LIFE CYCLE ASSESSMENT OF NICKEL CADMIUM BATTERY

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Abstract. The life cycle assessment of the battery will help one to identify the energy and cost associated with the product from the cradle to gate processes. The ecological footprint of a company can reduce the power of a brand when consumers avoid unsustainable practices. The performance of the product can be compared with its competitors. The potential areas of improvement can be identified, which in turn helps to improve the performance of the product. The energy associated with the product during processing, manufacturing, usage and transportation stages has been identified in this paper. The energy payback for the battery has been calculated, which can be used to compare batteries among each other. On finding the energy payback of the battery, a framework has been developed which can be used in future to compare different batteries. And the impact assessment helped to interpret the important areas of improvement and the sector producing maximum impact. And some methods which can be implemented to decrease the impact and burdens produced during the product development stages are discussed.

Keywords: Energy payback, Impact potential, Specific energy consumption, Environmental impact

1. INTRODUCTION

In most of the countries, energy policy has mainly three objectives, they are, to prevent climatic changes, reduce the consumption of fossil fuels, providing required energy at affordable rate [1]. Technologies to store electricity plays a major role in providing secure, safe and sustainable energy [2]. It helps to increase the market share of renewable energy [1]. In low carbon energy generation, electrical storage mechanism is the deciding factor because of the intermittent or variable nature of power generation [3]. When batteries are used for partially or fully electrified vehicles, batteries always help to reduce the power requirement and carbon dioxide emissions. There are no more conventionally-fueled cars in cities, 40% use of sustainable low carbon fuels in aviation; at least 40% cut in shipping emissions, 50% shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport. All of which will contribute to a 60% cut in transport emissions by the middle of the century [4]. Currently different types of electric batteries are available in the market for meeting the needs and necessities of the customers. By improving the functionality of the batteries will increase the demand for the product and thereby helps to increase the market share of the product energy storage systems are improved for different applications such as in electric cars, trucks and hybrid vehicles and for naval applications. Analysis of the performance of electric cars and competing powertrain options in terms of greenhouse gas emissions over their life cycle. It also discusses key challenges in the transition to electric mobility and feasible solutions possible which includes vehicle and
battery cost developments; supply and value chain sustainability of battery materials; implications of electric mobility for power systems; government revenue from taxation; and the interplay between electric, shared and automated mobility options [5].

Among different electric batteries available in the market, in this paper, life cycle assessment of Nickel cadmium battery is presented. Nickel cadmium pocket plate battery is a secondary battery. It is used for different applications such as fire alarm systems, signaling and telecommunication, Solar Photovoltaic, Instrumentation & Process control, Switchgear protection, Emergency lighting, Switchyard, UPS, Genset starting, Diesel Locomotive cranking, Electromagnetic lifters (EOT crane). It’s used for different applications due to its ability to withstand high temperature, high reliability, long operating life, faster charging compared to other electric batteries and low maintenance [5]. But there are some problems faced, while using nickel cadmium battery, they are, Nickel and Cadmium are costly metals and are highly toxic, they get heated during its operation and can get into thermal runaway mode.

Earlier products developed and consumed in the world followed linear economy, where the raw materials required for the development of the product was extracted according to requirement which is later processed and manufactured using some desired technique, sold to customers who use it during its lifecycle and disposed to the environment after its operating period [6]. In order to minimize the wastage of natural resources, materials from the products which completed its lifecycle need to be recollected and recycled, so that it can reduce the extensive extraction of natural resources to meet the demand. By including the process, the product’s economy can be changed from linear to circular. A product following circular economy helps in the development of the new product from the ‘lifecycle completed products’ [2]. Thus the requirement of freshly extracted materials to meet the demand can be reduced drastically. Understanding the positive outcomes of changing the product’s economy from linear to circular, different governments around the world have passed different policies and laws for the conversion of the product’s economy into a circular one [5]. Example, Dutch government announced a government-wide programme, which was developed for the circular economy, involving different departments to convert the Dutch economy to circular by 2050. It helps to provide improved economic benefits associated with the development of the product, increased growth of the economy with increase in spending due to lower prices of the product, appreciable saving of the material, the change in input and output leads to higher valuation of labor, which leads to increased employment opportunities and incentives for the innovative developments. Data to demonstrate how the global picture in research and innovation is changing and how Europe is positioned within the international context, underpinning the need for a more strategic approach to international cooperation in research and innovation in Europe [1].

Life cycle assessment of the Nickel Cadmium battery will help to analyses the energy input required by the product and the environmental impacts that the product tend to produce during its lifecycle. Cradle-to-gate life-cycle inventory analysis of lead-acid, nickel-cadmium, nickel-metal hydride, sodium-sulfur, and lithium-ion battery technologies has been reviewed and evaluated [6]. An algorithm was developed that will assess the ability of battery storage in capturing AC and DC power generated from photovoltaic cells, combined heat and power and wind turbines. The assessment includes the impact that the storage element has on the import and export of energy from the electrical grid. It showed when producing on site electricity through microgeneration, suitably sized storage can reduce export substantially (by over 90% in some cases) and store this energy at a typical round trip efficiency of 70-72%. The developed model accounted typical losses in a battery storage system, including losses associated with inverters, efficiency of charge/discharge cycles and power electronics [7]. The currently available data is reviewed and the impact of the production of several types of battery in terms of energy, raw materials and greenhouse gases is calculated and highlighted. The impact of the production of batteries is examined and presented. It is shown that the most
significant impact in many environmental areas in terms of production is caused by lithium based batteries. [8].

Life cycle assessment (LCA) is a tool which is used to identify the environmental impacts produced by the product during its ‘cradle-to-gate’ processes. This helps to quantify the environmental impact and environmental burden produced by the product, as shown in Figure 1. It helps to identify the sector, such as extraction, manufacturing, transportation, usage, etc., that is causing maximum impact which helps to identify the potential point of improvement. The energy payback is a measure of effectiveness of the product, lower the energy payback, better the product. By interpreting the gate-to-cradle process of the product, the different ways of improving the product’s lifecycle can be understood. The proper marketing technique implemented with the help of the results obtained from the life cycle analysis will help to improve the economic performance of the product keeping the process performance same. An investigation through a comparison of families of solar assisted cooling systems (with solar thermal or PV) for studies concerning the research of effective and environmentally friendly systems that exploit solar radiation for cooling and heating purposes. It compares five solar assisted H/C systems with LCA methodology [9]. Assessing life cycle GHG emissions from Plug-in hybrid electric vehicles (PHEVs) and find that they reduce GHG emissions by 32% compared to conventional vehicles, but have small reductions compared to traditional hybrids. Also it shows GHGs associated with lithium-ion battery materials and production account for 2–5% of life cycle emissions from PHEVs [10].

A detailed lifecycle inventory of an electric battery and a rough LCA of Battery-powered electric cars (BEV) based on mobility was compiled. The study shows that the environmental burdens of mobility were dominated by the operation phase regardless of whether a gasoline-fueled ICEV or European electricity fueled BEV is used [11].

During the life cycle of the battery the battery will consume a finite amount energy and cause the evolution of certain gases that are toxic to the environment and produce harmful effects. Life cycle assessment helps to quantify those impacts and burdens produced by the product under consideration and helps to compare the same with the other electric batteries. It helps in identifying the product which produces less harm to the environment. This paper makes two contributions: 1) identifying the energy input required by the product and the environmental impact produced by the same; 2) it provides energy payback of the battery which can be used to measure the effectiveness of the battery; 3) it provides a set of energy and environmental outcomes and identifies the potential area of improvement.

![Figure 1. Different stages of a product during its life cycle which are considered for life cycle assessment](image.png)
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2. **LIFE CYCLE ASSESSMENT**

The material used in the battery are obtained according to the design of the battery. The energy consumption per kg of the battery is calculated and converted in terms of a battery. LCA mainly consist of four steps, firstly, goal and scope definition, where the goal and intended use of LCA is defined. Assessment is scoped in terms of a) boundaries of the product system under consideration b) temporal and technological scope of the process in the product system c) Assessment parameters to be considered in the assessment.

2.1 **GOAL AND SCOPE DEFINITION**

Here the system considered is a nickel cadmium battery of 3.2Kg Nickel Cadmium Pocket Plate Batteries, 140 Ah at 1.2 V. The percentage weights of different components in a Nickel Cadmium battery is shown in Figure 2.

Here the focus is on the battery and not on the application to which it is subjected. The material used in the battery are obtained according to the design of the battery. The energy consumption per kg of the battery is calculated and converted in terms of a battery.

![Figure 2. Frequency distribution of Percentage weights of different components in a Nickel Cadmium battery](image)

Energy consumption is calculated in terms of the amount of electricity used, which is later converted in terms of cost, that is rupees, incurred for the development of the product. And Energy payback is calculated, in terms of energy input(E), (Wh), density of discharge(d), (%/100), mass of the battery(m), (kg), Specific Energy Density(w), (Wh/kg). Total energy input is the summation of energy consumption related to production, manufacturing, transport, use, miscellaneous operations. The energy output from the battery during its life time depends on the Specific energy density and the depth of discharge of the battery.

\[
\text{Energy payback} = \frac{E}{w \times m \times d} \quad \text{(1)}
\]

Secondly, life cycle inventory, the resource input and emission evolved from a system is considered and quantified, the Figure 3 shows the way of considering the inventory analysis of the system. It helps to identify the different raw materials and the corresponding quantity associated with the product. That is inventory analysis collects information on input and output, that is, environmental exchangers, of all the processes within the boundaries of the
product system. The compilation of inventory data for each individual process quantifies the input and output associated with the reference flow of the products as derived from the functional unit. For example, the data is typically presented as the total amount of emission of substance X evolved during the product development process. Processes considered in the LCA are:

![Image](image_url)

**Figure 3.** Boundaries assumed for the cradle-to-gate study evaluation

The function specificity is a fundamental characteristic of life cycle inventory and the ensuing impact assessment, and consistent with the purpose of LCA to evaluate the environmental impacts.

### 2.2 INVENTORY ANALYSIS

Some of the steps used to calculate the manufacturing cost and energy consumption are explained as,

1. **KOH (electrolyte):** 268 kg of KOH is used to prepare 1 kl of electrolyte, which can be used to produce 21428 number of batteries which requires 2.19 MJ/Kg.

2. **Nickel:** 0.8 kg of Ni(OH)2 is used for 140 Ah. Cost of Ni(OH)2 is Rs 900/Kg. Electricity cost is taken as Rs 6.7/units. Converting ‘Kwhr’ into MJ/Kg, by multiplying with ‘3.6’. Equating energy consumed during product development process with the cost of electricity, gives 120.375 MJ/Kg for the battery considered.

3. **Distilled water:** 1.85 l of distilled water is used per battery. A litre of distilled water is assumed to cost Rs 20. It gives total cost associated with distilled water in the battery as Rs 3.03.

4. **Use:** The battery is assumed to operate for 2000 cycles. And assuming domestic cost of electricity/unit as Rs 5 therefore total cost of use/battery as Rs 1680.

5. **Transportation:** Assuming the product developed in Hyderabad to be sent to United States of America, where cost of transferring 2 kg is $ 51. Therefore for a battery weighing 3.2 kg, cost about Rs 4896, assuming the conversion rate as Rs 60 for $1

6. **Cadmium:** About 0.7567 kg of cadmium, costing 275 RS/kg, is required for 1 battery considered. And the product consuming 34.875 MJ/Kg.

And there are some miscellaneous operations in accordance to the product development stages of the product in the industry, which sum up a total energy consumption in accordance to the development of the battery considered as an average of 2341.2064 MJ/Kg. and total life cycle cost of the battery a 10973.275 Rs on an average. The Table 1 shows the production and manufacturing energy associated with the battery considered.
Table 1. Production Energy and Manufacturing Energy associated with different materials used in the production of battery

| Material                  | Production Energy (MJ/Kg) | Manufacturing Energy (MJ/Kg) |
|---------------------------|---------------------------|-----------------------------|
| Cadmium                   | 193                       | 34.875                      |
| Ni sulphate -> Ni Hydroxide | 90.6                     | 120.375                     |
| Recycled Ni               | 37                        | 96.48                       |
| KOH                       | 38.2                      | 2.19                        |
| Steel                     | 37.2                      | 1.507                       |
| Polypropylene             | 80                        | 0.2                         |

The production energy associated with the battery is obtained from the literature survey. Manufacturing energy is obtained from an industry leading the sector, in order to get a realistic point of view in accordance to the manufacturing sector, where the manufacturing energy associated with polypropylene is assumed as 0.2 MJ/Kg, after consulting with an engineer in the same industry that we considered to calculate manufacturing cost.

2.3 IMPACT ASSESSMENT

Environmental impact assessment is used to identify possible environmental impacts that the product will cause on to the environment. It helps in identifying the toxic gases evolved, solid and liquid wastes produced during it’s lifecycle. It helps to identify the potential area of improvement and the environment implications that the changes will create on the environment. It helps in the decision making process of the management in deciding the sector where the highest amount of investment is required. The step also helps to design and re-design the product in terms of social, cultural and aesthetic perspectives. Thereby the input energy and cost requirements of the product can be reduced drastically. The step need to be implemented in the planning stage itself to improve the efficiency and to reduce the cost incurred in developing the product.

It addresses impacts produced due to evolution of toxic gases and other pollutants, such as global warming. Eutrophication of water bodies due to solid and liquid wastes, loss of natural resources including renewable and non-renewable, impacts on human health due to noise and radiation when exposed during operation. Environmental exchanges of all different various processes through which the product moves during it’s life cycle is collected, such as inputs required, waste produced, recyclables, output product expected in each processes. The steps to correlate the emissions evolved in each process into the environmental impacts produced. Such as gases like carbon dioxide, methane has ability to absorb infrared radiation. Here the components such as volatile organic compound(VOC), carbon monoxide(CO), Nitrogen oxide(NOx), Nitrous oxide(N2O), particulate matter(PM), sulphur oxide, methane, carbon dioxide(CO2), heavy metal such as cadmium, cobalt, nickel will be released during their entire life of the product. The quantity of the above said components are obtained from the literature survey, which is used to find the impact potential. The impact potential helps to identify the impact of these components creating on the environment. Table 2 shows the abbreviation of different gases evolved during the life cycle of the battery.
Table 2. Abbreviations of different gases evolved during the life cycle of Nickel Cadmium Battery

| Abbreviation | Description       |
|--------------|-------------------|
| CO           | Carbon Monoxide   |
| CO2          | Carbon Dioxide    |
| CH4          | Methane           |
| PM           | Particulate Matter|
| N2O          | Nitrous oxide     |
| NOx          | Nitrogen oxides   |
| SOx          | Sulphur oxides    |
| Cd           | Cadmium           |
| Ni           | Nickel            |
| Co           | Cobalt            |

Table 3. Different impact potentials calculated in accordance to the battery

| G/K G     | Resource Depletion Potential | Global Warming Potential | Acidification Potential | Eutrophication Potential | Photochemical Potential | Human Toxicity |
|-----------|------------------------------|--------------------------|-------------------------|--------------------------|-------------------------|-----------------|
| 0.9       | -                            | 9.9                      | -                       | -                        | 0.0063                 | 0.0456          |
| 3.8       | -                            | -                        | -                       | -                        | -                       | -               |
| 11.1      | -                            | 7.77                     | 1.443                   | -                        | 8.658                   | -               |
| 18.3      | -                            | -                        | -                       | -                        | -                       | -               |
| 19.8      | -                            | 19.8                     | -                       | -                        | -                       | 23.76           |
| 14.9      | -                            | 417.2                    | -                       | 0.1043                   | -                       | -               |
| 0.1       | -                            | 26.5                     | -                       | -                        | -                       | -               |
| 9900      | -                            | 9900                     | -                       | -                        | -                       | -               |
| 1.0       | 1.6072E-09                  | 10353.6                  | 27.57                   | 1.443                    | 0.1106                  | 32.469          |

Where, CO means Carbon Monoxide, CO2 means Carbon Dioxide, CH4 means Methane, PM means Particulate Matter, N2O means Nitrous oxide, NOx means Nitrogen oxides, SOx means Sulphur oxides, Cd means Cadmium, Ni means Nickel, Co means cobalt.

Different types of impact potentials are used to evaluate the product in terms of design for environment. The Table 3 shows the different potentials calculated for the battery considered during it is lifecycle using the equation 2,3,4,5,6,7. Some of them are discussed below:

a) Global warming potential (GWP):
The amount of CO2, N2O, CH4 and VOCs evolved during the gate-to-cradle processes are observed and its multiplied with their respective GWP potentials to obtain corresponding GWP. It’s a factor measuring the amount of heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide. where, ec\textsubscript{2,k} is the GWP factor of ‘k’ gas, and B\textsubscript{k} is the quantity of gas in ‘Kg’.

b) Human toxicity potential (HTP):
It is a quantitative toxic equivalency potential (TEP) that has been introduced to express the potential harm of a unit of chemical released into the environment. HTP includes both inherent toxicity and generic source-to-dose relationships for pollutant emissions. HTP is calculated by summing up the toxic releases in all different media, such as air, water and soil.

where \( ec_{7,k,A} \), \( ec_{7,k,W} \), and \( ec_{7,k,S} \) are human toxicological classification factors for the effects of the toxic emission to air, water and soil, respectively. \( B_{k,A}, B_{k,W} \) and \( B_{k,S} \) represent the respective emissions of different toxic substances into the three media.

c) Photochemical Oxidants Creation Potential (POCP):
Photochemical oxidants creation potential (POCP), is usually expressed relative to the POCP classification factors of ethylene and is calculated as:
\[ B(k) \]
\[ = \text{the emission of VOCs.} \]
\[ ec_{6,k} \] is their photochemical oxidation factor.

d) Eutrophication Potential
Eutrophication is characterized by dense algal and plant growth owing to increased concentration of chemical nutrients needed for photosynthesis. Eutrophication potential (EP) is defined as the potential to cause over-fertilisation of water and soil, which can result in increased growth of biomass. It is calculated as:
\[ EP = \sum B_{k} \]
where \( B_{k} \) is the emission of NO\textsubscript{x}, N, PO\textsubscript{4} and COD and \( ec_{5,k} \) are their respective eutrophication potentials. EP is expressed relative to PO\textsubscript{4}3-.

e) Acidification Potential
Acidification potential (AP) is based on the contributions of SO\textsubscript{2}, NO\textsubscript{x}, HCl, NH\textsubscript{3} to the potential acid deposition, i.e. on their potential to form H\textsuperscript{+} ions. AP is calculated where \( ec_{4,k} \) represents the acidification potential of gas \( k \) expressed relative to the AP of SO\textsubscript{2}, and \( B_{k} \) is its emission in kg per functional unit.

f) Resource Depletion potential
Abiotic resource depletion includes depletion of nonrenewable resources, i.e. fossil fuels, metals and minerals. Abiotic resources are defined as natural sources (including energy sources), such as iron ore and crude oil, which are regarded as “nonliving”. Abiotic depletion is one of the impact categories to be taken into account in Life Cycle Assessment. It is also one of the most frequently discussed impact categories. The total impact is calculated as:
\[ \sum B_{k} \]
where \( B_{k} \) is the quantity of a resource used per functional unit and \( ec_{1,k} \) represents total estimated world reserves of that resource.

Table 4 shows the abbreviation of different impact potentials calculated for the battery during the life cycle of the battery.

| RDP       | Resource Depletion potential |
|-----------|------------------------------|
| GWP       | Global warming potential     |
| AP        | Acidification Potential      |
### Interpretation

Interpretation is the fourth and final stage in the LCA of the battery. The interpretation depends mainly on the different impact potentials evaluated. It helps to identify the processes to be modified in order to develop the product more effectively with respect to design for environment. Calculating the energy payback of the battery helps to understand the effectiveness of the battery. Maximum amount of carbon emissions are due to transportation, a more efficient method of transferring product from one place to another helps to decrease the carbon dioxide emissions drastically. Salvage value is not considered during the LCA study, considering salvage value can increase energy payback due to increase in energy consumption and cost incurred during the product development stages. Most of the industries are conducting energy audition periodically, usually between 6 months, through an external energy auditing consultancy. Having an internal audit team can help to change the process layout of the product development process in such a way that the energy audit process can be less cumbersome and more effective, showing realistic value. Energy auditing a plant with a process layout designed for environment helps to identify the potential area of impact accurately.

| EP | Eutrophication Potential |
|----|--------------------------|
| POCP | Photochemical Oxidants Creation Potential |
| RDP | $E_1 = \sum_{k=1}^{n} B(k) / c(k)$ |
| GWP | $E(2) = \sum_{n=1}^{b} c(n) + B(k)$ |
| AP | $E_4 = \sum_{k=1}^{n} e(4,k)B(k)$ |
| EP | $E_5 = \sum_{k=1}^{n} e(5,k)B(k)$ |
| POCP | $E_6 = \sum_{k=1}^{n} e(6,k)B(k)$ |
| HTP | $E_7 = \sum_{k=1}^{n} e(7,k)B(k) - \sum_{k=1}^{n} e(7,k)B(k) + \sum_{k=1}^{n} e(7,k)B(k)$ |

Energy payback $= \frac{1637802}{50 \cdot 3.2 \cdot 0.8} = 12795.33$

where,

Energy input, $E=1637802$ (Wh), Specific Energy Density (Wh/kg) = 50 (Wh/kg), mass, $m=3.2$ (kg), density of discharge, $d=80\%$. The energy payback is calculated based on equation 1.

The waste, recyclables from each process will produce an impact on the environment in their own ways. Characterization of these impacts will be based on the corresponding impact potential score of each gases.
Condition monitoring helps to increase the reliability of the machines, by predicting the fault in the machine and its location of the fault which helps to identify the severity of the fault in the machine element and thereby planning the maintenance accordingly to reduce the non-production time or idle time and improving the production process and rate of production, and the process as a whole which helps to decrease the manufacturing and related overhead costs, thereby helps to decrease the total cost incurred on the product and which in turn helps to increase the market competitiveness and market share of the product drastically. Marketing the product developed through a process, techniques, and materials which produce a less environment impact and burden compared to its counterparts helps to improve its acceptance among the consumers. It helps to compare the same with different kinds of batteries to observe the relative advantage and disadvantage. Environmental burdens and impacts produced during the cradle to gate processes of the battery. Understanding the marketing strategy, that need to be applied, inorder to get a larger market share. Considering a mid-size car with a mileage of 7.5 litres per 100 kilometres. Then impact produced by the battery weighing 3.2Kg equals impact of running the car for 123.0469 km.

3. CONCLUSION

The work is mainly focused on life cycle assessment of nickel cadmium battery for various applications. The various important data are collected based on real time industrial consumptions. The following important conclusions are drawn from the present study:

The total energy input required for the development of nickel cadmium battery is 1637802 (Wh). The different types of impact potentials are calculated and quantified in detail. The considerable impact of the emissions during the product development stages, such as global warming potential as 10353.6, human toxicity potential summed up to 32.469, photochemical Oxidants Creation Potential equals 0.1106, total Eutrophication Potential produced by the product is 1.443, acidification Potential equals 27.57, and total resource Depletion potential as 1.6*10^-9 due to heavy metal extraction and emission during different product development stages. Considering a mid-size car with a mileage of 7.5 liters per 100 kilometers. Then impact produced by the battery weighing 3.2Kg equals impact of running the car for 123.0469 km.

Future work involves comparison of LCA analysis of different grade of batteries. Identification of potential area of improvement in the process and product development stages and infrastructure required to meet the needs and requirements according to the guidelines of design for environment.

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