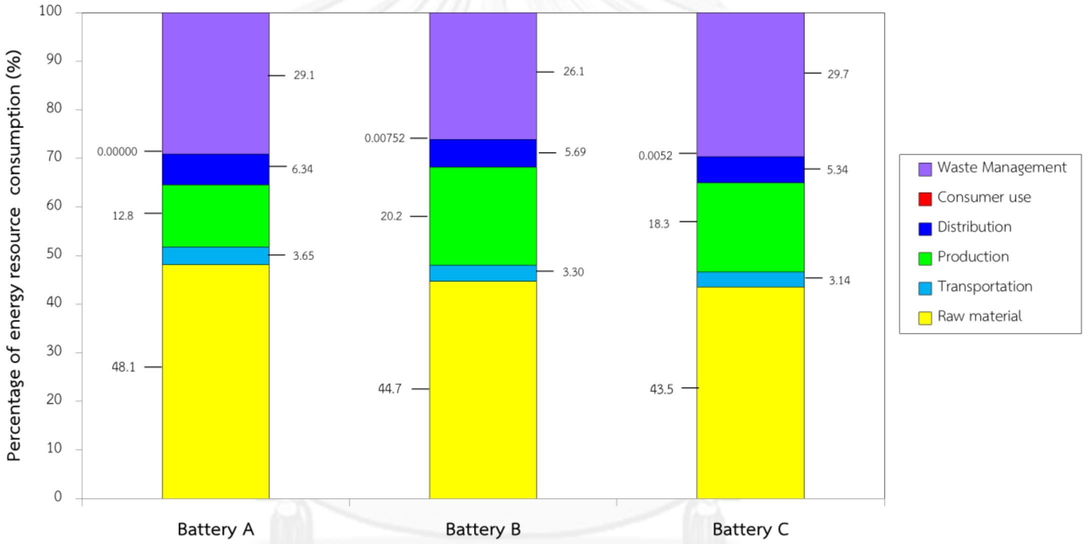


Figure 4-11 Distribution of energy resource consumption throughout life cycle of three types of vehicle battery

4.2 Hotspot analysis and option proposition

The findings from the previous section, as summarized again in Table 4-2, suggest that major life cycle stages with highest environmental impacts were taken place at the raw material acquisition stage by the extracted lead, and at the neutralization process, with sodium hydroxide. However, heavy metal potential was excluded in the trend, because the landfill of lead became the main impact for this stage. The comparison among the three types of vehicle batteries proved that gas, metal emission and energy consumption of Battery C were higher than Battery B and Battery A, respectively. This is virtually due to a larger amount of lead and sulfuric in Battery C which caused more environmental impacts. To mitigate such impacts, improvement options should be placed at these two major stages. In this work, two potential proposed as delineated belows:

1.) Recycling material option
2.) Chemical replacement

In the collection option, the spent batteries have to be returned to the recycling facilities. Five percentages of collections of spent batteries were assumed, i.e. 0%, 25%, 50%, 75%, and 100%. Typical collection percentage for spent batteries in Thailand was estimated to be around 75% [3] and this 75% collection percentage was set as a baseline scenario. The collected spent batteries had to go through the recycling facilities where the various components in the batteries were recycled at their typical recycling efficiencies as mentioned below.

In the second option, it was proposed that $Ca(OH)_2$ be used to neutralize H_2SO_4 instead of NaOH as the two bases were reported to be used interchangeably [20, 23, 27] When the different chemicals were used to neutralize the acid, it was found that the different products were occurred in the waste management stage, as displayed in Equations (4.1) [28] and (4.2) [27].

$$H_2SO_4(aq) + 2NaOH(aq) \longrightarrow Na_2SO_4(aq) + 2H_2O(l) \qquad (4.1)$$

$$H_2SO_4(aq) + Ca(OH)_2(aq) \longrightarrow CaSO_4(aq) + 2H_2O(l) \qquad (4.2)$$

This study assumed four scenarios in part of chemical replacement, i.e. 1) baseline scenario; 75% of spent batteries could be collected and NaOH was used to neutralize acid in the spent batteries (standard case scenario), 2) Option A; 75% of spent batteries could be collected and other strong base, $Ca(OH)_2$ was used to neutralize acid in the spent batteries 3) Option B; all spent batteries could be collected and NaOH was used to pretreat acid in the spent batteries, and 4) all spent batteries could be collected and other strong base, $Ca(OH)_2$ was used to neutralize acid in the spent battery, displayed in Table 4-1.

Table 4-1 Potential options to reduce the environmental impacts

Scenarios	Percentage of collection	Used chemicals in waste management stage	Description
Baseline scenario	75%	NaOH	Seventy-five percentage of spent battery collection is applied and NaOH is used for the neutralization process.
Option A	75%	$Ca(OH)_2$	Seventy-five percentage of spent battery collection is used and $Ca(OH)_2$ is used for the neutralization process.
Option B	100%	NaOH	One hundred percentage of spent battery collection is achieved and NaOH is used for the neutralization process.
Option C	100%	$Ca(OH)_2$	One hundred percentage of spent battery collection is used and $Ca(OH)_2$ is used for the neutralization process.

These two options were comparatively evaluated for their environmental impacts in the next section.

This study proved that the hot spot of all impacts was taken place at the raw material acquisition stage, the extracted lead was the important cause. In addition, the second hotspot was at the waste management with sodium hydroxide (the main origin). Option propositions were proposed to reduce all five environmental impacts, i.e. 1) Material recycling option and 2) Chemical replacement which were in option evaluation article.

4.3 Option Evaluation

In this section, the two options proposed in the previous section were evaluated for their environmental impacts as detailed below.

4.3.1 Material recycling option

There were several components of vehicle batteries that could be recycled, i.e. lead, polypropylene, polyethylene, and carton. How effective the recycle of battery can be depended on two major factors. The first is the collection efficiency of old batteries, and the second is the recycling efficiency of each particular material.

Table 4-2 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (0% collection of spent batteries)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO_2eq	35.2	0.322	6.82	1.44	0.00	18.6	**62.3**
Battery B			44.0	0.390	14.6	1.23	0.00	23.3	**83.4**
Battery C			59.3	0.602	19.1	1.67	0.00	38.3	**119**
Battery A	Acidification	kgSO_2eq	0.836	0.0144	0.0198	0.0219	0.0000000	0.0689	**0.961**
Battery B			1.03	0.0177	0.0469	0.0268	0.0000209	0.0843	**1.21**
Battery C			1.40	0.0244	0.0615	0.0364	0.0000209	0.139	**1.66**
Battery A	Ozone depletion	kgCFC_{11}eq	1.64E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	9.91E-07	**4.35E-06**
Battery B			2.04E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	1.21E-06	**5.67E-06**
Battery C			2.72E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.98E-06	**7.99E-06**
Battery A	Heavy matal emission	kgPbeq	2.44E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	2.07E-02	**4.54E-02**
Battery B			3.02E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	2.56E-02	**5.66E-02**
Battery C			3.96E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	3.37E-02	**7.44E-02**
Battery A	Energy resource consumption	MJ LHV	516	39.2	138	67.9	0	312	**1072**
Battery B			653	48.3	295	83.2	0.110	381	**1462**
Battery C			920	66.5	387	113	0.110	628	**2116**

Various collection percentages of spent batteries were set out, i.e. 0%, 25%, 50%, 75%, and 100%, whereas the recycling efficiencies were obtained from literature. Table 4-4 shows the total quantities of components that can be recycled with 0%, 25%, 50%, 75%, and 100% collection. There were only three materials that can be recycled, i.e. lead [29] (main component of a spent battery), plastic [30] (polypropylene for cover and container, and polyethylene for separator), and carton [29] (box for package). This recycling efficiency of all recycling materials in the spent battery is shown in Table 4-3.

Emissions of pollution throughout the battery were the summation of waste (W_1 to W_7) as depicted in Figure 4-12. Raw materials were used for the calculation from the virgin material (R_1) and the recycling material (R_2).

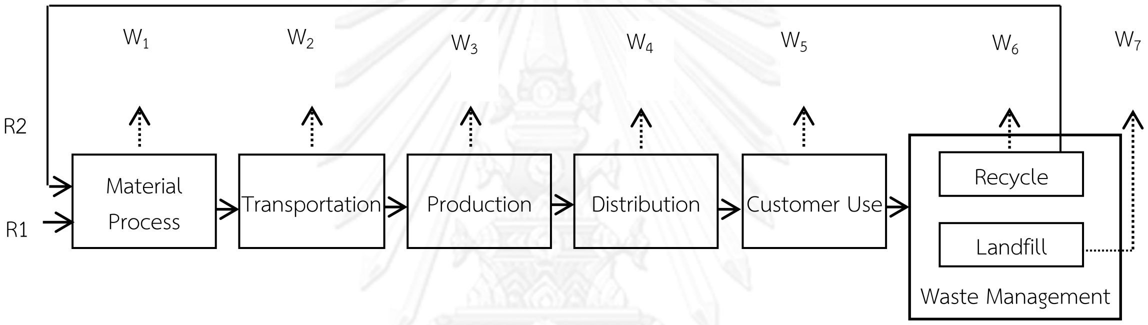


Figure 4-12 Flow chart of emission throughout vehicle batteries

Table 4-3 Recycling efficiency of all recycling materials in the spent battery

Materials	Initial amount of materials (kg)	Recycling amount of materials (kg)
Lead (Goedkoop et al. (2010))	1.5446	1
Plastic (Weigel (2011))	100	6.5
Carton (Goedkoop et al. (2010))	1.03	1

The total recovery of each recyclable component is equal to the product of recycling efficiency, percentage of collection and initial amount of component as illustrated in Equation (4.3).

$$\boxed{\text{Total recycling component} = \text{Recycling efficiency} \times \text{Percentage of collection} \times \text{Initial amount of component (kg)}} \quad (4.3)$$

Table 4-4 Summary of the total quantities of components that can be recycled with 0%, 25%, 50%, 75%, and 100% collections

No.	Raw materials	Unit	*Battery A*					*Battery B*					*Battery C*				
			0%	25%	50%	75%	100%	0%	25%	50%	75%	100%	0%	25%	50%	75%	100%
1	Extracted lead	kg	15.2	12.7	10.3	7.80	5.35	18.8	15.7	12.7	9.65	6.6	24.6	20.6	16.6	12.7	8.7
2	Recycling lead	kg	-	2.5	4.9	7.4	9.8	-	3.0	6.1	9.1	12.1	-	4.0	8.0	12.0	15.9
3	Polypropylene	kg	1.20	1.18	1.16	1.14	1.13	1.49	1.46	1.44	1.41	1.39	2.50	2.46	2.42	2.38	2.34
4	Recycling polypropylene	kg	-	0.02	0.04	0.06	0.08	-	0.02	0.05	0.07	0.10	-	0.04	0.08	0.12	0.16
5	Polyethylene	kg	0.30	0.29	0.29	0.28	0.28	0.56	0.55	0.54	0.54	0.53	0.92	0.90	0.89	0.87	0.86
6	Recycling polyethylene	kg	-	0.00	0.01	0.01	0.02	-	0.01	0.02	0.03	0.04	-	0.01	0.03	0.04	0.06
7	Polycarbonate	kg	0.008	0.008	0.008	0.008	0.008	0.011	0.011	0.011	0.011	0.011	0.016	0.016	0.016	0.016	0.016
8	2NaOH	kg	13.4	6.68	6.68	6.68	6.68	16.3	16.3	16.3	16.3	16.3	27.0	27.0	27.0	27.0	27.0
9	Na_2SO_4	kg	6.68	0.17	0.12	0.06	0.01	8.17	8.17	8.17	8.17	8.17	13.5	13.5	13.5	13.5	13.5
10	Carton	kg	0.23	0.1	0.1	0.2	0.2	0.31	0.23	0.16	0.08	0.01	0.46	0.35	0.24	0.13	0.01
11	Recycling carton	kg	-	41.3	41.3	41.3	41.3	-	0.07	0.15	0.22	0.30	-	0.11	0.22	0.33	0.45

Battery A was the representative for the calculation to find amount of both initial and recycling material for a battery with 75% collection, as shown in Table 4-5.

Table 4-5 Amount of components that can be recycled with 75% collection

No.	Materials	Recycling materials (kg)	Virgin materiasl (kg)
1	Lead	= (1/1.5446) x (75/100) x 15.1654 = 7.36	= 15.1654 – 7.36 = 7.80
2	Polypropylene	= (6.5/100) x (75/100) x 1.2036 = 0.0587	= 1.2036 – 0.0587 = 1.1449
3	Polyethylene	= (6.5/100) x (75/100) x 0.297 = 0.01448	= 0.297 – 0.0587 = 0.283
4	Carton	= (1/1.03) x (75/100) x 0.23 = 0.167	= 0.23 – 0.167 = 0.0625

Similar calculation could be performed when the collection percentage of spent batteries varied from 0%, 25%, 50%, 75%, and 100%.

It became obvious that a higher collection percentage would result in a lower release of emission and a lesser energy resource consumption. In contrast, using a larger amount of the extracted virgin materials affected the environmental more seriously. Figures 4-13 to 4-17 demonstrate the environmental impacts obtained from the recycling of the used batteries with various collection percentages (from 0 to 100%). For Battery A, by increasing the collection ratio from 0 to 100%, the greenhouse gas emission could be cut down from 62.3 to 47.2 kgCO_2eq which was equivalent to the reduction percentage of 24.2% (see Figure 4-13). However, it was estimated that about 75% of spent batteries could be collected [3]; therefore, this condition was assumed to be the typical collection scenario. Within this scenario, an additional greenhouse gas saving of 6.23-7.41% could be achieved depending on the type of battery.

Similarly, Figure 4-14 demonstrates that acidification potential could be reduced by as much as 35.3% when the collection percentage increased from 0 to 100 (for Battery A). But for the typical 75% collection efficiency, the saving of 11.0-12.0% of sulfur dioxide emission could be well achieved.

Comparison of CFC_{11} emission at various collection percentages is presented in Figure 4-15. It was revealed that approximately 10.8% of CFC_{11} emission could be released when the collection percentage increased from 0 to 100. However, the comparison between the typical collection scenario and 100% collection efficiency showed that CFC_{11} could be saved 2.50-2.93%.

Lead emission is illustrated in Figure 4-16 at various collected percentages where it was shown that approximately 62.3% of lead emission could be saved when the collection percentage increased from 0 to 100. The typical collection practice of 75% could save 28.7-29.2% of lead emission.

Figure 4-17 demonstrates energy resource consumption from the life cycle of vehicle batteries at various collection percentages where it was shown that approximately 13.3% of used energy could be saved when the collection percentage increased from 0 to 100. When the typical collection practice of 75% was compared with 100% collection efficiency, one could see an additional used energy saving of 3.06-3.69%.

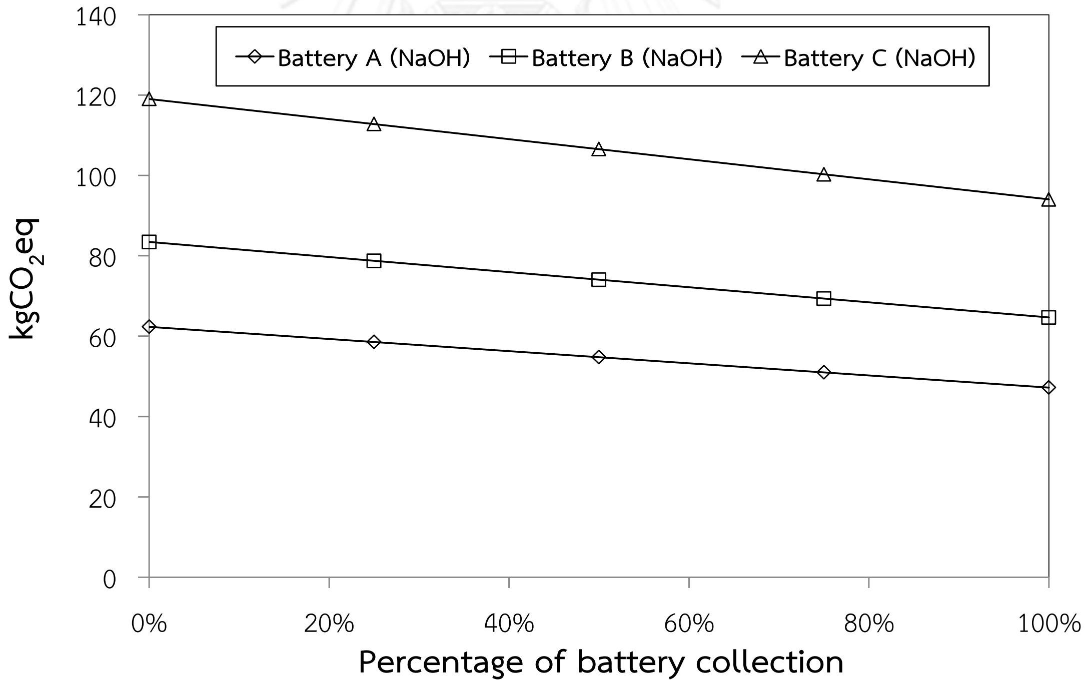


Figure 4-13 Comparison of GHG emission at various collection percentages

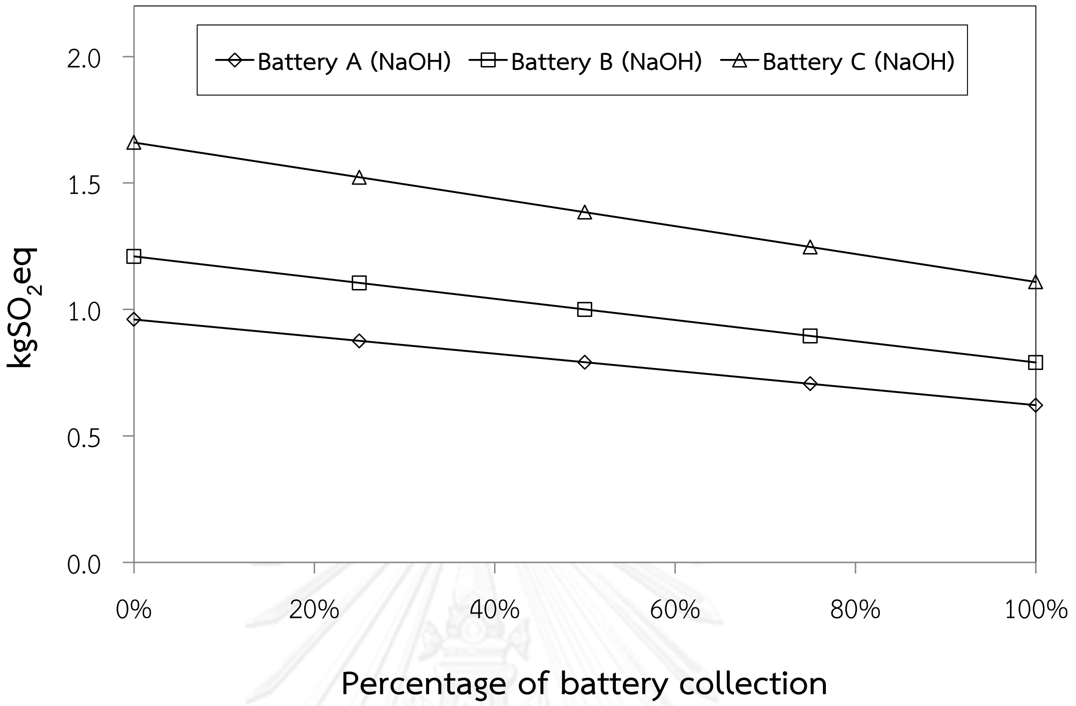


Figure 4-14 Comparison of sulfur dioxide emission at various collection percentages

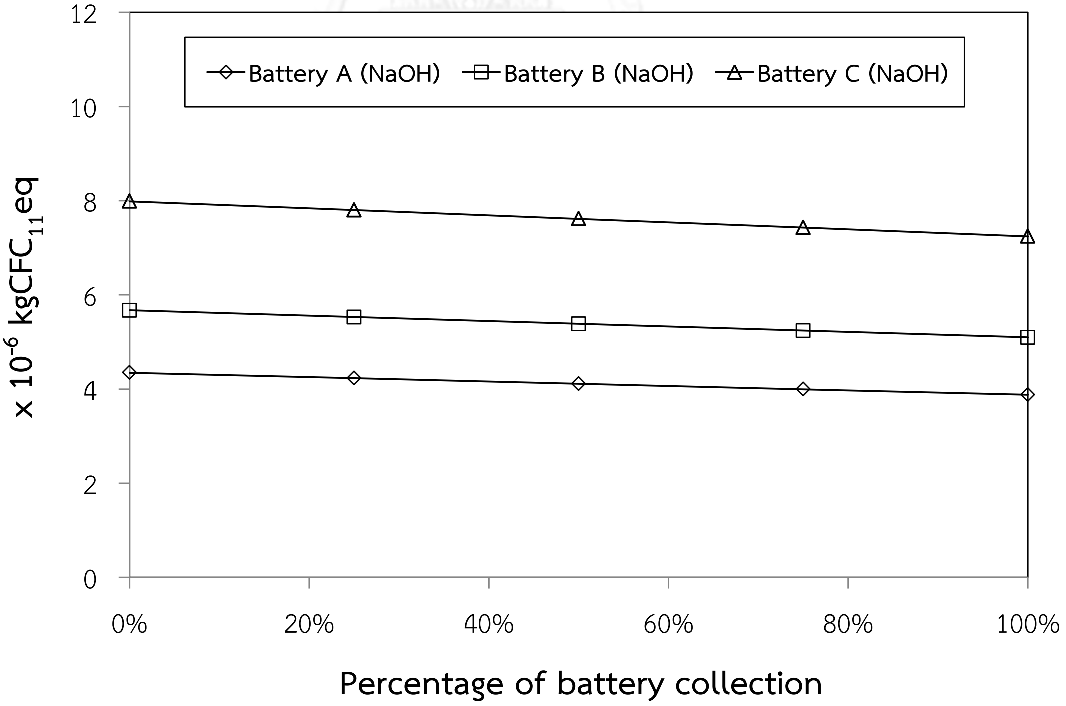


Figure 4-15 Comparison of CFC_{11} emission at various collection percentages

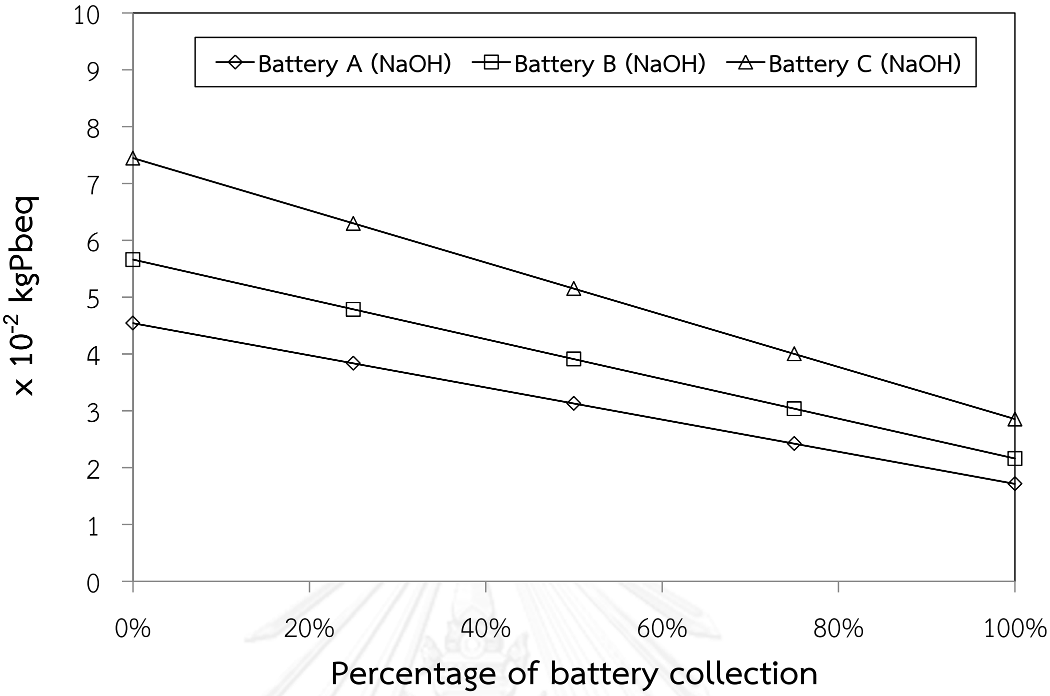


Figure 4-16 Comparison of lead emission at various collection percentages

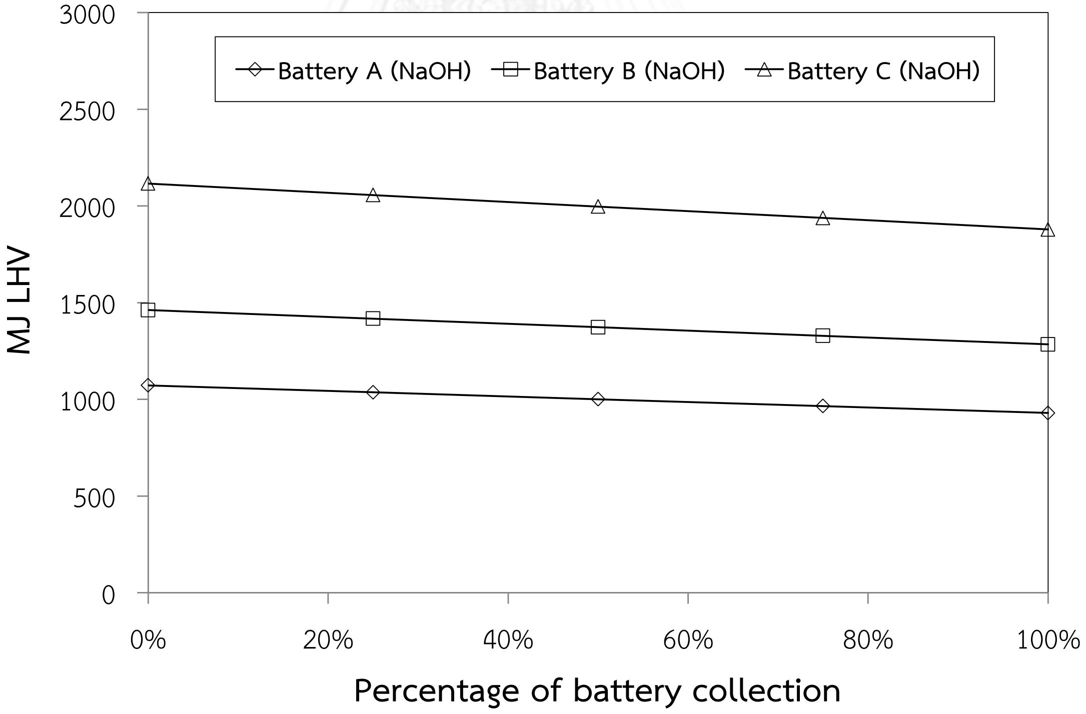
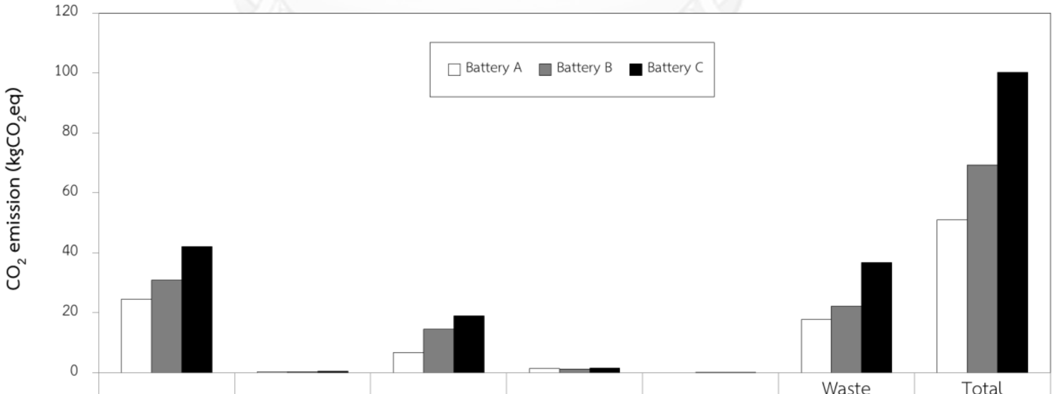


Figure 4-17 Comparison of energy resource consumption at various collection percentages

When considered the 75% collected option, Figure 4-18 displays that the highest greenhouse gas was released from Battery C at 100 kgCO_2eq, followed by Battery B and Battery A that released 69.3 and 51.0 kgCO_2eq, respectively. The first and second hotspots were still the same as the Non recycling case scenario. The raw material acquisition stage was responsible for 41.9-48.2% of their life cycles (Figure 4-19), and the extracted lead accounted for 62.0-65.3% from all materials in this stage. The second hot spots were taken place in the waste management stage which accounted for 32.2-36.7% from all emission throughout their life cycles (see Figure 4-19). The sodium hydroxide, used in treatment of sulfuric acid was needed before emitting to the environment, was the main cause for 78.1-79.9% from all material in this stage.

Sulfur dioxide emission of the representatives is shown in Figure 4-20, the highest sulfur dioxide was released at 1.25 kgSO_2eq from Battery C followed by Battery B (0.895 kgSO_2eq), and Battery A that released 0.706 kgSO_2eq. All types of vehicle battery had the same hotspots at the raw material acquisition stage, accounted for 79.1-82.4% from all stages throughout their life time (Figure 4-21) by the extracted lead process used for casting process (the main causes of emission, 62.3-65.0% of all materials in this stage). In addition, the waste management stage was still the second hotspot accounted for 9.35-11.1% from all stages, as illustrated in Figure 4-21. The sodium hydroxide (neutralization process) was the main origin which was responsible for 98.56-98.7% from this stage.



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Total (kgCO2eq)
□ Battery A	24.6	0.322	6.82	1.44	0.000000	17.8	51.0
▨ Battery B	30.9	0.390	14.6	1.23	0.000149	22.3	69.3
■ Battery C	42.1	0.602	19.1	1.67	0.000149	36.8	100

Figure 4-18 Carbon dioxide emission throughout life cycle of three types of vehicle battery (75% collection)

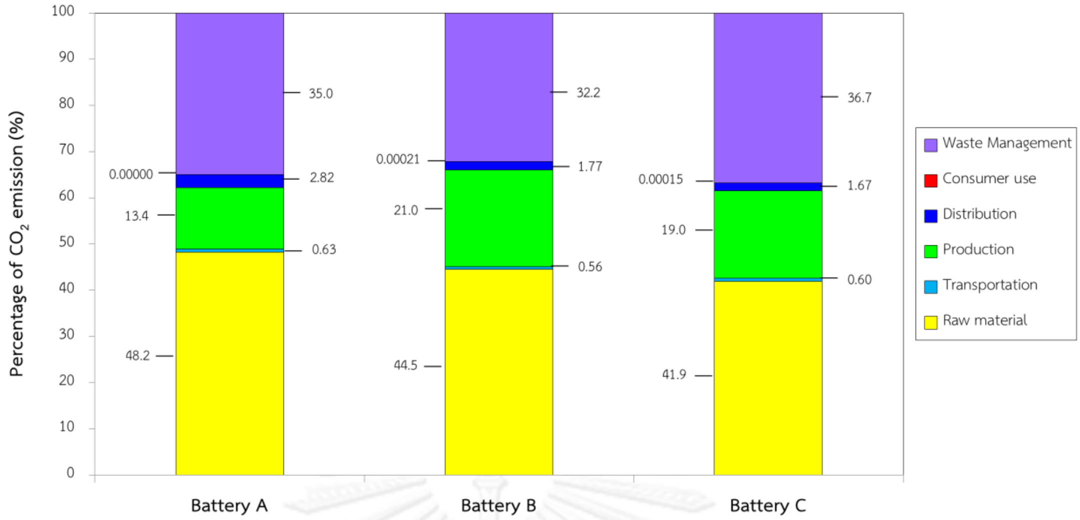
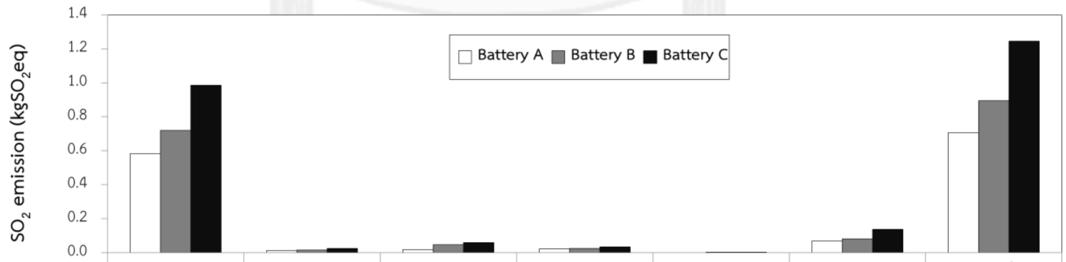


Figure 4-19 Distribution of carbon dioxide emission throughout life cycle of three types of vehicle battery (75% collection)

Figure 4-22 illustrates in terms of CFC_{11} equivalent, Battery C emitted the highest CFC_{11} (7.43E-06 kgCFC_{11}eq) whereas the second and third CFC_{11} emissions were taken from Battery B and battery A, at 5.24E-06 and 4.00E-06 kgCFC_{11}eq, respectively. The first and second hotspots of CFC_{11} emissions were responsible for 29.9-33.2% and 22.3-25.8% from all stages of life cycle of vehicle batteries (Figure 4-23), which were the raw material acquisition stage and waste management stage. The percentage of main case for CFC_{11} was 57.0-58.6% from the extracted lead (the first hotspot stage) and 93.5-94.3% from sodium hydroxide for the second hotspot stage.



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Total (kgSO2eq)
☐ Battery A	0.582	0.0144	0.0198	0.0219	0.0000000	0.0684	0.706
▨ Battery B	0.720	0.0177	0.0469	0.0268	0.0000209	0.0837	0.895
■ Battery C	0.987	0.0244	0.0615	0.0364	0.0000209	0.138	1.25

Figure 4-20 Sulfur dioxide emission throughout life cycle of three types of vehicle battery (75% collection)

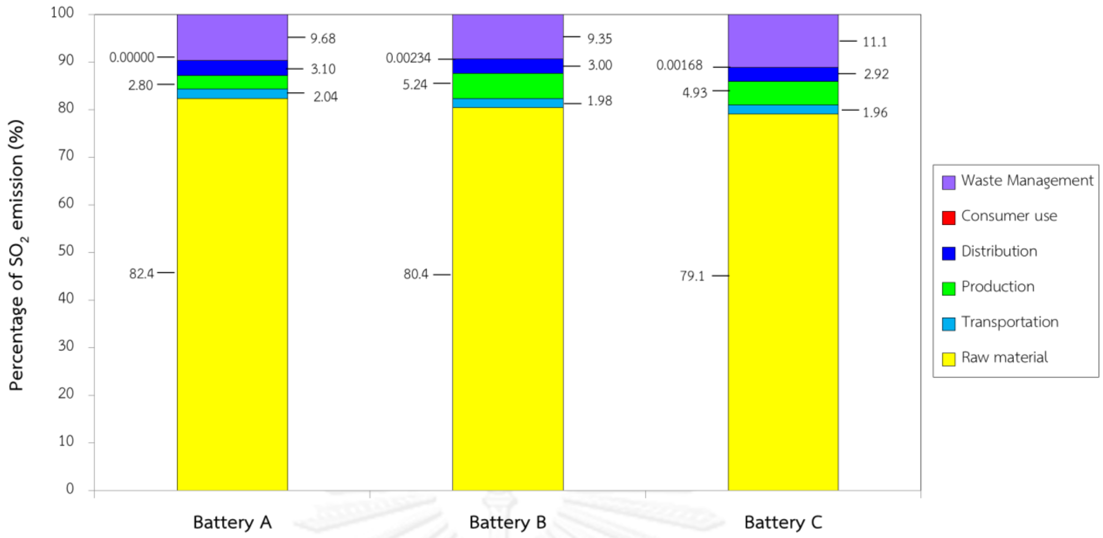
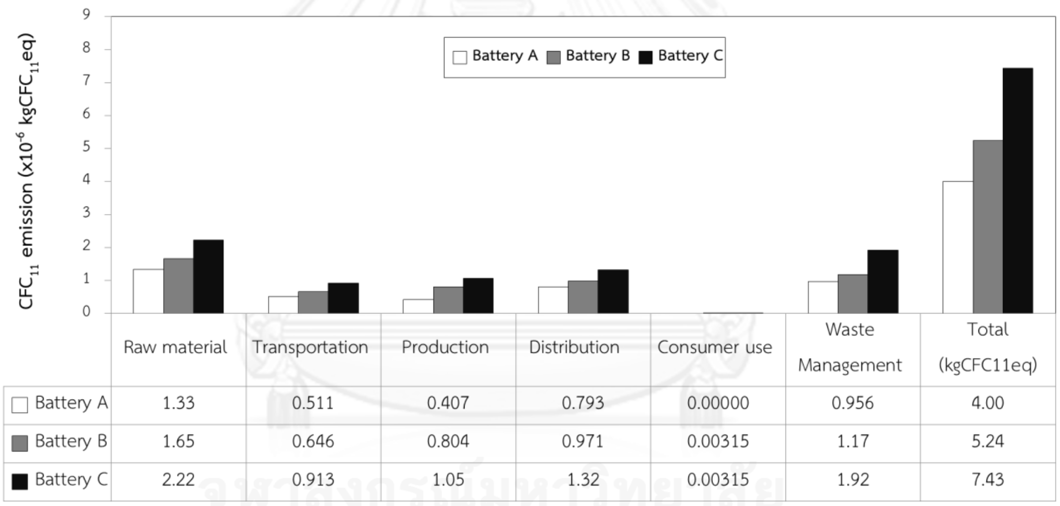


Figure 4-21 Distribution of sulfur dioxide emission throughout life cycle of three types of vehicle battery (75% collection)



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Total (kgCFC11eq)
☐ Battery A	1.33	0.511	0.407	0.793	0.00000	0.956	4.00
▨ Battery B	1.65	0.646	0.804	0.971	0.00315	1.17	5.24
■ Battery C	2.22	0.913	1.05	1.32	0.00315	1.92	7.43

Figure 4-22 CFC_{11} emission throughout life cycle of three types of vehicle battery (75% collection)

Figure 4-24 demonstrates all lead emissions where Battery C released lead more than the Battery B and Battery A, which accounted for 4.00E-02, 3.03E-02 and 2.42E-02 kgPbeq, respectively. Lead emission was not significantly different between the first and second hot spots (the raw material acquisition stage as the first and the waste management stage as the second). The first and second hotspots were responsible for 53.2-53.6% and 45.2-45.5% of all stages of life cycles, as illustrated in Figure 4-25. The major cause of impacts from the first hot spot, i.e. the extracted lead process, accounted for 95.2-95.5% of the total emission from this stage; on the other hand, landfill of lead emitted as much as 96.4-97.3% of the total emission from the waste management stage.

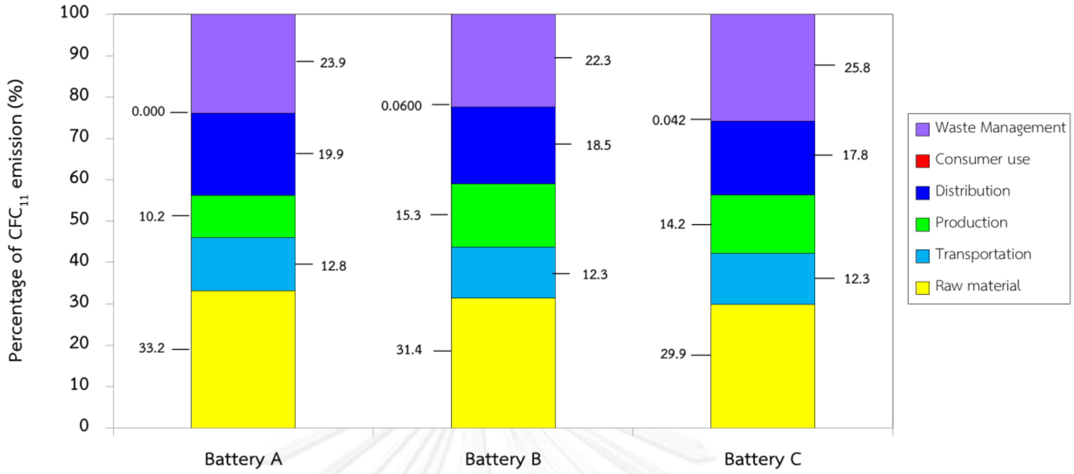
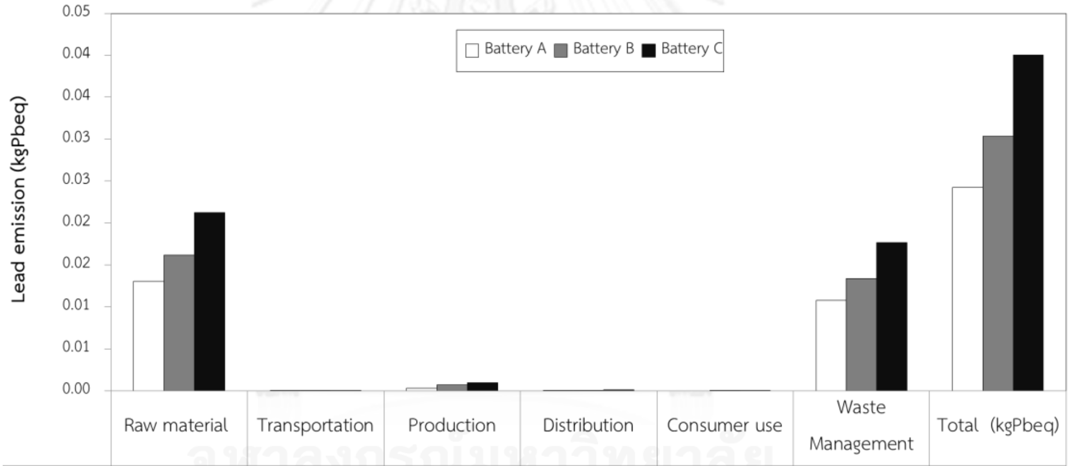


Figure 4-23 Distribution of CFC_{11} emission throughout life cycle of three types of vehicle battery (75% collection)



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Total (kgPbeq)
☐ Battery A	1.31E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	1.08E-02	2.42E-02
▨ Battery B	1.62E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	1.34E-02	3.03E-02
■ Battery C	2.12E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	1.77E-02	4.00E-02

Figure 4-24 Lead emission throughout life cycle of three types of vehicle battery (75% collection)

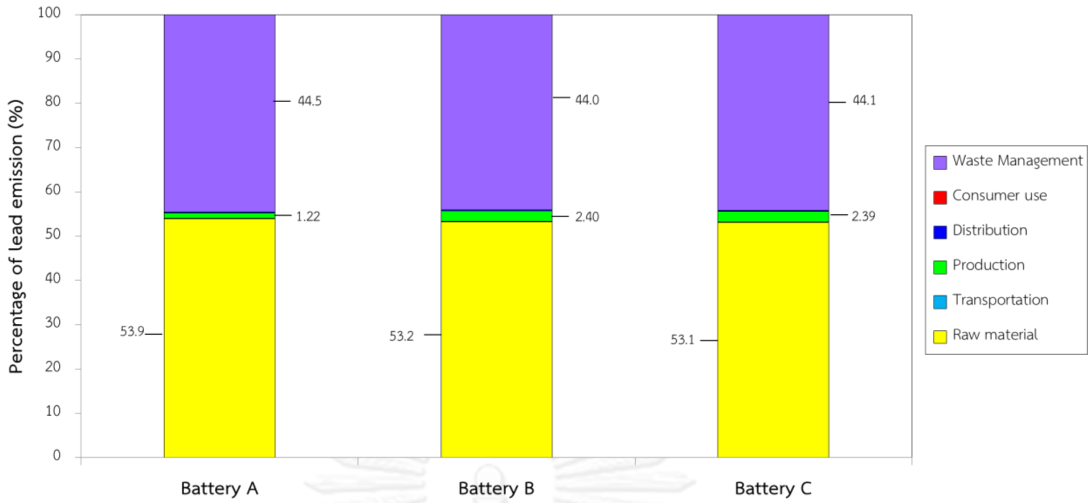
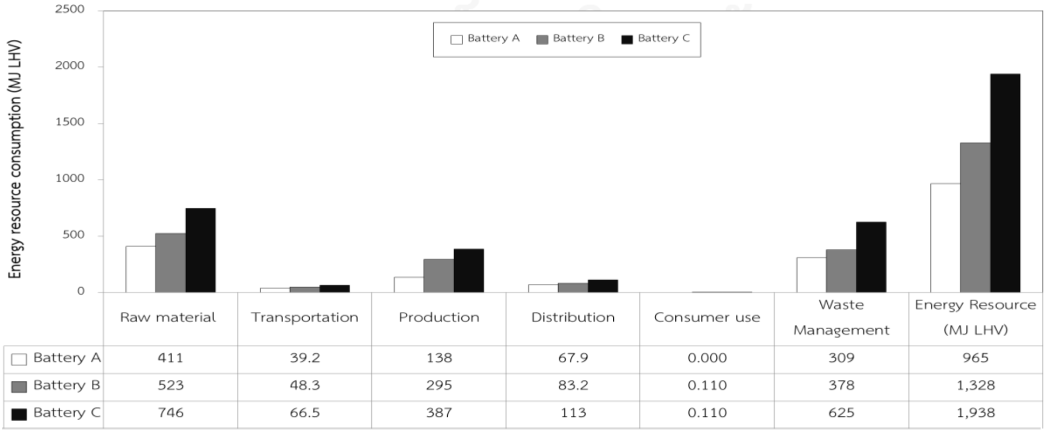


Figure 4-25 Distribution of lead emission throughout life cycle of three types of vehicle battery (75% collection)

Finally, the impact regarding the consumption of energy was analyzed and the results are displayed in Figure 4-26. It was found that Battery C consumed the highest amount of energy at 1,938 MJ LHV; whilst Battery B and Battery A accounted for 1,328 and 965 MJ LHV, respectively. All types of vehicle batteries required the highest amount of energy at the raw material acquisition stage at 38.5-42.6% of the overall energy consumption (Figure 4-27), and within this, 42.6-47.6% was from the extracted lead process. The second used energy was taken place at the waste management stage which was calculated for 28.5-32.2% throughout life cycles. Again, the neutralization process was responsible for 98.6-98.8% of the overall impact. Five environmental impacts from this scenario are displayed in Table 4-6 below.



	Raw material	Transportation	Production	Distribution	Consumer use	Waste Management	Energy Resource (MJ LHV)
☐ Battery A	411	39.2	138	67.9	0.000	309	965
▨ Battery B	523	48.3	295	83.2	0.110	378	1,328
■ Battery C	746	66.5	387	113	0.110	625	1,938

Figure 4-26 Energy resource consumption throughout life cycle of three types vehicle battery (75% collection)

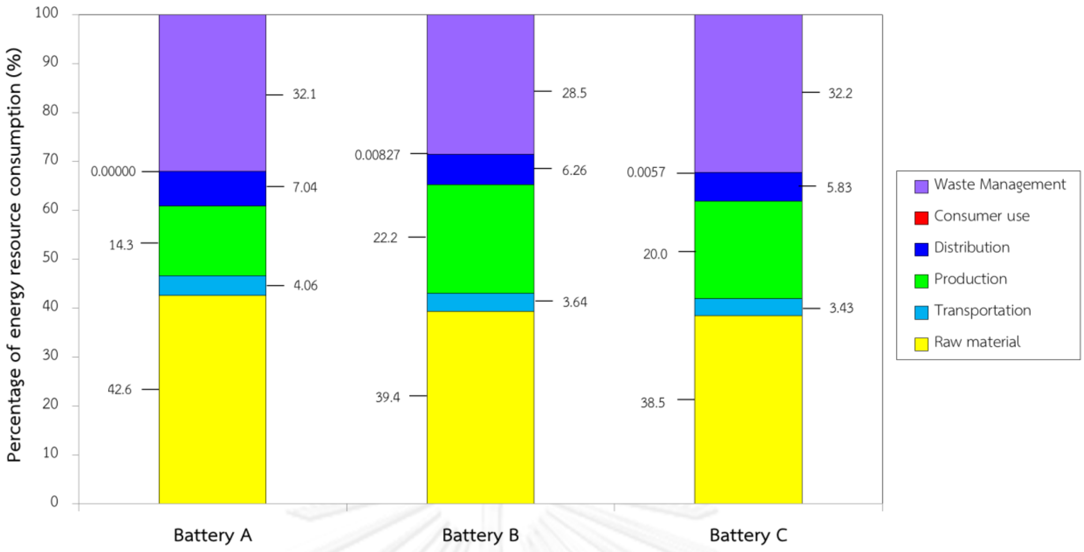


Figure 4-27 Distribution of energy resource consumption throughout life cycle of three types of vehicle battery (75% collection)

Table 4-6 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (75% collection of spent batteries)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO_2eq	24.6	0.322	6.82	1.44	0.000000	17.8	**51.0**
Battery B			30.9	0.390	14.6	1.23	0.000149	22.3	**69.3**
Battery C			42.1	0.602	19.1	1.67	0.000149	36.8	**100**
Battery A	Acidification	kgSO_2eq	0.582	0.0144	0.0198	0.0219	0.0000000	0.0684	**0.706**
Battery B			0.720	0.0177	0.0469	0.0268	0.0000209	0.0837	**0.895**
Battery C			0.987	0.0244	0.0615	0.0364	0.0000209	0.138	**1.25**
Battery A	Ozone depletion	kgCFC_{11}eq	1.33E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	9.56E-07	**4.00E-06**
Battery B			1.65E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	1.17E-06	**5.24E-06**
Battery C			2.22E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.92E-06	**7.43E-06**
Battery A	Heavy matal emission	kgPbeq	1.31E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	1.08E-02	**2.42E-02**
Battery B			1.62E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	1.34E-02	**3.03E-02**
Battery C			2.12E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	1.77E-02	**4.00E-02**
Battery A	Energy resource consumption	MJ LHV	411	39	138	68	0	309	**965**
Battery B			523	48	295	83	0	378	**1328**
Battery C			746	66	387	113	0	625	**1938**

4.3.2 Chemical replacement

It was indicated in previous sections that one of the main factors that led to significant environmental problems was the use of sodium hydroxide (NaOH) in neutralization process. The study was proposed here to replace NaOH with some other more environmental benign chemicals. Calcium hydroxide ($Ca(OH)_2$) was one of the strong bases which could be used effectively to replace NaOH in the neutralization process [20, 23] . This section showed how this chemical replacement affected the overall environmental problems of vehicle batteries. Three case scenarios were assumed, i.e. (1) Option A, (2) Option B, (3) Option C, as described in Table 4-2.

The comparison between the baseline scenario and potential options was evaluated in this section. The result showed that Option C which was when 100% collection of spent batteries and $Ca(OH)_2$ was used to neutralization process, unsurprisingly provided the best environmental performance, and the overall CO_2 emission from Battery A, Battery C, and Battery B could be reduced by 25.5%, 24.8%, and 23.0%, respectively. Option A saw a reduction in CO_2 emission as follows: 18.6% (Battery C), 18.1% (Battery A), and 16.3% (Battery B). Two potential options (Option C and Option A) helped reduce CO_2 emission more than Option B. The chemicals used in the neutralization process helped release less CO_2 for global warming, followed by Figure 4-28.

Acidification could be analyzed in terms of SO_2 equivalent, Figure 4-29 illustrates that Option C was still the best option for reducing SO_2 emission, but only marginally better than the other two batteries, i.e. the reduction in SO_2 emission for the three options were within the range of 20.3-21.2%.

Replacing NaOH with $Ca(OH)_2$ had significant influence CFC_{11} emission (Figure 4-30) with 12.7-14.1% reduction in CFC_{11} emission could be achieved from Option C. The second best option was Option A which could save 10.0-11.6% CFC_{11}eq when compared with the use NaOH. The increase in collection percentage from 75% to 100% in some options might not significant help reduce the impact as the reduction was only marginal when compared with that of the major hot spot. However, chemical replacement option (with $Ca(OH)_2$ instead of NaOH), i.e. Options C and A, could markedly lower the impact which gives a potential improvement to the overall environmental performance of the vehicle batteries.

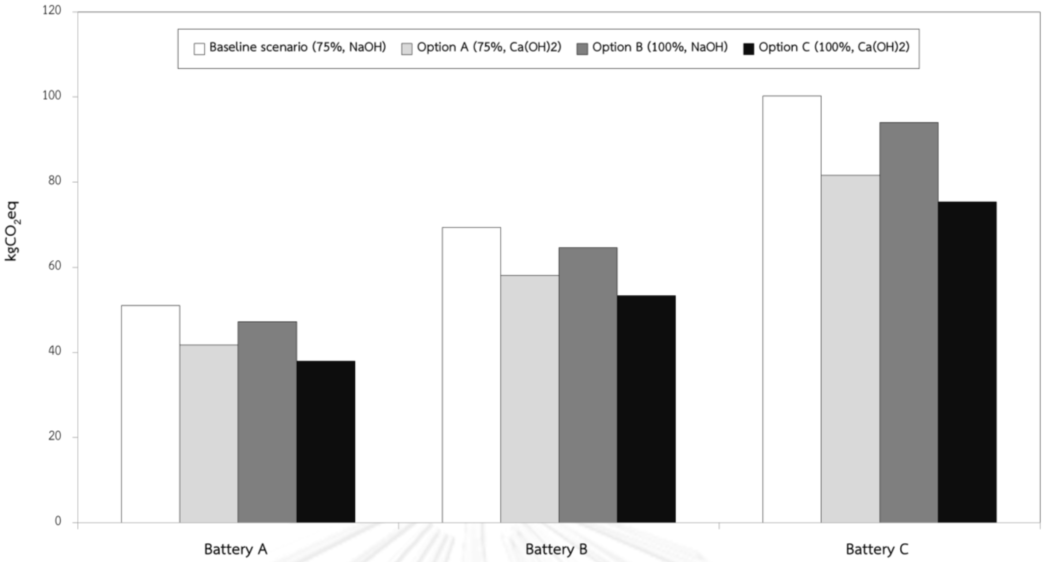


Figure 4-28 Three potential options for reducing CO_2 emission of three types of vehicle batteries

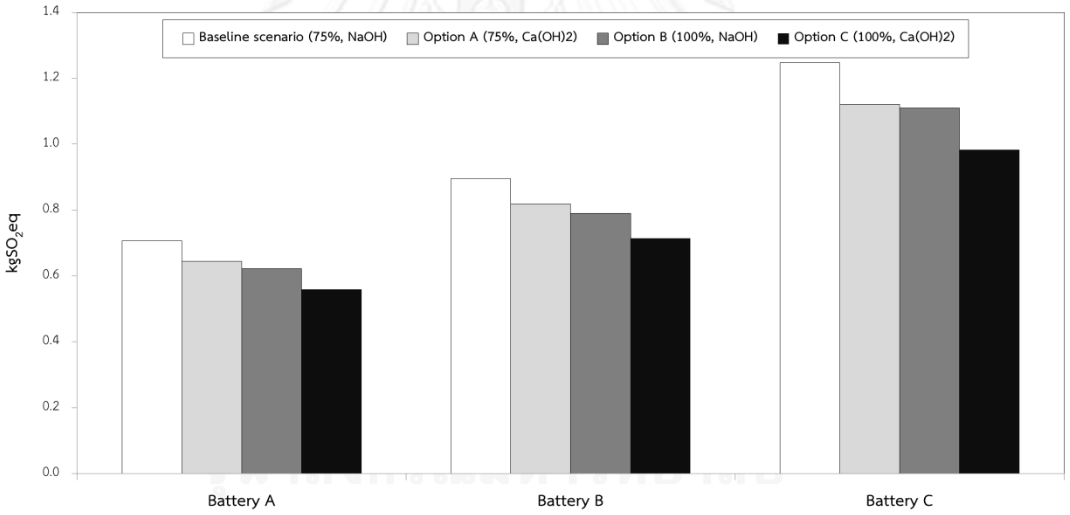


Figure 4-29 Three potential options for reducing SO_2 emission of three types of vehicle batteries

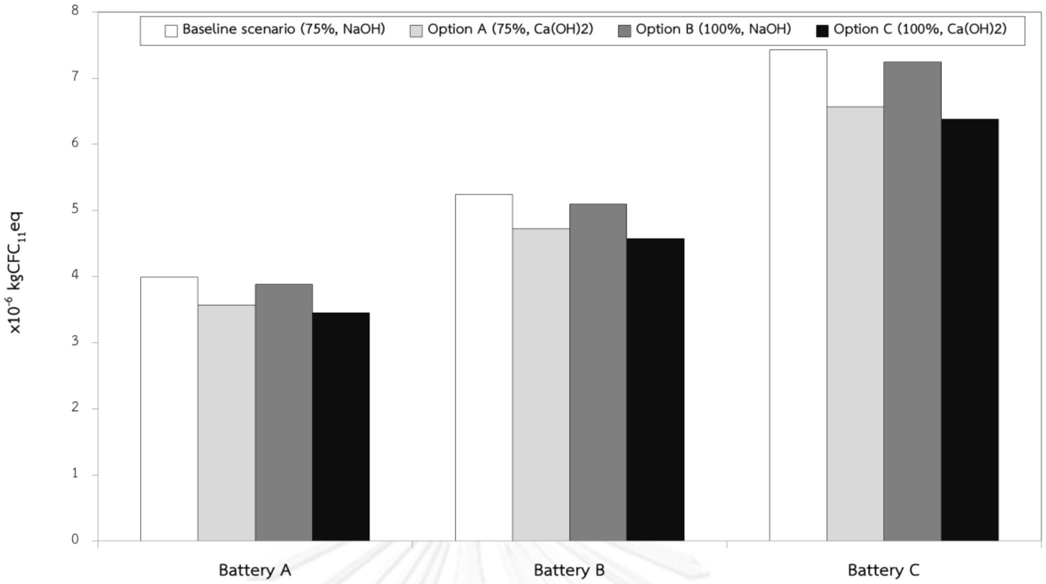


Figure 4-30 Three potential options for reducing CFC$_{11}$ emission of three types of vehicle batteries

Figure 4-31 illustrates that by 100% collection of the waste could reduce lead leakage quite drastically. Options C and B were regarded as the good options which could yield a high reduction in lead emission, and the reduction of lead emission for Battery A was 29.2-29.7%, Battery B 28.8-29.3%, and Battery C 28.7-29.3%.

On the other hand, Figure 4-32 reveals that using Ca(OH)2 instead of NaOH could reduce the requirement of energy quite drastically. Option C which was regarded as the best option could yield a high reduction in energy resource consumption, i.e. reduction for Battery A, Battery C, and Battery B: 32.0%, 31.5%, and 28.5%, respectively. The second best option was Option A which reduced used energy for all types of battery by 25.1-28.5%.

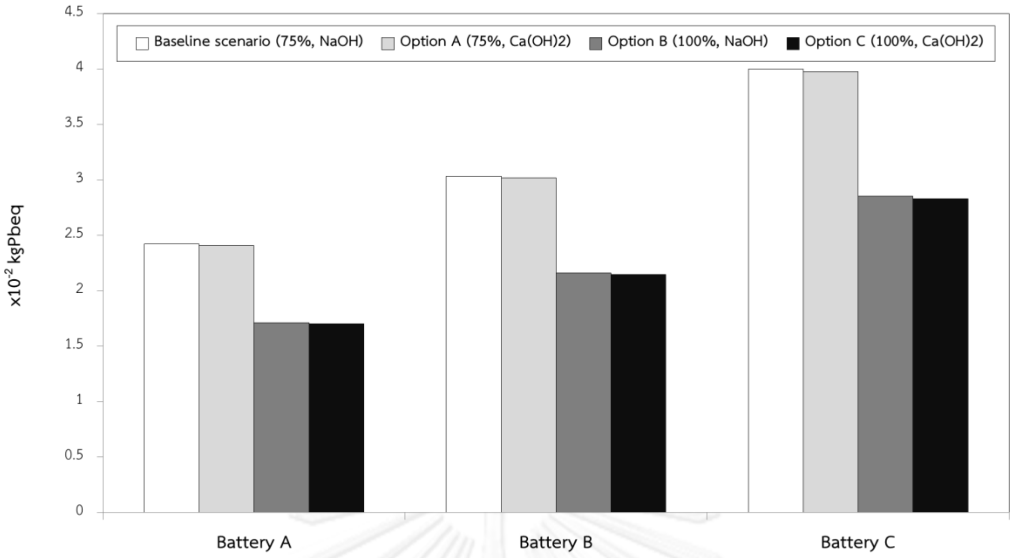


Figure 4-31 Three potential options for reducing lead emission of three types of vehicle batteries

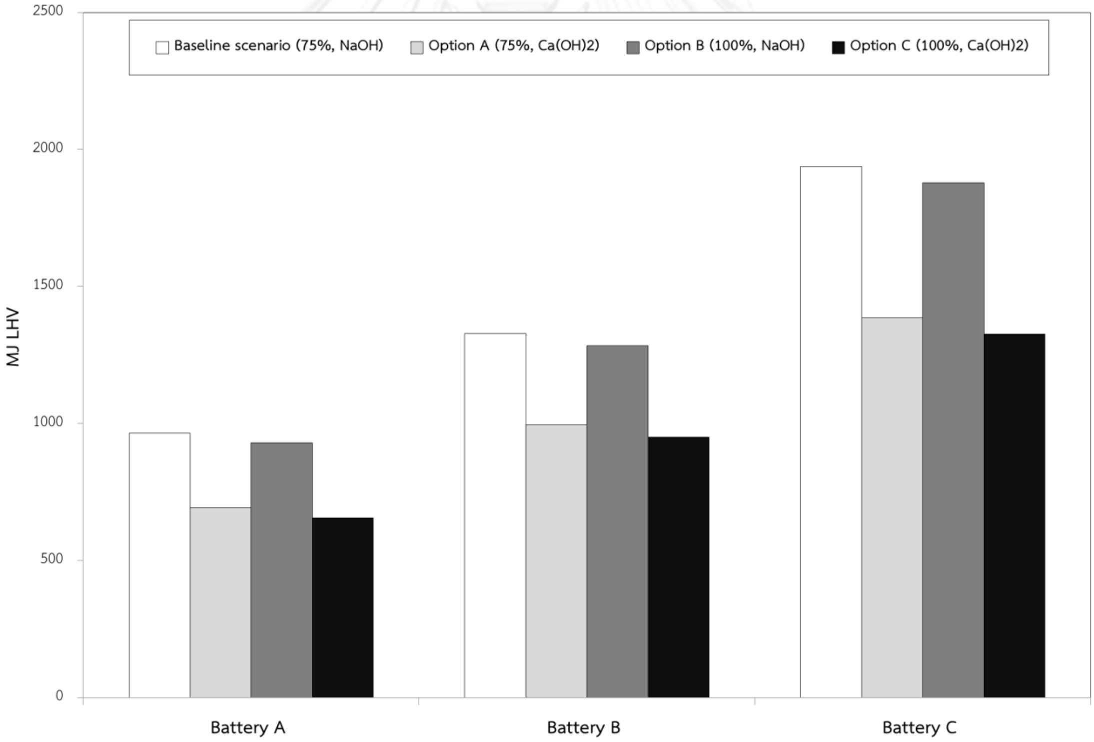


Figure 4-32 Three potential options for reducing energy resource consumption of three types of vehicle batteries

4.4 Economic analysis

In this last section of the discussion, economic evaluation of each type of vehicle batteries was given as supporting information for the readers to use in making decision on the selection of the vehicle battery. The basic cash flow of all types of vehicle batteries was classified into: 1) purchase a new battery; and 2) turning in an old battery and purchasing a new one. Prices of the new batteries with and without the turning in of the old batteries are given in Table 4-7 whereas the cash flow analysis is given in Table 4-8.

Table 4-7 Prices of three types of vehicle battery (Per 1 unit)

Options of purchase	**Price of three types of batteries (THB)**		
	Battery A	***Battery B***	***Battery C***
Purchase a new battery	4,300-4,500	3,200-3,600	2,300-2,500
Turning in an old battery and purchasing a new one	3,900-4,200	2,800-3,200	1,900-2,200

Purchase a new Battery A had the average price at 4,400 baht per a unit, and Battery B at 3,400 baht per a unit; however, the functional unit of this study was 4 years therefore the overall price of this type of battery including the bank interest (if the initial cash was debited in the bank for 4 years) became 4,533 baht. Similarly, Batteries B and C, when considered the depreciation and bank interest, cost 4,474.23 baht and 4,717.7 baht, respectively. However, turning in the old battery and purchase a new one could help save the cost as the old battery had a value when being exchanged for the new one. Calculation (including bank interest and depreciation) demonstrated that Battery A, Battery B, Battery C had the average prices of 4,050, 3,948.13, and 4,029.71 baht per one functional unit, respectively. Appendix D displays the calculation of three types of battery in two purchase option for 4 years.

Table 4-8 Cash flow analysis of the three types of vehicle battery (Per 1 FU)

Basic cash flows and costs/ Type of vehicle batteries	Price of three types of batteries (THB)		
	Batter A	*Battery B*	*Battery C*
1. Purchase a new battery	4,400	3,400	2,400
2. Cost per 1 FU	4,400	4,533	4,800
3. Interest	-	58.77	82.30
4. Net amount	4,400	4,474	4,718
1. Turning in an old batter and purchasing a new one	4,050	3,000	2,050
2. Cost per 1 FU	4,050	4,000	4,100
3. Interest	-	51.87	70.29
4. Net amount	4,050	3,948	4,030

4.5 Concluding remarks

- All evaluated environmental impacts throughout the life cycle of the maintenance free battery (Battery A) was lower than the hybrid (Battery B) and conventional one (Battery C), respectively. Both the non-recycling case and seventy-five percentage of recycling material case scenarios had the same trend of spent battery collection. All environmental impacts had the hotspots at the raw material acquisition stage and the second hotspots at the waste management stage. The extracted lead and sodium hydroxide had serious influence to all impacts.

- Recycling materials of the higher collection percentage of spent batteries demonstrated a lower release of emission and a lesser energy resource consumption.

- There were two options to lessen the environmental impacts, i.e. 1) A higher recyclable materials, 2) Chemical replacement. The higher collection percentage of spent batteries would lead to a lower release of emission and a lesser energy resource consumption. In addition, chemical replacement (using $Ca(OH)_2$ instead of NaOH) in the waste management stage could reduce the impacts.

- Each environmental mitigating option could be further classified into three scenarios, i.e. Option A (75% collection, $Ca(OH)_2$ as pretreatment chemical), Option B (100% collection, NaOH), Option C (100%, $Ca(OH)_2$ as pretreatment chemical). In general, Option C provides the highest potential of reducing most of environmental impacts. Option A gave the second best when focused mainly on global warming potential, ozone depletion, and energy resource consumption whereas Option B provided the second best performance when acidification and energy resource consumption.

- Purchase a new battery: although Battery A was better than Batteries B and C in terms of environmental consideration, turning in an old battery and purchasing a new one was better for Battery B than the other two. These impact analyses both in environmental and economical points of view can be summarized as each battery's radar finger print as displayed in Figure 4-33. This kind of information can be further used in making a decision on the selection of the battery depending on the specific preference of the customers.

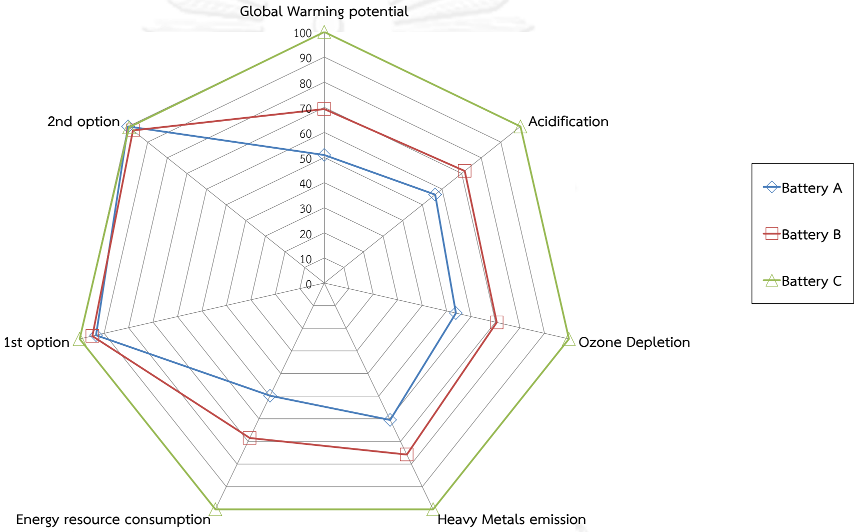


Figure 4-33 Environmental impacts and purchased options radar finger print of the batteries

CHAPTER V

CONTRIBUTIONS AND RECOMENDATION

5.1 Contributions

This study was one of the few that provided information on the environmental impacts based on the overall life cycle of vehicle batteries (cradle to grave). Raw material acquisition was revealed to be the major hot spot where impacts were mostly created associated options for the mitigation were proposed accordingly.

The results from this work could be useful for both governmental and private sectors depending on how they made use of the data. Governmental sector benefited from the knowledge of the major hot spots and should try to make policy to promote the recycling of spent batteries and the change of neutralizing chemical for such industry. Meanwhile industry might need to carry out further economic analysis on such options to ensure not only safe and green, but also the most profitable operation. Moreover, an economic analysis was also carried out to provide additional cost information which might help customers to make a proper decision on how to select the target battery.

Very similar study had been carried out by MTEC & TEI on the LCA of vehicle battery. The work was based on slightly different assumptions particularly on the usage phase where the impact generated from the operation of the car was also included. The following tables (Tables 5-1 to 5-3) provide the comparison between the results of that work with the findings from this study.

Table 5-1 Comparison between MTEC & TEI study and this study

		MTEC & TEI	This study
1.	Objectives	■ To provide an LCA case study for the EcoDesign of vehicle batteries. ■ To compare environmental impacts between 2 types of battery: maintenance free and conventional batteries ■ To propose methods to decrease energy consumption and environmental impacts	■ To evaluate environmental impacts throughout the life cycle of the three types of vehicle batteries, i.e. maintenance free, hybrid, and conventional batteries ■ To investigate potential options that help lessen the impacts from three types of vehicle battery
2.	Scopes and system boundary	■The study covered the environmental impacts throughout the life cycle of the vehicle batteries production, i.e. raw material, production process, usage, transportation (f) and waste management.	■ The study covered the environmental impacts throughout the life cycle of the vehicle batteries production, i.e. raw material, transportation, production, distribution, customer use, and waste management.

Table 5-1 Comparison between MTEC & TEI study and this study (cont.)

		MTEC & TEI	This study
3.	Evaluation	■ Mid-point impacts and End-point impacts ■ Five environmental impacts 1) Global warming potential 2) Acidification 3) Ozone depletion 4) Heavy metal 5) Energy resource	■ Mid-point impacts ■ Five environmental impacts 1) Global warming potential 2) Acidification 3) Ozone depletion 4) Heavy metal 5) Energy resource
4.	Assumptions (Only the uncommon ones are listed here)	■ Usage stage included the use of vehicle (where the battery was installed), i.e. fuel consumption in the vehicle was considered in the evaluation	■ Usage stage only considered the use of battery within the vehicle (only DI water used in the battery)

Table 5-1 Comparison between MTEC & TEI study and this study (cont.)

	MTEC & TEI	This study
	■ Waste management: undefined calculation ■ Transportation and distribution: not included in evaluation	■ Waste management: recycling/treatment were considered where the recycled materials were recycled back to the battery production. ■ Transportation and distribution: included in evaluation

Table 5-2 Mid-point impacts in between a maintenance free and conventional products (MTEC & TEI)

Types of battery	Impact categories	Unit	Raw material acquisition	Production	Customer Use	Waste management	Total
Maintenance free	Global warming	$kgCO_2eq$	14.8	3.86	54.0	-10.9	**61.8**
Conventional			30.5	17.5	54.5	-21.6	**80.9**
Maintenance free	Acidification	$kgSO_2eq$	0.305	0.0188	0.241	-0.298	**0.266**
Conventional			0.646	0.0638	0.244	-0.593	**0.361**
Maintenance free	Ozone depletion	$kgCFC_{11}eq$	8.29E-09	1.91E-07	6.07E-08	8.16E-07	**1.08E-06**
Conventional			4.71E-08	3.89E-07	1.50E-07	1.63E-06	**2.21E-06**
Maintenance free	Heavy matal emission	kgPbeq	4.38E-06	7.86E-06	2.67E-05	5.65E-06	**4.46E-05**
Conventional			1.95E-05	2.55E-05	2.69E-05	1.13E-05	**8.33E-05**
Maintenance free	ergy resource consumpti	MJ LHV	258	84.7	795	-108	**1030**
Conventional			521	249	814	-216	**1370**

Table 5-3 Mid-point impacts during three types of vehicle products

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	$kgCO_2eq$	24.6	0.322	6.82	1.44	0.000000	17.8	**51.0**
Battery B			30.9	0.390	14.6	1.23	0.000149	22.3	**69.3**
Battery C			42.1	0.602	19.1	1.67	0.000149	36.8	**100**
Battery A	Acidification	$kgSO_2eq$	0.582	0.0144	0.0198	0.0219	0.0000000	0.0684	**0.706**
Battery B			0.720	0.0177	0.0469	0.0268	0.0000209	0.0837	**0.895**
Battery C			0.987	0.0244	0.0615	0.0364	0.0000209	0.138	**1.25**
Battery A	Ozone depletion	$kgCFC_{11}eq$	1.33E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	9.56E-07	**4.00E-06**
Battery B			1.65E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	1.17E-06	**5.24E-06**
Battery C			2.22E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.92E-06	**7.43E-06**
Battery A	Heavy matal emission	kgPbeq	1.31E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	1.08E-02	**2.42E-02**
Battery B			1.62E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	1.34E-02	**3.03E-02**
Battery C			2.12E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	1.77E-02	**4.00E-02**
Battery A	ergy resource consumptio	MJ LHV	411	39	138	68	0	309	**965**
Battery B			523	48	295	83	0	378	**1328**
Battery C			746	66	387	113	0	625	**1938**

There were discrepancies between the results from MTEC & TEI and the findings from this work. This was primarily due to the differences in the scope of the two works. A few major differences could be identified.

(i) Usage stage: MTEC & TEI assumed that the environmental load generated from the use of vehicles be allocated to the batteries, whereas this work confined the scope at the use of battery itself (which of course only consumed distilled water). Due to this assumption, the impacts from the usage stage from the work of MTEC & TEI were always higher than what obtained from this work.

(ii) Recycle stage: MTEC & TEI treated the recycled materials as the substitutes for virgin materials. However, this work assumed that all recycled materials were used to replace the material in the production of battery. Therefore negative impacts were reported from MTEC & TEI work, whereas in this work, the impacts from the recycling of materials were included, and the impacts of the virgin raw materials that could be replaced were deducted from the overall impact at that particular stage.

As there were no details given regarding the waste management in the evaluation by MTEC & TEI, it is not possible at this point to examine the exact reasons for the discrepancies in the results of the two studies.

5.2 Recommendation for further studies

As stated in the previous section, this work only focused on the technical part and bases its calculation solely on the criteria set out in the life cycle assessment. This, however, did not cover the economic analysis of the proposed options seriously throughout life cycle of the products. It will be interesting for further work to look closely into detail on how these options could be conducted which will lead to the actual implementation of the results from this work.

REFERENCES

1. Ministry of industry (Thailand Automotive Instutute), *Master Plan of Thailand Automotive Industry (2012-2016).* 2012: p. 1-108.
2. Export-Import Bank of Thailand (The business analysis, A.a., *Vehicle Battery Industry of Thailand.* 2005.
3. Wechagarn, B., *Environmental management of lead-Acid type used car batteries in Thailand*. 2007, Silapakorn University.
4. Delaware Health and Social Services (Division of Public Health), *Lead Poisoning*. 2009. p. 1-2.
5. United Nations Environment Programme, *Lead Exposure and Human Health*. 2013.
6. Thailand Greenhouse Gas Management Organization (Public Organization), *Carbon Footprint Guildline of Thailand*, 3, Editor. 2011.
7. *Defining Life cycle Assessment*. US Environmental Protection Agency
8. Suesareetham, N., *T5 OR T8 Fluorescent Lamp: Making Decision With Their Carbon Footprints*, in *Graduate School* 2010, Chulalongkorn University
9. Graedel, T.E., *Streamlined Life-Cycle Assessment*. 1998. 18-22.
10. International Organisation for Standardisation (ISO), *ISO 14040 (2006): Environmental Management – Life Cycle Assessment*. 2006.
11. Thailand Greenhouse Gas Management Organization (Public Organization). *Greenhouse Gas & Climate Change*. [cited 2011, May 20]; Available from: http://www.tgo.or.th/index.php?option=com_content&view=article&id=46:what-is-ghg&catid=35:greenhouse-effect&Itemid=55.
12. Department of Lands. *Global Warming*. 2008 [cited 2011, May 22]; Available from: http://www.dol.go.th/sms/interesting.htm.
13. Thai Meteorological Department. *Acid Rain*. 2007 [cited 2012, May 7]; Available from: http://ozone.tmd.go.th/acid.htm.
14. Thai Meteorological Department. *Ozone Depleting Substance*. 2007 [cited 2012, May 28]; Available from: http://ozone.tmd.go.th/ods.htm.
15. Royal Thai Army. *Battery*. [cited 2012, Feburary 15]; Available from: http://www.rta.mi.th/15900u/SDMP/Interest/Magazine/training.html.
16. MTEC and TEI, *LCA - EcoDesign : Batteries*. 2008.

17. Lead Battery Recycling World. *The History Of Battery*. [cited 2011, November 1]; Available from: http://www.lead-battery-recycling.com/the-history-of-battery.html.
18. Institute for Innovative learning (Mahidol University). *A secondary battery* [cited 2012, Febuary 15]; Available from: http://www.il.mahidol.ac.th/e-media/electrochemistry/web/secondary_cell.htm.
19. UNITED STATES DEPARTMENT OF LABOR, *Lead Battery Manufacturing*.
20. Tulyakorn, A., *Treatment of Wastewater from Lead Recycling Battery*, in *Environmental Technology*. 2000, King Mongkut's University of Technology Thonburi.
21. Sullivan, J.L. and L. Gaines, *A Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs.* 2010: p. 1-36.
22. Rydh, C.J. and M. Karlstrom, *Life cycle inventory of recycling portable nickel-cadmium batteries.* Resource, Conservation and Recycling, 2002. **34**: p. 289-309.
23. Salomone, R., et al., *An Eco-balance of a Recycling Plant for Spent Lead-Acid Batteries.* Environmental Management, 2005. **35**(2): p. 206-219.
24. Rydh, J.C., *Environmental Assessment of Vanadium Redox and Lead-acid Batteries for Stationary Energy Storage.* Power Sources, 1999. **80**: p. 21-29.
25. Frost, P.C., *Developments in lead-acid batteries: a lead producer's perspective.* Power Sources, 1999. **78**: p. 256-266.
26. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change.
27. Cann, G.M., P.A. Clasisse, and J.P. Lorimer, *Production of Gypsum Products from Waste Battery Acid.*
28. Gregorius, R. *Sodium Hydroxide and Sulfuric Acid*. 1991 [cited 2014, March 14]; Available from: http://newton.dep.anl.gov/askasci/chem03/chem03874.htm.
29. Goedkoop, M., et al., *SimaPro 7 Tutorial*. 2010.
30. Weigel, M., *Energy and Economic Value of Plastics and Municipal Solid Wastes* 2011.

APPENDICES

APPENDIX A

Emission Factor in each stage

Table A-1 Emission factors of materials in raw material acquisition stage

No	List	unit	E.F. (kgCO_2eq/unit)	E.F. (kgSO_2eq/unit)	E.F. (kgCFC_{11}eq/unit)	E.F. (kgPbeq/unit)	E.F. (MJ LHV/unit)
1	Lead (extraction)	**kg**	2.0588	0.048499	9.99E-08	0.0015982	25.072
		Reference data	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Lead, primary, at plant /RER S, ECOINVENT 2.0	Lead, primary, at plant /RER S, ECOINVENT 2.0	Lead, primary, at plant /RER S, ECOINVENT 2.0	Lead, primary, at plant /RER S, ECOINVENT 2.0	Lead, primary, at plant /RER S, ECOINVENT 2.0
2	Lead (Recycle)	**kg**	0.63206	0.014115	5.45E-08	6.23E-05	11.9498
		Reference data	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Lead, secondary, at plant/RER S	Lead, secondary, at plant/RER S	Lead, secondary, at plant/RER S	Lead, secondary, at plant/RER S	Lead, secondary, at plant/RER S
3	Polypropylene	**kg**	1.6862	0.0061502	6.73E-10	0.0000209	75.13
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Converted data from JEMAI Pro using Thai Electricity Grid	Polypropylene, granulate, at plant/RER S, ECOINVENT 2.0	Polypropylene, granulate, at plant/RER S, ECOINVENT 2.0	Polypropylene, granulate, at plant/RER S, ECOINVENT 2.0	Polypropylene, granulate, at plant/RER S, ECOINVENT 2.0
4	Polypropylene (Recycle)	**kg**	0.008377	0.000031	2.83E-07	1.08E-06	1.07089
		Reference data	Calculation	Calculation	Calculation	Calculation	Calculation
		Reference database	-	-	-	-	-

Table A-1 Emission factors of materials in raw material acquisition stage (cont.)

No	List	unit	E.F.	E.F.	E.F.	E.F.	E.F.
			(kgCO_2eq/unit)	(kgSO_2eq/unit)	(kgCFC_{11}eq/unit)	(kgPbeq/unit)	(MJ LHV/unit)
5	Polyethylene	kg	1.617	0.0064174	8.9E-10	0.0000248	77.313
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Converted data from JEMAI Pro using Thai Electricity Grid	Polyethylene, HDPE, granulate, at plant/RER S, ECOINVENT 2.0	Polyethylene, HDPE, granulate, at plant/RER S, ECOINVENT 2.0	Polyethylene, HDPE, granulate, at plant/RER S, ECOINVENT 2.0	Polyethylene, HDPE, granulate, at plant/RER S, ECOINVENT 2.0
6	Polyethylene (Recycle)	MJ	0.008377	0.000031	2.83E-07	1.08E-06	1.07089
		Reference data	Calculation	Calculation	Calculation	Calculation	Calculation
		Reference database					
7	Polycarbonate	kg	6.7364	0.02432	2.56E-09	0.000097	107.53
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Converted data from JEMAI Pro using Thai Electricity Grid	Polycarbonate, at plant/RER S, ECOINVENT 2.0	Polycarbonate, at plant/RER S, ECOINVENT 2.0	Polycarbonate, at plant/RER S, ECOINVENT 2.0	Polycarbonate, at plant/RER S, ECOINVENT 2.0
8	Sulfuric acid	kg	0.12105	0.013455	1.58E-08	0.0000131	2.1221
		Reference data	Eco-indicator 95(SimaPro 7.3.2)	Eco-indicator 95(SimaPro 7.3.2)	Eco-indicator 95(SimaPro 7.3.2)	Eco-indicator 95(SimaPro 7.3.2)	Eco-indicator 95(SimaPro 7.3.2)
		Reference database	Sulphuric acid, liquid, at plant/RER S ECOINVENT 2.0	Sulphuric acid, liquid, at plant/RER S ECOINVENT 2.0	Sulphuric acid, liquid, at plant/RER S ECOINVENT 2.0	Sulphuric acid, liquid, at plant/RER S ECOINVENT 2.0	Sulphuric acid, liquid, at plant/RER S ECOINVENT 2.0

Table A-1 Emission factors of materials in raw material acquisition stage (cont.)

No	List	unit	E.F.	E.F.	E.F.	E.F.	E.F.
			($kgCO_2eq/unit$)	($kgSO_2eq/unit$)	($kgCFC_{11}eq/unit$)	(kgPbeq/unit)	(MJ LHV/unit)
9	Carton	**kg**	0.826	0.0041430	1.04E-07	4.14E-05	30.051
		Reference data	TGO's guideline	Eco-indicator 95(SimaPro 7.3.2)	Eco-indicator 95(SimaPro 7.3.2)	Eco-indicator 95(SimaPro 7.3.2)	Eco-indicator 95(SimaPro 7.3.2)
		Reference database	ECOINVENT 2.0, IPCC 2007 GWP 100a	Packaging, corrugated board, mixed fibre, single wall, at plant/RER S, ECOINVENT 2.0	Packaging, corrugated board, mixed fibre, single wall, at plant/RER S, ECOINVENT 2.0	Packaging, corrugated board, mixed fibre, single wall, at plant/RER S, ECOINVENT 2.0	Packaging, corrugated board, mixed fibre, single wall, at plant/RER S, ECOINVENT 2.0
10	Carton (Recycle)	**kg**	0.95376	2.80E-03	8.41E-08	0.0000311	15.83
		Reference data	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Corrugated board, recyclingfibre, single wall, at plant RERS	Corrugated board, recyclingfibre, single wall, at plant RERS	Corrugated board, recyclingfibre, single wall, at plant RERS	Corrugated board, recyclingfibre, single wall, at plant RERS	Corrugated board, recyclingfibre, single wall, at plant RERS

Table A-2 Emission factor of vehicles in transportation and distribution stages

No	Type of vehicles	unit	Full load	E.F. ($kgCO_2eq$/unit)		E.F. ($kgSO_2eq$/unit)		E.F. ($kgCFC_{11}eq$/unit)		E.F. (kgPbeq/unit)		E.F. (MJ LHV/unit)		Reference data	Reference database
				100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading		
1	Transport, lorry 3.5-7.5 t EURO3 RER S 1.5 tons	ton	1.5	0.47323	0.00037	0.002654	2.15E-06	9.60E-08	7.40E-11	7.02E-06	1.21E-09	8.2256	0.00537	Eco-indicator 95 (SimaPro 7.3.2)	Transport, lorry 3.5-7.5t, EURO3/tkm /RER, ECOINVENT 2.0
2	Transport, lorry 3.5-7.5 t EURO3 RER S 7 tons	ton	7	0.47323	0.00037	0.002654	2.15E-06	9.60E-08	7.40E-11	7.02E-06	1.21E-09	8.2256	0.00537	Eco-indicator 95 (SimaPro 7.3.2)	Transport, lorry 3.5-7.5t, EURO3/tkm /RER, ECOINVENT 2.0
3	Transport, lorry 3.5-7.5 t EURO3 RER S 8.5 tons	ton	8.5	0.47323	0.00037	0.002654	2.15E-06	9.60E-08	7.40E-11	7.02E-06	1.21E-09	8.2256	0.00537	Eco-indicator 95 (SimaPro 7.3.2)	Transport, lorry 3.5-7.5t, EURO3/tkm /RER, ECOINVENT 2.0

Table A-2 Emission factor of vehicles in transportation and distribution stages (cont.)

No	Type of vehicles	unit	Full load	E.F. ($kgCO_2eq/unit$)		E.F. ($kgSO_2eq/unit$)		E.F. ($kgCFC_{11}eq/unit$)		E.F. (kgPbeq/unit)		E.F. (MJ LHV/unit)		Reference data	Reference database
				100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading		
4	Transport, lorry 16-32 t EURO3 RER S 11 tons	ton	11	0.18093	0.00089	0.00112	5.63E-06	3.82E-08	1.78E-10	2.04E-06	2.74E-09	3.0416	0.01296	Eco-indicator 95 (SimaPro 7.3.2)	Transport, lorry 16-32t, EURO3/tkm /RER, ECOINVENT 2.0
5	Transport, lorry 16-32 t EURO3 RER S 16 tons	ton	16	0.18093	0.00089	0.00112	5.63E-06	3.82E-08	1.78E-10	2.04E-06	2.74E-09	3.0416	0.01296	Eco-indicator 95 (SimaPro 7.3.2)	Transport, lorry 16-32t, EURO3/tkm /RER, ECOINVENT 2.0
6	Transport, lorry more 32 t EURO3 RER S 32 tons	ton	32	0.11806	0.00113	0.000736	7.24E-06	2.58E-08	2.27E-10	1.47E-06	3.45E-09	2.0449	0.01654	Eco-indicator 95 (SimaPro 7.3.2)	Transport, lorry >32t, EURO3/tkm /RER, ECOINVENT 2.0

Table A-2 Emission factor of vehicles in transportation and distribution stages (cont.)

No	Type of vehicles	unit	Full load	E.F. (kgCO$_2$eq/unit)		E.F. (kgSO$_2$eq/unit)		E.F. (kgCFC$_{11}$eq/unit)		E.F. (kgPbeq/unit)		E.F. (MJ LHV/unit)		Reference data	Reference database
				100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading		
7	Transport, lorry 4 wheels 7 tons, runs in rough conditions	ton	7	0.1613	0.3718	-	-	-	-	-	-	-	-	Thai LCI data	-
8	Transport, lorry 4 wheels 7 tons, runs in normal conditions	ton	7	0.1399	0.3105	-	-	-	-	-	-	-	-	Thai LCI data	-
9	Transport, lorry 6 wheels 8.5 tons, runs in rough conditions	ton	8.5	0.0743	0.509	-	-	-	-	-	-	-	-	Thai LCI data	-
10	Transport, lorry 6 wheels 11 tons, runs in normal conditions	ton	11	0.0609	0.4882	-	-	-	-	-	-	-	-	Thai LCI data	-

Table A-2 Emission factor of vehicles in transportation and distribution stages (cont.)

No	Type of vehicles	unit	Full load	E.F. ($kgCO_2eq/unit$)		E.F. ($kgSO_2eq/unit$)		E.F. ($kgCFC_{11}eq/unit$)		E.F. (kgPbeq/unit)		E.F. (MJ LHV/unit)		Reference data	Reference database
				100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading		
11	Transport, lorry 10 wheels 16 tons, runs in rough conditions	ton	16	0.0634	0.7451	-	-	-	-	-	-	-	-	Thai LCI data	-
12	Transport, lorry 10 wheels 16 tons, runs in normal conditions	ton	16	0.0529	0.5851	-	-	-	-	-	-	-	-	Thai LCI data	-
13	Transport, lorry, semi-trailer, 18 wheels 32 tons, runs in normal conditions	ton	32	0.0441	0.8612	-	-	-	-	-	-	-	-	Thai LCI data	-
14	Transport, lorry more, 22 wheels 32 tons, runs in normal conditions	ton	32	0.0456	1.0122	-	-	-	-	-	-	-	-	Thai LCI data	-

Table A-2 Emission factor of vehicles in transportation and distribution stages (cont.)

No	Type of vehicles	unit	Full load	E.F. (kgCO$_2$eq/unit)		E.F. (kgSO$_2$eq/unit)		E.F. (kgCFC$_{11}$eq/unit)		E.F. (kgPbeq/unit)		E.F. (MJ LHV/unit)		Reference data	Reference database
				100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading		
15	Transport, trailer, 4 wheels, 1.5 tons, runs in normal conditions	ton	1.5	0.2136	0.2395	-	-	-	-	-	-	-	-	Thai LCI data	-
16	Transport, trailer, 6 wheels, 11 tons, runs in normal conditions	ton	11	0.0542	0.4337	-	-	-	-	-	-	-	-	Thai LCI data	-
17	Transport, trailer, 10 wheels, 16 tons, runs in rough conditions	ton	16	0.0549	0.6732	-	-	-	-	-	-	-	-	Thai LCI data	-
18	Transport, trailer, 10 wheels, 16 tons, runs in normal conditions	ton	16	0.0451	0.57	-	-	-	-	-	-	-	-	Thai LCI data	-

Table A-2 Emission factor of vehicles in transportation and distribution stages (cont.)

No	Type of vehicles	unit	Full load	E.F. ($kgCO_2eq/unit$)		E.F. ($kgSO_2eq/unit$)		E.F. ($kgCFC_{11}eq/unit$)		E.F. (kgPbeq/unit)		E.F. (MJ LHV/unit)		Reference data	Reference database
				100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading	100% Loading	0% Loading		
19	Transport, trailer more, 18 wheels, 32 tons, runs in normal conditions	ton	32	0.0401	0.7805	-	-	-	-	-	-	-	-	Thai LCI data	-

Table A-3 Emission factor of utilities in production stages

No	List	unit	E.F.	E.F.	E.F.	E.F.	E.F.
			(kgCO_2eq/unit)	(kgSO_2eq/unit)	(kgCFC_{11}eq/unit)	(kgPbeq/unit)	(MJ LHV/unit)
1	Natural gas (Upstream)	**MJ**	0.0099	4.45E-05	7.56E-09	4.00E-08	1.1899
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	ECOINVENT 2.0	Natural gas, high pressure, at consumer/RER S, ECOINVENT 2.0	Natural gas, high pressure, at consumer/RER S, ECOINVENT 2.0	Natural gas, high pressure, at consumer/RER S, ECOINVENT 2.0	Natural gas, high pressure, at consumer/RER S, ECOINVENT 2.0
2	Natural gas (Combustion)	**MJ**	0.0561	5.16E-05	5.77E-09	3.39E-08	1.1811
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	ECOINVENT 2.0, IPPC 2007 GWP 100a	Natural gas, burned in gas motor, for storage/MJ/GLO S, Ecoinvent 2.0	Natural gas, burned in gas motor, for storage/MJ/GLO S, Ecoinvent 2.0	Natural gas, burned in gas motor, for storage/MJ/GLO S, Ecoinvent 2.0	Natural gas, burned in gas motor, for storage/MJ/GLO S, Ecoinvent 2.0
3	Electricity	**kWh or MJ**	0.6093/kWh	6.80E-04/MJ	6.39E-09/MJ	1.13E-05/MJ	3.4219/MJ
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Electricity, at grid mix GTO	Electricity, low voltage, production , at grid/ RER S, ECOINVENT 2.0	Electricity, low voltage, production , at grid/ RER S, ECOINVENT 2.0	Electricity, low voltage, production , at grid/ RER S, ECOINVENT 2.0	Electricity, low voltage, production , at grid/ RER S, ECOINVENT 2.0
4	Water supply	**kg**	0.0003	1.36E-06	1.57E-11	2.61E-08	0.0061784
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	ECOINVENT 2.0	Tap water, at user/RER S, ECOINVENT 2.0	Tap water, at user/RER S, ECOINVENT 2.0	Tap water, at user/RER S, ECOINVENT 2.0	Tap water, at user/RER S, ECOINVENT 2.0

Table A-3 Emission factor of utilities in production stages (cont.)

No	List	unit	E.F. (kgCO_2eq/unit)	E.F. (kgSO_2eq/unit)	E.F. (kgCFC_{11}eq/unit)	E.F. (kgPbeq/unit)	E.F. (MJ LHV/unit)
5	Soft water	**kg**	0.02416	7.11E-08	3.08E-12	2.33E-09	0.00029526
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Converted data from JEMAI Pro using Thai Electricity Grid	Water, completely softened, at plant/kg/RER S, ECOINVENT 2.0	Water, completely softened, at plant/kg/RER S, ECOINVENT 2.0	Water, completely softened, at plant/kg/RER S, ECOINVENT 2.0	Water, completely softened, at plant/kg/RER S, ECOINVENT 2.0
6	DI water	**kg**	0.0000258	3.63E-06	5.46E-10	6.54E-08	0.01908
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	ECOINVENT 2.0	Water, deionised, at plant/kg/CH S, ECOINVENT 2.0	Water, deionised, at plant/kg/CH S, ECOINVENT 2.0	Water, deionised, at plant/kg/CH S, ECOINVENT 2.0	Water, deionised, at plant/kg/CH S, ECOINVENT 2.0

Table A-4 Emission factors of materials in waste management stage

No.	List	unit	E.F.	E.F.	E.F.	E.F.	E.F.
			($kgCO_2eq/unit$)	($kgSO_2eq/unit$)	($kgCFC_{11}eq/unit$)	(kgPbeq/unit)	(MJ LHV/unit)
1	Lead (Landfill)	**kg**	0.0090875	0.0000639	4.61E-09	1.34E-03	0.31827
		Reference data	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Disposal, cement, hydrated, 0% water, to residual material landfill/CH S	Disposal, cement, hydrated, 0% water, to residual material landfill/CH S	Disposal, cement, hydrated, 0% water, to residual material landfill/CH S	Disposal, cement, hydrated, 0% water, to residual material landfill/CH S	Disposal, cement, hydrated, 0% water, to residual material landfill/CH S
2	Polypropylene (Landfill)	**kg**	2.32	8.89E-05	4.08E-05	1.13E-04	0.32612
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	ECOINVENT 2.0	Disposal, polypropylene, 15.9% water, to sanitary landfill/CH S	Disposal, polypropylene, 15.9% water, to sanitary landfill/CH S	Disposal, polypropylene, 15.9% water, to sanitary landfill/CH S	Disposal, polypropylene, 15.9% water, to sanitary landfill/CH S
3	Polyethylene (Landfill)	**kg**	2.32	8.92E-05	4.08E-09	0.00013358	0.32664
		Reference data	TGO's guideline	Calculation	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	ECOINVENT 2.0	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH S	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH S	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH S	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH S
4	Polycarbonate (Landfill)	**kg**	2.32	9.17E-05	4.09E-09	0.00069637	0.33252
		Reference data	TGO's guideline	Calculation	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Ecoinvent 2.0, IPPC 2006 GWP 100a	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH S	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH S	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH S	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH S

Table A-4 Emission factors of materials in waste management stage (cont.)

No.	List	unit	E.F.	E.F.	E.F.	E.F.	E.F.
			($kgCO_2eq/unit$)	($kgSO_2eq/unit$)	($kgCFC_{11}eq/unit$)	(kgPbeq/unit)	(MJ LHV/unit)
5	Sodium hydroxide	**kg**	1.0662	5.05E-03	6.70E-08	9.13E-06	22.841
		Reference data	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S	Sodium hydroxide, 50% in H2O, production mix, at plant/RER S
6	Sodium sulfate	**kg**	0	5.27E-05	2.82E-09	7.29E-08	0.19848
		Reference data	TGO’s guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	2006 IPCC Guidelines for National Greenhouse Gas Inventoried : Volume 5 : Waste	Disposal, inert waste, 5% water, to inert material landfill/CH S	Disposal, inert waste, 5% water, to inert material landfill/CH S	Disposal, inert waste, 5% water, to inert material landfill/CH S	Disposal, inert waste, 5% water, to inert material landfill/CH S
7	Calcium hydroxide	**MJ**	0.75105	0.000732	7.00E-08	1.50E-06	4.8045
		Reference data	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Lime, hydrated, packed, at plant/CH S, ECOINVENT 2.0	Lime, hydrated, packed, at plant/CH S, ECOINVENT 2.1	Lime, hydrated, packed, at plant/CH S, ECOINVENT 2.2	Lime, hydrated, packed, at plant/CH S, ECOINVENT 2.3	Lime, hydrated, packed, at plant/CH S, ECOINVENT 2.4
8	Calcium sulfate	**kg**	0	5.27E-05	2.82E-09	7.29E-08	0.19848
		Reference data	TGO’s guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	2006 IPCC Guidelines for National Greenhouse Gas Inventoried : Volume 5 : Waste	Disposal, gypsum, 19.4% water, to inert material landfill/CH S	Disposal, gypsum, 19.4% water, to inert material landfill/CH S	Disposal, gypsum, 19.4% water, to inert material landfill/CH S	Disposal, gypsum, 19.4% water, to inert material landfill/CH S

Table A-4 Emission factors of materials in waste management stage (cont.)

No.	List	unit	E.F.	E.F.	E.F.	E.F.	E.F.
			(kgCO_2eq/unit)	(kgSO_2eq/unit)	(kgCFC_{11}eq/unit)	(kgPbeq/unit)	(MJ LHV/unit)
9	Carton (Landfill)	**kg**	2.93	5.27E-05	2.82E-09	7.29E-08	0.19848
		Reference data	TGO's guideline	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)	Eco-indicator 95 (SimaPro 7.3.2)
		Reference database	Ecoinvent 2.0, IPPC 2006 GWP 100a	Disposal, packaging cardboard, 19.6% water, to sanitary landfill/CH S	Disposal, packaging cardboard, 19.6% water, to sanitary landfill/CH S	Disposal, packaging cardboard, 19.6% water, to sanitary landfill/CH S	Disposal, packaging cardboard, 19.6% water, to sanitary landfill/CH S

APPENDIX B

Five environmental impacts in all stages throughout life cycle of vehicle batteries at various percentages

Table B-1 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (0% collection, NaOH)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO_2eq	35.2	0.322	6.82	1.44	0.00	18.6	**62.3**
Battery B			44.0	0.390	14.6	1.23	0.00	23.3	**83.4**
Battery C			59.3	0.602	19.1	1.67	0.00	38.3	**119**
Battery A	Acidification	kgSO_2eq	0.836	0.0144	0.0198	0.0219	0.0000000	0.0689	**0.961**
Battery B			1.03	0.0177	0.0469	0.0268	0.0000209	0.0843	**1.21**
Battery C			1.40	0.0244	0.0615	0.0364	0.0000209	0.139	**1.66**
Battery A	Ozone depletion	kgCFC_{11}eq	1.64E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	9.91E-07	**4.35E-06**
Battery B			2.04E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	1.21E-06	**5.67E-06**
Battery C			2.72E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.98E-06	**7.99E-06**
Battery A	Heavy matal emission	kgPbeq	2.44E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	2.07E-02	**4.54E-02**
Battery B			3.02E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	2.56E-02	**5.66E-02**
Battery C			3.96E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	3.37E-02	**7.44E-02**
Battery A	Energy resource consumption	MJ LHV	516	39.2	138	67.9	0.000	312	**1072**
Battery B			653	48.3	295	83.2	0.110	381	**1462**
Battery C			920	66.5	387	113	0.110	628	**2116**

Table B-2 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (25% collection, NaOH)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO_2eq	31.7	0.322	6.82	1.44	0.00	18.3	**58.5**
Battery B			39.6	0.390	14.6	1.23	0.00	22.9	**78.7**
Battery C			53.6	0.602	19.1	1.67	0.00	37.8	**113**
Battery A	Acidification	kgSO_2eq	0.751	0.0144	0.0198	0.0219	0.0000000	0.0687	**0.876**
Battery B			0.93	0.0177	0.0469	0.0268	0.0000209	0.0841	**1.10**
Battery C			1.26	0.0244	0.0615	0.0364	0.0000209	0.139	**1.52**
Battery A	Ozone depletion	kgCFC_{11}eq	1.54E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	9.79E-07	**4.23E-06**
Battery B			1.91E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	1.20E-06	**5.53E-06**
Battery C			2.55E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.96E-06	**7.80E-06**
Battery A	Heavy matal emission	kgPbeq	2.06E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	1.74E-02	**3.84E-02**
Battery B			2.55E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	2.15E-02	**4.78E-02**
Battery C			3.35E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	2.84E-02	**6.30E-02**
Battery A	Energy resource consumption	MJ LHV	481	39.2	138	67.9	0.000	311	**1036**
Battery B			610	48.3	295	83.2	0.110	380	**1417**
Battery C			862	66.5	387	113	0.110	627	**2056**

Table B-3 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (50% collection, NaOH)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO_2eq	28.1	0.322	6.82	1.44	0.00	18.1	**54.8**
Battery B			35.2	0.390	14.6	1.23	0.00	22.6	**74.0**
Battery C			47.8	0.602	19.1	1.67	0.00	37.3	**107**
Battery A	Acidification	kgSO_2eq	0.667	0.0144	0.0198	0.0219	0.0000000	0.0685	**0.791**
Battery B			0.82	0.0177	0.0469	0.0268	0.0000209	0.0839	**1.00**
Battery C			1.12	0.0244	0.0615	0.0364	0.0000209	0.138	**1.38**
Battery A	Ozone depletion	kgCFC_{11}eq	1.43E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	9.67E-07	**4.11E-06**
Battery B			1.78E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	1.18E-06	**5.39E-06**
Battery C			2.39E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.94E-06	**7.61E-06**
Battery A	Heavy matal emission	kgPbeq	1.68E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	1.41E-02	**3.13E-02**
Battery B			2.08E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	1.74E-02	**3.91E-02**
Battery C			2.74E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	2.30E-02	**5.15E-02**
Battery A	Energy resource consumption	MJ LHV	446	39.2	138	67.9	0.000	310	**1001**
Battery B			566	48.3	295	83.2	0.110	379	**1373**
Battery C			804	66.5	387	113	0.110	626	**1997**

Table B-4 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (75% collection, NaOH)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO$_2$eq	24.6	0.322	6.82	1.44	0.000000	17.8	**51.0**
Battery B			30.9	0.390	14.6	1.23	0.000149	22.3	**69.3**
Battery C			42.1	0.602	19.1	1.67	0.000149	36.8	**100**
Battery A	Acidification	kgSO$_2$eq	0.582	0.0144	0.0198	0.0219	0.0000000	0.0684	**0.706**
Battery B			0.720	0.0177	0.0469	0.0268	0.0000209	0.0837	**0.895**
Battery C			0.987	0.0244	0.0615	0.0364	0.0000209	0.138	**1.25**
Battery A	Ozone depletion	kgCFC$_{11}$eq	1.33E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	9.56E-07	**4.00E-06**
Battery B			1.65E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	1.17E-06	**5.24E-06**
Battery C			2.22E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.92E-06	**7.43E-06**
Battery A	Heavy matal emission	kgPbeq	1.31E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	1.08E-02	**2.42E-02**
Battery B			1.62E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	1.34E-02	**3.03E-02**
Battery C			2.12E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	1.77E-02	**4.00E-02**
Battery A	Energy resource consumption	MJ LHV	411	39	138	68	0.000	309	**965**
Battery B			523	48	295	83	0.110	378	**1328**
Battery C			746	66	387	113	0.110	625	**1938**

Table B-5 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (100% collection, NaOH)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO_2eq	21.1	0.322	6.82	1.44	0.000000	17.6	**47.2**
Battery B			26.5	0.390	14.6	1.23	0.000149	22.0	**64.6**
Battery C			36.3	0.602	19.1	1.67	0.000149	36.4	**94**
Battery A	Acidification	kgSO_2eq	0.497	0.0144	0.0198	0.0219	0.0000000	0.0682	**0.622**
Battery B			0.615	0.0177	0.0469	0.0268	0.0000209	0.0835	**0.790**
Battery C			0.849	0.0244	0.0615	0.0364	0.0000209	0.138	**1.11**
Battery A	Ozone depletion	kgCFC_{11}eq	1.22E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	9.44E-07	**3.88E-06**
Battery B			1.52E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	1.16E-06	**5.10E-06**
Battery C			2.05E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.90E-06	**7.24E-06**
Battery A	Heavy matal emission	kgPbeq	9.28E-03	2.71E-05	2.95E-04	5.80E-05	0.00E+00	7.47E-03	**1.71E-02**
Battery B			1.15E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	9.27E-03	**2.16E-02**
Battery C			1.51E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	1.23E-02	**2.85E-02**
Battery A	Energy resource consumption	MJ LHV	376	39	138	68	0.000	309	**930**
Battery B			480	48	295	83	0.110	377	**1284**
Battery C			688	66	387	113	0.110	623	**1878**

Table B-6 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (0% collection, $Ca(OH)_2$)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO_2eq	35.2	0.322	6.82	1.44	0.00	9.3	**53.1**
Battery B			44.0	0.390	14.6	1.23	0.00	12.0	**72.1**
Battery C			59.3	0.602	19.1	1.67	0.00	19.7	**100**
Battery A	Acidification	kgSO_2eq	0.836	0.0144	0.0198	0.0219	0.0000000	0.0064	**0.898**
Battery B			1.03	0.0177	0.0469	0.0268	0.0000209	0.0078	**1.13**
Battery C			1.40	0.0244	0.0615	0.0364	0.0000209	0.012	**1.53**
Battery A	Ozone depletion	kgCFC_{11}eq	1.64E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	5.63E-07	**3.92E-06**
Battery B			2.04E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	6.90E-07	**5.15E-06**
Battery C			2.72E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.11E-06	**7.12E-06**
Battery A	Heavy matal emission	kgPbeq	2.44E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	2.06E-02	**4.53E-02**
Battery B			3.02E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	2.55E-02	**5.64E-02**
Battery C			3.96E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	3.35E-02	**7.42E-02**
Battery A	Energy resource consumption	MJ LHV	516	39.2	138	67.9	0.000	39	**799**
Battery B			653	48.3	295	83.2	0.110	48	**1128**
Battery C			920	66.5	387	113	0.110	77	**1564**

Table B-7 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries

(25% collection, $Ca(OH)_2$)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO_2eq	31.7	0.322	6.82	1.44	0.00	9.1	**49.3**
Battery B			39.6	0.390	14.6	1.23	0.00	11.7	**67.5**
Battery C			53.6	0.602	19.1	1.67	0.00	19.2	**94**
Battery A	Acidification	kgSO_2eq	0.751	0.0144	0.0198	0.0219	0.0000000	0.0062	**0.813**
Battery B			0.93	0.0177	0.0469	0.0268	0.0000209	0.0076	**1.03**
Battery C			1.26	0.0244	0.0615	0.0364	0.0000209	0.012	**1.40**
Battery A	Ozone depletion	kgCFC_{11}eq	1.54E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	5.51E-07	**3.80E-06**
Battery B			1.91E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	6.76E-07	**5.01E-06**
Battery C			2.55E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.09E-06	**6.94E-06**
Battery A	Heavy matal emission	kgPbeq	2.06E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	1.73E-02	**3.82E-02**
Battery B			2.55E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	2.14E-02	**4.77E-02**
Battery C			3.35E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	2.81E-02	**6.27E-02**
Battery A	Energy resource consumption	MJ LHV	481	39.2	138	67.9	0.000	38	**763**
Battery B			610	48.3	295	83.2	0.110	47	**1083**
Battery C			862	66.5	387	113	0.110	75	**1504**

Table B-8 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (50% collection, $Ca(OH)_2$)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	$kgCO_2eq$	28.1	0.322	6.82	1.44	0.00	8.8	**45.5**
Battery B			35.2	0.390	14.6	1.23	0.00	11.3	**62.8**
Battery C			47.8	0.602	19.1	1.67	0.00	18.7	**88**
Battery A	Acidification	$kgSO_2eq$	0.667	0.0144	0.0198	0.0219	0.0000000	0.0060	**0.729**
Battery B			0.82	0.0177	0.0469	0.0268	0.0000209	0.0074	**0.92**
Battery C			1.12	0.0244	0.0615	0.0364	0.0000209	0.012	**1.26**
Battery A	Ozone depletion	$kgCFC_{11}eq$	1.43E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	5.40E-07	**3.68E-06**
Battery B			1.78E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	6.62E-07	**4.86E-06**
Battery C			2.39E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.07E-06	**6.75E-06**
Battery A	Heavy matal emission	kgPbeq	1.68E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	1.40E-02	**3.12E-02**
Battery B			2.08E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	1.73E-02	**3.90E-02**
Battery C			2.74E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	2.28E-02	**5.13E-02**
Battery A	Energy resource consumption	MJ LHV	446	39.2	138	67.9	0.000	37	**728**
Battery B			566	48.3	295	83.2	0.110	46	**1039**
Battery C			804	66.5	387	113	0.110	74	**1445**

Table B-9 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (75% collection, $Ca(OH)_2$)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	$kgCO_2eq$	24.6	0.322	6.82	1.44	0.000000	8.6	**41.8**
Battery B			30.9	0.390	14.6	1.23	0.000149	11.0	**58.1**
Battery C			42.1	0.602	19.1	1.67	0.000149	18.2	**82**
Battery A	Acidification	$kgSO_2eq$	0.582	0.0144	0.0198	0.0219	0.0000000	0.0059	**0.644**
Battery B			0.720	0.0177	0.0469	0.0268	0.0000209	0.0072	**0.819**
Battery C			0.987	0.0244	0.0615	0.0364	0.0000209	0.012	**1.12**
Battery A	Ozone depletion	$kgCFC_{11}eq$	1.33E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	5.28E-07	**3.57E-06**
Battery B			1.65E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	6.47E-07	**4.72E-06**
Battery C			2.22E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.05E-06	**6.56E-06**
Battery A	Heavy matal emission	kgPbeq	1.31E-02	2.71E-05	2.95E-04	5.80E-05	0.00E+00	1.07E-02	**2.41E-02**
Battery B			1.62E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	1.32E-02	**3.02E-02**
Battery C			2.12E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	1.74E-02	**3.98E-02**
Battery A	Energy resource consumption	MJ LHV	411	39	138	68	0.000	36	**692**
Battery B			523	48	295	83	0.110	45	**995**
Battery C			746	66	387	113	0.110	73	**1386**

Table B-10 Summary of five environmental impacts in all stages throughout life cycle of vehicle batteries (100% collection, $Ca(OH)_2$)

Types of battery	Impact categories	Unit	Raw material acquisition	Transportation	Production	Distribution	Customer Use	Waste management	Total
Battery A	Global warming	kgCO_2eq	21.1	0.322	6.82	1.44	0.000000	8.4	**38.0**
Battery B			26.5	0.390	14.6	1.23	0.000149	10.7	**53.4**
Battery C			36.3	0.602	19.1	1.67	0.000149	17.7	**75**
Battery A	Acidification	kgSO_2eq	0.497	0.0144	0.0198	0.0219	0.0000000	0.0057	**0.559**
Battery B			0.615	0.0177	0.0469	0.0268	0.0000209	0.0070	**0.714**
Battery C			0.849	0.0244	0.0615	0.0364	0.0000209	0.011	**0.98**
Battery A	Ozone depletion	kgCFC_{11}eq	1.22E-06	5.11E-07	4.07E-07	7.93E-07	0.00E+00	5.17E-07	**3.45E-06**
Battery B			1.52E-06	6.46E-07	8.04E-07	9.71E-07	3.15E-09	6.33E-07	**4.57E-06**
Battery C			2.05E-06	9.13E-07	1.05E-06	1.32E-06	3.15E-09	1.04E-06	**6.38E-06**
Battery A	Heavy matal emission	kgPbeq	9.28E-03	2.71E-05	2.95E-04	5.80E-05	0.00E+00	7.36E-03	**1.70E-02**
Battery B			1.15E-02	3.40E-05	7.27E-04	7.10E-05	3.77E-07	9.13E-03	**2.15E-02**
Battery C			1.51E-02	4.76E-05	9.54E-04	9.64E-05	3.77E-07	1.21E-02	**2.83E-02**
Battery A	Energy resource consumption	MJ LHV	376	39	138	68	0.000	36	**657**
Battery B			480	48	295	83	0.110	44	**950**
Battery C			688	66	387	113	0.110	71	**1326**

APPENDIX C

Economic Analysis

Table C-1 Prices of three types of battery in each option (Per 1 unit)

Options of purchase	Prices of three types of batteries (Baht)					
	Battery A	*Average*	*Battery B*	*Average*	*Battery C*	*Average*
Purchase a new battery	4,300-4,500	4,400	3,200-3,600	3,400	2,300-2,500	2,400
Turn an old battery and purchase a new one	3,900-4,200	4,050	2,800-3,200	3,000	1,900-2,200	2,050

Table C-2 Calculation of three types of battery in two purchase option for 4 years

Battery A	*Battery B*	*Battery C*
Purchase a new battery (4,400 baht) 1 FU = 4,400 baht Net amount = 4,400 baht	Purchase a new battery (3,400 baht) 1 FU = 4,533 baht 1st year, balance 1,133*(101.7/100) = 1,152.261 baht 2st year, balance 1,152.261*(101.7/100) = 1,171.85 baht 3st year, balance 1,171*(101.7/100) = 1,191.77 baht Interest = 1,191.77 - 1,133 = 58.77 baht Net amount =4,533 – 58.77 = 4,474.23 baht	Purchase a new battery (2,400 baht) 1 FU = 4,800 baht 1st year, balance 2,400*(101.7/100) = 2,440.8 baht 2st year, balance 2,440.8*(101.7/100) = 2,482.3 baht Interest = 2,482.30 - 2,400 = 82.3 baht Net amount =4,800 – 82.30 = 4,717.7 baht
Turn an old battery and purchase a new one (4,050 baht) 1 FU = 4,050 baht Net amount = 4,050 baht	Turn an old battery and purchase a new one (3,000 baht) 1 FU = 4,000 baht 1st year, balance 1,000*(101.7/100) = 1,017 baht 2st year, balance 1,017*(101.7/100) = 1,034.289 baht 3st year, balance 1,034.289*(101.7/100) = 1,051.87 baht Interest = 1,051.87 - 1,000 = 51.87 baht Net amount =4,000 – 51.87 = 3,948.13 baht	Turn an old battery and purchase a new one (2,050 baht) 1 FU = 4,100 baht 1st year, balance 2,050*(101.7/100) = 2,084.85 baht 2st year, balance 2,084.85*(101.7/100) = 2,120.29 baht Interest = 2,120.29 - 2,050 = 70.29 baht Net amount =4,100 – 70.29 = 4,029.71 baht

Resource: Bank of Thailand (24 March 2014)

SCB 12 months per interest 1.07 Baht

VITA

Miss. Chuleekorn Sawettavong was born on June 24th, 1988 in Udonthani province, Thailand. She finished her bachelor's degree of General Science (Environmental Science), Faculty of Science, Chulalongkorn University, Bangkok, Thailand in 2006-2009. She pursued her master's degree in the International Postgraduate Program in Environmental Management, (Hazardous Waste Management), Graduate School, Chulalongkorn University, Bangkok, Thailand under the management of Center of Excellent for Environmental and Hazardous Waste Management (EHWM) in 2010-2014.

Presentations:

Chuleekorn Sawettavong, Nonthaphat Suesareetham, and Prasert Pavasant. "Carbon Footprints of vehicle batteries". International Conference on Sustainable Environmental Technologies (ICSET), on April 26-27, 2012, in Bangkok, Thailand.

Chuleekorn Sawettavong and Prasert Pavasant. "Life Cycle Assessment of vehicle batteries". International Conference on Environmental and Hazardous Substance Management towards a Green Economy (EHSM 2013), on May 21-23, 2013 in Bangkok,Thailand.