Environment Protection Engineering

Vol. 39 2013 No. 1

DOI: 10.5277/EPE130108

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LIFE CYCLE ASSESSMENT OF LEAD ACID BATTERY. CASE STUDY FOR THAILAND

Over the past ten years, the automobile manufacturing basis has shifted to Thailand, thus transforming the country into an automobile industrial hub in Asia. An integral part of this industry, lead acid battery manufacturing has exhibited tremendous growth with increasing trends toward new manufacturing technology. This research aimed to study life cycle assessments of lead-acid automobile battery manufactured in Thailand by comparing conventional batteries with calcium-maintenance free batteries. Global warming and acidification are the largest environmental impacts associated with both battery types. Changing from conventional batteries to calcium-maintenance free batteries is able to reduce environmental impact by approximately 28% due to longer usage life and reduced utilization of manufacturing resources and energy. The greenhouse gases and acidification caused by one conventional battery amounted to 102 kg CO_2 and 0.94 kg SO_2, respectively. These amounts decrease to 72 kg CO_2 and 0.56 kg SO_2, respectively, when calcium-maintenance free technology is used. Raw material procurement is found to have the greatest environmental impact, followed by product usage. In this study, the information on environmental impact is incorporated with MET matrix principles to propose guidelines for environmental improvement throughout the battery life cycle.

1. INTRODUCTION

The automobile battery industry is one of Thailand’s automotive parts industries with manufacturing and export capacity. From 2005 to 2009, the average annual production volume for automobile batteries was approximately 14.5 million with an average annual growth rate of 7.5% per year [1]. Most Thai automobile battery manufacturers are joint ventures with foreign companies (especially Japan) and usually receive technology transfer from foreign joint venture companies. At present, these technology transfers are beginning to shift toward new innovations on a larger scale. In the

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past, the most common automobile battery technology in Thailand involved the conventional lead-acid type employed grids made from lead–antimony alloys which yield batteries requiring the addition of water at regular intervals to extend usage life. The conventional type with grids of lead-antimony alloy undergo self-discharge at the rate of 0.5–1.0% of daily capacity during long storage periods or at high temperatures. Batteries need to be charged at the factory if original quality is desired [2]. The inconveniences associated with using this conventional type of battery marked the beginning of changes in the technology employed in Thai automobile battery manufacturing to the manufacture of calcium-maintenance free batteries. This technology lowers the antimony content of the alloy and a substantially antimony-free lead–calcium–tin alloy has resulted in maintenance-free batteries without the requirement to add water throughout the usage life because the structural use of raw materials and the production process differ from those of the abovementioned conventional battery. In addition, distributors can store this type of battery for longer periods of time because the maintenance-free batteries with grids of a lead–calcium–tin alloy can suffer a self--discharge of approximately 0.1% of the daily capacity [2]. At present, the production ratio of calcium-maintenance free type for one of the largest manufacturers in Thailand is approximately 35% with continuing upward trends [3].

The shift in technology from conventional batteries to calcium-maintenance free batteries has also brought about changes in environmental impact trends due to the manufacture of automobile batteries. These environmental impacts can be considered as basic data to accompany decisions on investment promotion in the automobile battery industry by the Thailand Board of Investment (BOI) which issued *Investment Promotion Policy for Sustainable Development*) in 2010–2012 [4]. Moreover, this information on environmental impact can be used to identify ways for improving the product life cycle in order to reduce environmental impact and increase environmental performance. Therefore, from the aforementioned turning point of innovation in automobile lead acid battery manufacturing, this research has been conducted for the purpose of finding answers to the following questions:

- What are the environmental impacts of automobile battery manufacturing? What is the extent of these environmental impacts?
- Does the new technology of automobile battery manufacturing help reduce environmental impacts? How much?
- What types of eco-design guidelines should be formed for automobile battery manufacturing?

Life cycle assessment (LCA) is generally considered very useful as a means of identifying environmental hot-spots in the product development stage. To facilitate the use of LCA, this paper examined and discussed some critical issues pertaining to the LCA of lead acid battery technology in the context of a case study on the conventional and calcium-maintenance free battery types. This study employed LCA in compliance with ISO 14040-14043 standards with SimaPro 7.1 software to calculate and analyze the extent of environmental impact. Eco-indicator 95 was used to evaluate mid-point and end-point impacts [5–8].

2. METHODS

The method of study for the LCA was carried out according to the steps outlined in standard sequence ISO14040.

Table 1

The raw materials for conventional (C) and calcium maintenance free (F) battery

Component	Calcium-maintenance free battery		Conventional battery	
	Material	Weight [g/battery]	Material	Weight [g/battery]
Positive grid	Pb alloy C21	1.953	PbSb 2.5%	2.079
Positive oxide	pure lead	3.236	pure lead	2.995
Chemical	acid	361	acid	419
	DI	412	DI	416
	other chemicals	3	other chemicals	3
Negative grid	Pb alloy	1.638	PbSb2.5%	1.638
Negative oxide	pure lead	3.322	pure lead	3.322
Chemical	acid	385	acid	385
	DI	444	DI	444
	other chemicals	55	other chemicals	48
Separator	PE	241	paper + glass mat.	375
Top lead	PbSb 3.2%	997	PbSb 3.2%	975
Container	PP	635	PP	825
Cover	PP	260	PP	189
Cover–bushing	PbSb 3.2%	126	PbSb 3.2%	138
Vent plug	PP	16	PP	29
Indicator	acrylic	7	–	
Acid 50%	SG 1.395	3.720	SG.1.395	3.730
Di	DI water	2.400	DI water	2.350
Charging electricity	electric	5.13 kWh	electric	5.13 kWh
Pulp mould	pulp paper	63	pulp paper	63
PE shrink wrap	PE	465 000 mm^2	–	–
Sticker	EUPO 80 um	18 782 mm^2	EUPO 80 um	1972 mm^2
Warranty card	paper	30 000 mm^2	–	–
Manual	paper	62 580 mm^2	–	–
Terminal cap/positive	PP	2	–	–
Terminal cap /negative	PP	2	–	–
Sealing foil	–	–	foil	2
Carton/inner	paper	276	paper	178
Carton/outer	–	–	paper	158
Staple	–	–	Fe	35

2.1. SCOPE AND SYSTEM BOUNDARIES

Two types of automobile batteries were studied, i.e. a conventional battery and a calcium-maintenance free battery, which has a longer lifetime than the conventional one. The boundaries of the systems studied extend to include raw materials, production, transportation (of raw materials, products and waste), utilization and disposal.

Table 1 shows the comparison of the raw materials of a conventional battery and calcium-maintenance free battery used in this study. The main production processes of an automobile battery are divided into seven stages: grid casting, oxide mixing, pasting, curing, formation, assembly and packaging [10], the analytical boundaries of which can be seen in Fig. 1. The types of environmental impact to be studied can be divided into five groups: global warming (GW), acidification (AD), ozone depletion (OD), heavy metal (HM), and energy resources (ER).

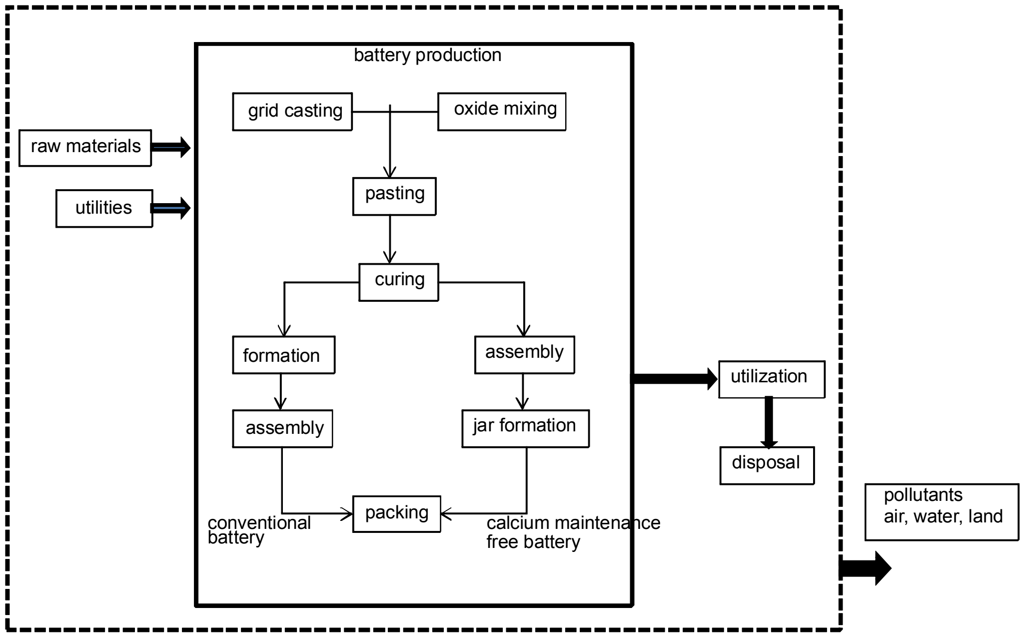

Fig. 1. System boundaries of the battery

2.2. FUNCTIONAL UNIT

Battery usage is typically over a period of two years in conditions replicating normal use (according to testing criteria outlined by the standard Toyota lifecycle test) for a small-size pickup truck. The conventional battery was used over a period of two years, while the calcium-maintenance free battery was used over four years. The maximum A·h capacity is 80 and 90 for the conventional battery and the calcium-maintenance free battery, respectively. A maximum size is equal to 258 mm (width) × 171 mm (length) × 200 mm (height).

2.3. LIFE CYCLE INVENTORY

The information used in the LCA can be divided into primary data derived from the manufacturing process and transportation of products manufactured during the 2008 production year. Information on the period when the product was in use can be obtained from data used in the simulation test to determine actual use of a battery. For information outside the scope of the manufacture process or which cannot be stored directly such as data on raw materials, energy, electricity, water supply and recycling, the research team used secondary data sourced from inventory databases on the environment, basic materials and energy use in Thailand. For databases with no stored data on Thailand, information was sourced from international databases using the SimaPro 7.1 program [7], or literature data.

3. RESULTS

3.1. IMPACT ASSESSMENT

At this stage, the environmental impact of the product systems was assessed by separating the types of impact into five groups, namely; global warming, acidification, ozone depletion, heavy metal and energy resources using the Eco-Indicator 95 method. This method composed of classification, characterization, normalization and weighting in order to determine a single score which can be used as an index to categorize important environmental issues and highlight phases of manufacture that have the greatest impact.

Analysis of mid-point impact. When we consider the degree of each type of impact over the lifecycle of both types of batteries as presented in the bar chart in Fig. 2, it is apparent that the impact during the stage of obtaining and use of raw materials is relatively high; accounting for approximately 50% of all the various stages of product life and the impact from acidification as a result of using raw materials such as sulfuric acid used in the formation process during manufacture. Regarding the stage of disposal, although all expired batteries can be recycled, helping to reduce global warming, acidification and use of energy resources (negative value), recycling also results in the depletion of the ozone layer and the release of metal into the environment. Table 2 shows the comparison of the environment impacts of a conventional battery and calcium-maintenance free battery at raw material, production and use stage of lifecycle.

Fig. 2. Comparison of the ratios of mid-point impact for conventional (C) and calcium maintenance free (F) at each stage of the life cycle

Global warming. It is evident that the greatest degree of impact was on global warming and occurred during the stage of usage (54 kg CO_2 eq.) due to the large amount of energy used to charge the battery during usage. Both types of batteries produced similar CO_2 values at this stage. This was followed by the stage of obtaining raw materials, for which the calcium-maintenance free battery produced approximately half the CO_2 value generated by the conventional battery, due to the fact that working unit was equal to half that of the conventional battery. The production stage resulted in the lowest level of CO_2 output.

Ozone depletion. Table 2 shows production stage which has the greatest impact, followed by usage and obtaining raw materials, respectively. The impact on the depletion of the ozone results from the release of refrigerant substances, primarily CFC and HCFC which are produced by using electricity and through the manufacture of sodium hydroxide (NaOH) (for lead precipitation in wastewater treatment systems). Both of electricity production and NaOH production need natural gas for energy resource. The natural gas production use compressor station to transfer natural gas by pipeline to burn it in a power plant. Most of compressor stations/equipments are vapour-compression refrigeration using haloalkanes refrigerants. These refrigerants cause the ozone depletion problem.

Table 2

Comparison of mid-point impact for conventional (C) and calcium maintenance free (F) at each stage of the life cycle

Impact category	Unit	Raw material	Production	Use	Disposal	Total
Greenhouse – C	kg CO_2	3.03×10^{1}	1.75×10^{1}	5.45×10^{1}	-2.16×10^{1}	8.08×10^{1}
Greenhouse – F		1.48×10^{1}	3.86×10^{0}	5.40×10^{1}	-1.09×10^{1}	6.18×10^{1}
Ozone layer – C	kg CFC11	2.65×10^{-8}	3.89×10^{-7}	1.50×10^{-7}	1.63×10^{-6}	2.19×10^{-6}
Ozone layer – F		8.29×10^{-9}	1.91×10^{-7}	6.07×10^{-8}	8.16×10^{-7}	1.08×10^{-6}
Acidification – C	kg SO_2	6.28×10^{-1}	6.38×10^{-2}	2.44×10^{-1}	-5.93×10^{-1}	3.43×10^{-1}
Acidification – F		3.05×10^{-1}	1.88×10^{-2}	2.41×10^{-1}	-2.98×10^{-1}	2.66×10^{-1}
Heavy metals – C	kg Pb	1.24×10^{-5}	2.55×10^{-5}	2.69×10^{-5}	1.13×10^{-5}	7.62×10^{-5}
Heavy metals – F		4.38×10^{-6}	7.86×10^{-6}	2.67×10^{-5}	5.65×10^{-6}	4.46×10^{-5}
Energy resources – C	MJ LHV	5.18×10^{2}	2.48×10^{2}	8.14×10^{2}	-2.16×10^{2}	1.36×10^{3}
Energy resources – F		2.58×10^{2}	8.47×10^{1}	7.95×10^{2}	-1.08×10^{2}	1.03×10^{3}

Acidification. The greatest impact occurred while obtaining raw materials as a result of the release of a large quantities of sulfur dioxide gas (SO_2) which is a pollutant produced in the manufacture of lead and plastic beads (PP and PE) – the two principal raw materials used in the manufacturig of both types of batteries used in this study. This was followed by the impact from product use and production, both of which were due to the release SO_2 and NO_2 gas when burning fuel.

Heavy metal. It is evident that the greatest impact value from the release of heavy metal into the environment was equal to 2.7×10^{-5} kg Pb eq. per functional unit and caused by using car battery fuel. This was followed by the stage of obtaining raw materials and production, both of which release lead into the atmosphere in the form of water and air pollution. This was especially the case with the production of conventional batteries, which during the formation process release lead into the water source, unlike calcium-maintenance free batteries.

Energy resources. The results were similar to those found with global warming because both impact types are directly related. Energy usage was highest during product use when it was equal to 814 MJ and 795 MJ for the conventional and calcium-maintenance free batteries, respectively. This was followed by the stages of obtaining of raw materials and production.

From the analysis of all five impact groups it was apparent that obtaining raw materials and usage had the greatest impact in regards to use of energy, producing greenhouse gases and releasing metal into the environment. These types of environmental impact all stemmed from the use of fuel to power machinery. The radar chart in Fig. 3 shows that functional units are equal but over a two-year period the calcium-maintenance free battery uses only half as much battery lifetime as the conventional battery although fuel use was equal during the stage of product use. Thus, when we compare both types of product from the initial stage of obtaining raw materials, production and usage, we find that the calcium-maintenance free type battery has more environmental advantages than the conventional battery. These environmental impact values are shown as following; global warming, ozone layer depletion, acidification, heavy metal release and use of energy resources at 71.03%, 45.98%, 60.35%, 60.09% and 72.01%, respectively.

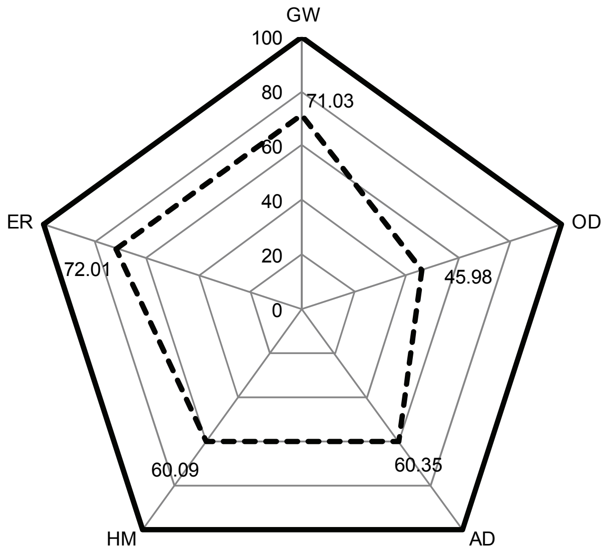

Fig. 3. A comparison of five types of impact at the stages of obtaining raw materials, production and use; solid line – conventional type, dashed line – calcium maintenance free type

Which raw material/manufacturing process has the highest environmental impact? In order to identify raw materials and battery manufacturing processes responsible for the important environmental issues and which can be used in the development and improvement of materials and manufacturing, the two most important issues (global warming and acidification) were considered at the stages of obtaining raw materials and manufacture. Figure 4 shows the percentage of impact on global warming and acidification from materials used in the manufacturing of a conventional battery. The total CO_2 eq. emission is 30.298 kg CO_2 eq. per functional unit. The greatest global warming impact occurred mainly as a result of using lead in manufacturing. Pure lead caused the greatest impact at 42%, followed by lead alloy at 35%, top lead (also a lead alloy) at 7%. The impact was found to be the result of using energy in the extraction, smelting and purification at the first place of manufacture. The acidification impact was caused from the manufacture of pure lead and lead alloy, both of which had an effect akin to that on global warming. The total SO_2 eq. emission is

0.628 kg SO_2 eq. and pure lead caused the greatest impact, producing acidification at 45%, followed by lead alloy at 39%.

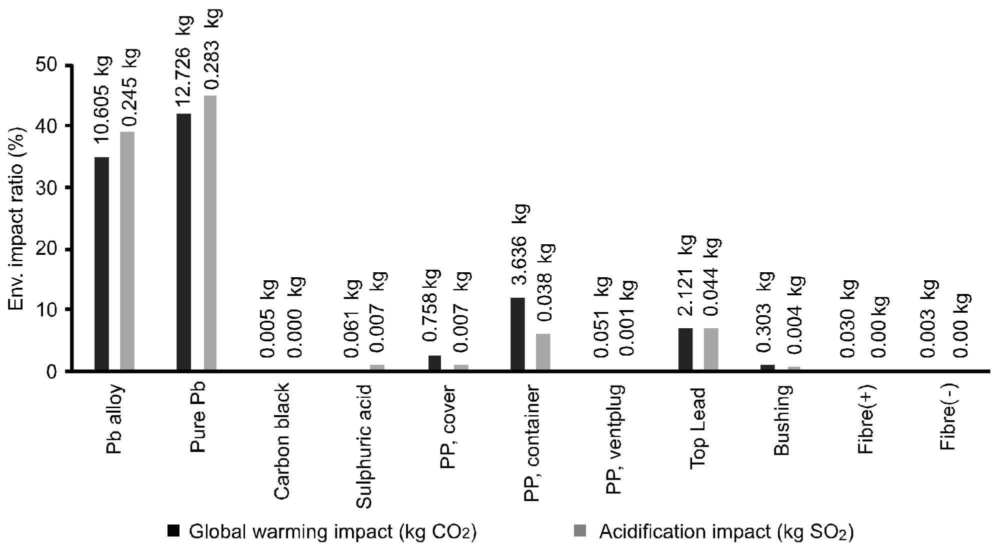

Fig. 4. Ratio of global warming impact and acidification at raw materials stage of a conventional battery

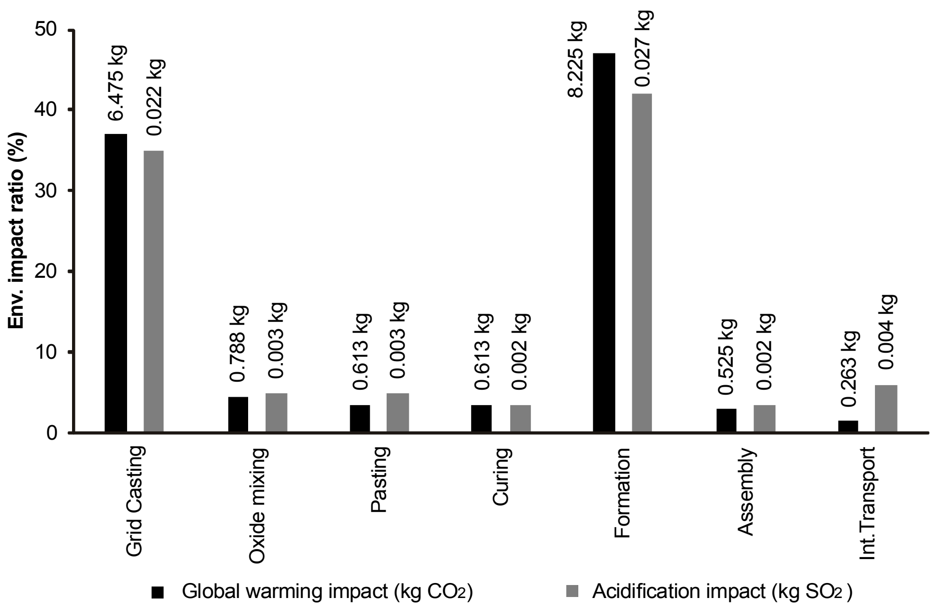

Fig. 5. Ratio of global warming impact and acidification at manufacturing stage of a conventional battery

Figure 5 shows the ratio of impact on global warming and acidification during the manufacturing process of a conventional battery. The total CO_2 eq. emission is 17.5 kg CO_2 eq. per functional unit. The formation process was the stage that caused the greatest global warming impact at 47%, followed by grid casting at 37%. The impact on acidification had a total value of 0.064 kg of SO_2 eq. It was discovered that the formation process was the stage that caused the greatest impact, followed by grid casting, resulting in acidification equal to 42% and 35%, respectively. The cause of the impact was attributed to manufacture and use of electrical energy. In addition, transportation of materials for manufacture caused a secondary impact, which had an impact value equal to 0.003 kg of SO_2 eq.

Analysis of end-point impacti. Analysis of the end-point impact was carried out using Eco-indicator 95 V2.03 /Europe (g), which compares normalization and weighting with the five types of environmental impact already calculated in the mid-point impact analysis using SimaPro 7.1 software.

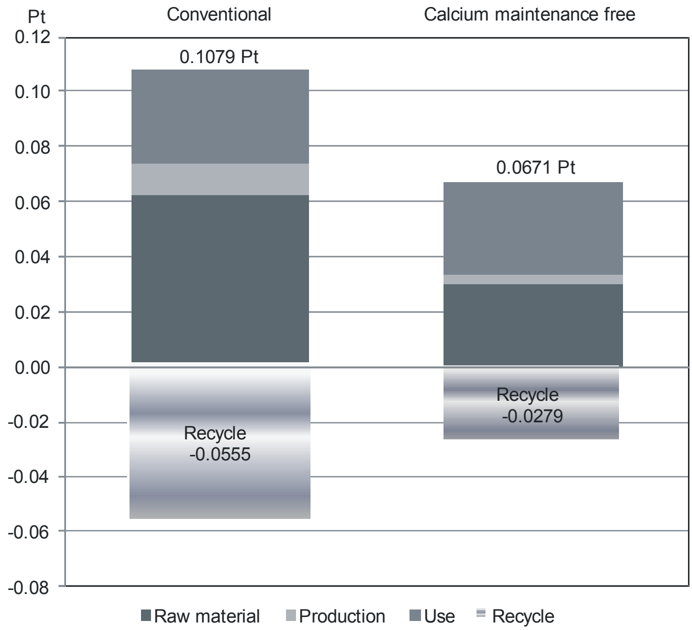

Fig. 6. A comparison of end-point impact for both types of battery based on five impact groups

From the analysis of end-point impact for the stages of obtaining raw materials, production and product use of product presented in Fig. 6, it is evident that the impact on one operational unit during use for the conventional and calcium-maintenance free batteries was equal to 0.1079 Pt and 0.0671 Pt respectively. However, if we include the recycling process after the battery had expired, these impact values decrease to 0.0524 Pt and 0.0392 Pt – equivalent to a reduction of 48.65% and 58.42% for the conventional battery and calcium-maintenance free battery, respectively. Thus, recycling is an important process in the move towards product development that is also environmentally friendly and easy to carry out. While a higher rate of recycling will greatly reduce the impact on the environment.

3.2. SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to assess the reliability of the results gathered and is usually presented in the form of a percentage of change or an absolute deviation value. The research group determined three possible options that may affect the results of the study by focusing on energy and raw materials, which cause acidification and global warming – the two main types of impact identified in the LCA summary outlined in Section 3.1. The three possible options and the sensitivity analysis in the form of absolute deviation values of the results is presented in Table 3. It was found that all three options produced only a marginal change to values (no more than 10%) and did not have an obvious effect on the overall results of the study.

Table 3

Sensitivity analysis of results based on three options proposed

Option	Course of action	Change [%]	Effect on results
1	Increase rate of fuel consumed during battery use throughout the entire two-year period by 20%	6.17	marginal
2	Reduce amount of fuel used for internal transportation by 20%	0.64	extremely marginal
3	Increase amount of natural gas used during grid casting and other processes by 10%	0.09	extremely marginal

3.3. MEANS OF DEVELOPING AND IMPROVING LEAD ACID BATTERY

Focusing on the environmental issues discussed in Section 3.1, the research group put forward their own ideas on ways to improve automobile batteries, for future batteries eco designed by the automobile industry. Possible improvements were proposed and separated according to the environmental issues that arose during the life cycle of a battery as shown by MET matrix (material–energy–toxicity matrix) in Table 4. These issues were then taken into consideration during the design and development of more environmentally friendly products [10]. Battery can be improved by using raw materials that can be recycled, choosing types of plastic that are environmentally friendly, such as PP or PE plastic, while avoiding those that have a high environmental impact, like PVC or nylon. Reducing the quantity and types of plastic used facilitates separation of pieces of plastic and plastic that can be recycled. Improving energy efficiency during the manufacturing process by outlining conditions suitable for using electricity in the formation process such as appropriate management of the production line or specifying a lot size in line with formation reduces the amount of electricity used and non-essential ion-free water. Due to managing the use of an electrically charged system it is uniform, especially during the initial period of electrification which has a relatively high volume of use etc. In addition, LCA carried out during the stage of battery utilization revealed that most types of environmental impact arise from the use of fuel in the electrical charging of a vehicle.

Table 4

MET matrix for a lead acid battery

Topic	Raw material	Manufacture	Transportation	Use	Disposal
Material	– lead – plastic PP – plastic PE – sulphuric acid – other chemicals	– use of raw materials producing hazardous waste	corrugated paper packaging	distilled water	– lead contamination in recycled material – remains/waste material that cannot be recycled
Energy	– transportation of raw materials – plastic molding	– use of energy (natural gas) in melting lead – use of energy (electricity) in formation process	transportation to distribution points	loss of power from stored energy in battery while using car	– fuel used in transporting /collecting materials – energy used in recycling materials
Toxicity	– lead vapour from melting /smelting – highly toxic chemical substance – hazardous metal from mining lead	– lead vapour in atmosphere – lead in water supply			– solid hazardous objects, lead contaminated – lead in wastewater from separating lead by electricity, chemicals – lead contaminated acid

Increasing the charge efficiency of batteries so as to prevent self-discharge is one way of helping to reduce impact on the environment during usage. The correct disposal of batteries is also a process that can help and one which should be promoted to develop a suitable battery collection and recycling network and prevent contaminated-lead from entering the plastic recycling chain. A production chain should also be established to deal with the different battery parts left after it has been separated, for example, finding a way of transferring the acid from old batteries into new batteries, etc. Moreover the battery industry should contribute to improve life cycle of lead battery by helping to design systems that will facilitate the identification and recovery of green batteries [11].

4. CONCLUSION

In order to continue to transform Thailand into a large automobile industrial hub in the Asia region, Thailand must adopt more and more sustainable approach to growth in automobile battery industry. Automobile batteries will be required to choose the suitable technology that meet both growing demands and reducing environmental impact. The study could confirm that it is environmentally preferable to calcium-maintenance free technology instead of conventional technology. A comparison of the environmental impact resulting from use of both automobile batteries over a two-year period revealed that the calcium-maintenance free battery was more beneficial to the environment than the conventional battery in all five environmental impact types due to the fact that it had a longer lifespan by more than two years. An assessment of the end-point impact throughout the entire lifecycle of the battery found that the calcium-maintenance free battery had approximately 28% less impact because the extent of impact during battery use was only slightly different.

Global warming and acidification were the most apparent forms of impact observed. The stage of obtaining raw materials had the most pronounced impact on the environment, followed by the stage of product use. Production had the least degree of impact, while management of waste batteries through recycling had a positive environmental impact. In the production phase, environmental impacts are dominated by formation (40%), grid casting (30%) and oxide mixing (5%). More than 90% of the environmental impact that occurred during battery use phase arose from charging the battery through burning fuel in the engine. The remaining 10% was from the use of distilled water and plastic bottles. Moreover the information on environmental impact derived from the LCA was incorporated with the principles of MET matrix to facilitate the analysis of other important environmental issues. These issues were analyzed and ways of improving the battery were proposed and separated according to the environmental issues that arose during the life cycle of the battery. The result of this study should be seen as environmental performance indication on how to even enhance the environmental friendliness of lead acid battery.

ACKNOWLEDGEMENTS

The authors thank Thai Industrial Standards Institute under EU White Paper project for funding this useful research.

REFERENCES

[1] Thai Customs Department, *Report of import-export of Thailand*, Thailand, 2010.
[2] YOSHIMURA T., YASUDA H., Development of maintenance-free dry calcium (MFDC) lead-acid battery for automotive use, J. Power Sources, 2006, 158, 1091.
[3] Yuasa Battery (Thailand) Public Company Limited, *Annual report 56-1 of Yuasa Battery*, 2010.
[4] Thailand Office of the Board of Investment, *Investment promotion policy for sustainable development*, BOI, Thailand, 2010.
[5] PRé Consultants, Eco-Indicator 95, Netherlands, 2010.
[6] Ministry of Housing, VROM and Centre of Environmental Science, Leiden University, L*ife cycle assessment: An operate guide to ISO standard*, Netherlands, 2001.
[7] PRé Consultants, SimaPro LCA software, Netherlands, 2010.
[8] TUKKER A., *Life cycle assessment as a tool in environmental impact assessment*, Environ. Impact Asses., 2000, 20, 435.
[9] U.S. Department of Labor/Occupational Safety & Health Administration, *Lead battery manufacturing*, , 2010.
[10] UNEP, ECODESIGN-A PROMISING APPROACH to sustainable production and consumption, UNEP, 2010.
[11] ROCHE M., TOYNE P., *Green lead – oxymoron or sustainable development for the lead-acid battery industry?* J. Power Sources, 2004, 133, 3.
[12] SULLIVAN J. L., GAINES L., *A review of battery life-cycle analysis: State of knowledge and critical needs*, Argonne National Laboratory, U.S., 2010.