NTNU
Kunnskap for en bedre verden

Department of Electric Energy

FENT2023 - Life cycle assessment of energy systems

LCA-study of rechargeable and disposable consumer batteries

Av :
10046, 10041, 10012, 10057

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Abstract

This Life Cycle Assessment is a project between four engineering students at NTNU Trondheim. It is a mandatory part for the course FENT2023, Life cycle assessments of energy systems and counts for 60% of our total grade, where the remaining 40% is a written exam. We have chosen to compare which type of battery is more sustainable, a disposable AA Alkaline battery, or a rechargeable Nickel-metal hydride battery. We will be looking at the production and manufacturing of the batteries.

This Life Cycle Assessment follows the ISO 14040 and 14044 standards. They provide a set of rules that helps insure the quality of the LCA. A framework is provided for conducting and reporting the results of an LCA in a systematic and transparent manner. The LCA consists of four major parts, with the first one being the Goal and Scope. Secondly, the Life Cycle Inventory provides the functions of the batteries and their inventory lists. The third part is the Impact Assessment, this is where the effect of the environmental impacts caused by the batteries will be looked upon. The interpretation is the final part of the LCA, at which the results will be analyzed and discussed and where we can see if the production and manufacturing of the batteries differ from each other.

The group has had multiple meetings throughout each week of the project period, and the work has been evenly distributed between each other. This project has given us a deeper insight in the use of everyday items, disposable or not, and their impacts on the environment. We would like to thank our course coordinator Angela Daniela La Rosa, the student assistants Fredrik Håheim Hvaara and Henrik Ystanes Dolmen for providing great help and giving us a better understanding of conducting our own LCA.

Executive summary

The objective of this study is to acknowledge how much more the production of rechargeable batteries is beneficial to the environment compared to disposable batteries. The study will provide with information about the emissions linked to the cradle-to-gate stages of life, and how the later use of the battery is crucial for the overall environmental impact. The NiMH battery gave bigger impacts to all environmental impact categories, this is likely because of the materials used to make the NiMH batteries are more energy craving, having more rare-earth materials and metals used than in the Alkaline battery. For the NiMH battery to be more benificial to the environment, the use and end-of-life impacts would have to be looked at. Each battery has their own area where they operate best at, the alkaline battery would be better suited for infrequently used devices, such as smoke detectors. Meanwhile the NiMH battery would be suited better for more frequently used devices that requires more power.

List of Abbreviations and Terms

Terms:	**Explanation:**
LCA	Life Cycle Assessment
$NiMH$	Nickel-Metal Hydride
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
$GWP100$	Global warming potential after a 100 years
GHG	Green house gases
Wh	Energy given in Watthour
V	Unit for electric voltage
IPCC	Integrated Pollution Prevention and Control
CFCs	Chlorofluorocarbons
HTP	Human toxitcity potential
EU	European Union
DALY	Disability-adjusted life years
USD2013	Unit in Damage Assessment, surpluss of resource production considering a 3% discount rate.
IEC	Interanational Electrotechnical commision
ISO	The international Standards Organization
IPCC	Intergovernmental Panel on Climate Change
SDG	Sustainability Development Goals
$NiO(OH)_2$	nickel hydroxide
MnO_2	manganese dioxide
Zn	Zinc
CTMP	A process which involves soaking the wood sodium sulfate before the grinding og the wood make the paper even stronger, an it occurs inside an electrolytic cell.
$Polyethylene$	A polymer considered as thermoplastics.
CFCs	chlorofluorocarbons
KOH	Potassium hydroxide electrolyte
HTP	Human toxicity Potential
CED	cumulative energy demand
FFDP	fossil fuel depletion potential
WDP	water depletion potential

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Introduction

As electronic devices become more standardized in our daily lives, the demand for batteries continues to grow[1]. Batteries are used in a variety of applications like radios, toys, calculators, remotes and other portable electronic devices. While both rechargeable and disposable batteries are widely available, there is a growing interest in determining which option is more environmentally sustainable.

To address this issue, a Life Cycle Assessment (LCA) can be conducted to evaluate the environmental impacts associated with production of rechargeable and disposable batteries. An LCA is a systematic method for evaluating the environmental impacts of a product or system throughout either the entire or parts of its life cycle.

The purpose of this LCA is to compare the environmental impacts of rechargeable versus disposable AA-batteries. Specifically, the study will focus on the following environmental impact categories: global warming potential, damage to human health, ecosystems and resource availability. The LCA will take into account factors such as the energy and emissions associated with material extraction, assembly and production of the batteries.

By conducting an LCA, we can gain a better understanding of the environmental impacts associated with rechargeable and disposable batteries and make informed decisions about which option is more sustainable. Rechargeable batteries could also be inferior to disposable ones, with their rated voltage at 1.2V, compared to 1.5V in disposable [2] [3]. If this LCA concludes that the production and manufacturing of these batteries give little difference on the impact categories, it means that the possible real difference could only be seen through the use and disposal of the batteries.

1 Goal and Scope

This research sticks to ISO standards 14040 and 14044. These provide a framework for conducting a *life cycle assessment* (LCA). ISO 14040 outlines the principles and structure of an LCA study, while ISO 14044 defines the requirements and guidelines for conducting an LCA. Both standards cover key components of an LCA study, such as defining the goal and scope, conducting a *life cycle inventory* (LCI), performing a life cycle impact assessment (LCIA), and interpreting the results. The standards also address reporting and critical review, limitations, value choices, and optional elements. The goal section of an LCA outlines the study's purpose, intended application, and audience. The scope defines the functional unit and presents impact categories, data requirements, and strategies for managing potential uncertainties and data gaps. At the end, the study's system boundaries are described.

1.1 Goal

The goal of this LCA is to assess the environmental impacts associated with the extraction, production and manufacturing of rechargeable and disposable AA-batteries. We specified two chemical typologies for the comparison: Nickel-metal Hydride(NiMH) for the rechargeable batteries and alkaline for the disposable batteries. This choice was made since the European market for disposable batteries is dominated by alkaline type of batteries compared to the zinc carbon and lithium types of batteries. The study aims to determine which battery type has a lower environmental impact in terms of the impact categories specified in section 1.2 and our chosen functional unit.

This report is a result of a Life Cycle Assessment(LCA) carried out by undergraduate engineering students from NTNU as part of a grade-based subject. The given assignment was conducted privately, and will only be reviewed by the course coordinator, hence will not be published in public. This project reflects on the students knowledge in LCA at bachelor's level, and intend to familiarize the students with the software *SimaPro* to perform an LCA analysis. This paper should not be reviewed as a reliable source when it comes to production of new batteries, however the results, given the data we used, could be a good indicator for where the priorities should lie, resulting possibly in a brighter future when it comes to battery development.

1.2 Scope

The Life Cycle Assesment (LCA), endeavors to scrutinize the ecological impacts of rechargeable and disposable AA batteries by examining their extraction, production and manufacturing. The functional unit is 1Wh of energy to a device utilizing AA batteries. This study shall evaluate the following endpoint environmental impact categories aswell as the midpoints included in the ReCePi2016 midpoint method.:

Impact categories
Global warming potential
Damage to human health
Damage to ecosystems
Damage to resource availabillity

If the outcome of this LCA demonstrates that there is little difference between the environmental impacts of rechargeable and disposable AA batteries solely during extraction, production and manufacturing, the scope may have to expand to encompass other stages of the batteries' life cycle, which include battery use and end-of-life.

The reliability of the results from SimaPro must carefully be taken into consideration. Some of the data may be old, or incorrect. Considering that this study is evaluating two batteries with vast differences, the results must be comparable. The batteries serve a corresponding function, however, they vary in materials and methods of production and manufacturing. The rechargeable battery also requires a charger, which would increase the impact assessment for the rechargeable battery, however this is neglected in the study. In addition there may be different use applications for these batteries even though they follow the same standards for dimensions and voltage.

1.2.1 Functional Unit

The objective of the two distinct systems is to provide electrical power to portable devices using AA batteries. It is important to note that disposable and rechargeable batteries do not have the same energy output due to the former's higher nominal capacity and operating voltage. Hence, it is inadequate to compare the two types based on a single battery, and an equivalent energy supply must be established. The functional unit selected is the provision of $1Wh$ of electrical energy using a household battery. This amount of energy is sufficient for a 1-hour operation of a 1 W device, regardless of the battery type (disposable or rechargeable).

To determine the mass of battery required to deliver 1Wh of electrical energy, it is necessary to have knowledge of the battery's nominal capacity (Ah) and operating voltage (V). This information can be obtained from the International Electrotechnical Commission's standard, IEC 60086-2 [4].

	Ah	V	$Wh = Ah \cdot V$
Alkaline battery	2,45	1,5	3,68
NiMH battery	1,91	1,2	2,29

Table 1: IEC standards for AA-batteries [4]

We have found an average weight of an alkaline battery to be 23,3 g and an average weight of a rechargeable NiMH battery to be 27,2 g. Calculating the required weight of battery to deliver 1Wh of electrical energy:

$$\frac{battery\ weight}{batterycapacity} = \frac{23,3g}{3,68Wh} = 6,33g/Wh \qquad (Alkaline) \tag{1}$$

$$\frac{battery\ weight}{batterycapacity} = \frac{27,2g}{2,29Wh} = 11,88g/Wh \qquad (NiMH) \tag{2}$$

The battery masses calculated using the above method will be utilized in SimaPro to enable a fair comparison between the batteries. This is important because it allows us to compare the same amount of energy delivered from each battery. For instance, by comparing a 6.33g alkaline battery with an 11.88g NiMH battery, we can accurately compare the impacts of the batteries based on their energy delivery capability.

1.2.2 System boundary

For this LCA, which focuses on the comparison of two kinds of batteries, we have chosen to only look at the production of both. The use of specifically the rechargeable battery would be difficult to look into, and the waste handling also varies a lot. The amount of waste that is recycled and statistics for this is hard to come by and varies from country to country. We have therefore chosen a cradle to gate system boundary. This means that we will look at extraction, raw materials transport, material and part production, assembly and lastly quality control. Later on in this LCA we will discuss how the use of the rechargeable batteries could affect the impact of this battery, since this is important for making a good comparison.

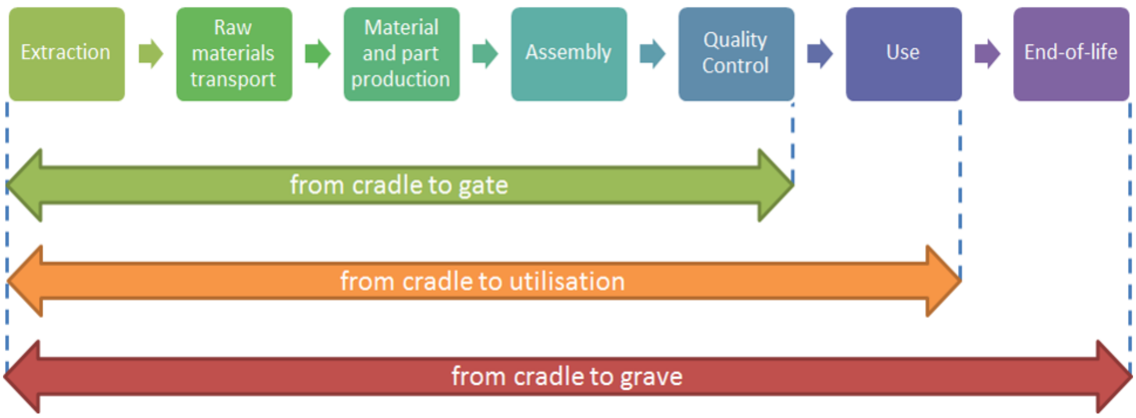

Figure 1: System boundaries, cradle to gate, cradle to grave and cradle to utilisation

2 Life cycle Inventory

The LCI phase of this report will provide descriptions on Nickel-metal hydride and Alkaline batteries. Then assumptions are made to provide an inventory list of both batteries.The LCI framework is made according to the ISO 14040 [5] and ISO 14044 [6].

2.1 Nickel-metal hydride batteries

2.1.1 What is a Nickel-metal hydride battery?

Nickel-metal hydride batteries is a rechargeable battery technology used mainly in portable consumer electronics and earlier-generation electric vehicles. Ni-MH batteries use a cathode of nickel hydroxide $NiO(OH)_2$, an anode of a hydrogen absorbing alloy MH and an electrolyte of Potassium hydroxide KOH. The battery operates through reversible electrochemical reactions as shown in equations 5, 3 and 4. [7]

Cathode:

$$NiO(OH) + H_2O + e^- \rightleftharpoons NiO(OH)_2 + (OH)^- \tag{3}$$

Anode:

$$MH + OH^- \rightleftharpoons M + H_2O + e^- \tag{4}$$

Overall reaction:

$$NiO(OH) + MH \rightleftharpoons NiO(OH)_2 + M \tag{5}$$

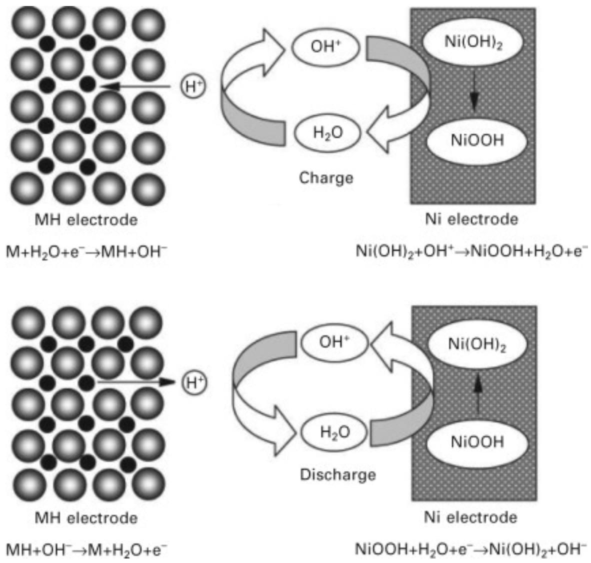

Figure 2: Reaction process of a Ni-MH battery while charging and discharging Source: F. Feng, M. Geng and D.O. Northwood, International Journal of Hydrogen Energy, 26 (2001) 725–734, copyright © Elsevie

2.1.2 Manufacturing and Production

The production and manufacturing of a Nickel-Metal hydride battery, $NiMH$, is a complex and precise process that requires high-quality metals and attention to details. The result is a battery that can be recharged and reused multiple times.

The NiMH battery is typically made up of a cylindrical metal casing. It includes a negative electrode made of hydrogen-absorbing alloy and a positive electrode made of nickel-hydroxide. The battery also includes an electrolyte solution made up of potassium hydroxide. [8]

Manufacturing of the battery typically involves mixing raw materials to form a slurry, which is applied to the electrodes and dried. The slurry serves as the current collector for the positive electrode. The electrodes are then rolled and compressed and rolled into typically a cylindrical casing and the electrolytes are added. Both the electrodes and electrolytes are sealed into the casing, and the battery undergoes a series of tests until it is ready to be used. [8]

2.1.3 Inventory List

Nickel-metal hydride (NiMH) use a nickel-based positive electrode and a hydrogen-absorbing negative electrode (usually made of a metal hydride alloy). Materials in NiMH batteries vary vastly depending on the spesific design and manufacturer.

The main components of an Nickel-metal hydride AA battery typically include:

1.**Positive electrode**: Nickel hydroxide $NiO(OH)_2$, a highly porous metal that allows for good electrolyte penetration and good cycling stability

2.**Negavtive electrode**: NiMH batteries usually use a hydrogen-absorbing metal alloy like $AB5(LaNi_5)$ or $AB2(TiMn2_)$.

3.**Electrolyte**: The electrolyte in a NiMH battery is usually a solution of potassium hydroxide (KOH) in water.

4.**Separator**: The separator in a NiMH battery are commonly either made of polyethylene or polypropylene.

5.**Current collector**: In NiMH batteries, current collectors are typically made of nickel or copper.

Component	Material	Amount (%)
Input		
Anode and cathode	Nickel	43.5
	Cobalt	5.5
Anode	Rare earth(mainly Lanthanum)	11
	Manganese	1.5
	Polytetrafluoroethylene	0.5
Cathode	Zinc	2
Electrode separator	Polypropylene	6
	Acrylic acid	0.5
Can + plastic coat	Steel	21
	Polyvinyl chloride	2
Electrolyte	Potassium hydroxide solution (35 %_wt)	6.5
Output		
NiMH battery	The entire composition of the battery	100%

Table 2: Inventory for Nickel-metal hydride AA battery

2.2 Alkaline batteries

2.2.1 What is an alkaline battery and its function

Alkaline batteries were first discovered by Dr Ernst Waldemar Jungner in Sweden in the early 1900s but the first mass-production did not take place until the early 1960s [9]. Alkaline batteries, like other batteries, operate with a negative and a positive cell to conduct electrons throughout an electrode. The Alkaline battery is created using chemical reactions between the negative *Zinc* electrode and the positive *Manganese dioxide* electrode, with a basic *potassium hydroxide* (KOH) solution as the electrolyte which has a pH-value above 7. The two half-reactions are given as:

Anode:

$$Zn_{(s)} + 2OH^-_{(aq)} \tag{6}$$

Cathode:

$$2MnO_{2(s)} + H_2O_{(l)} + 2e^- \rightleftharpoons Mn_2O_{3(s)} + 2OH^-_{(aq)} \tag{7}$$

Overall reaction:

$$Zn_{(s)} + 2MnO_{2(s)} + H_2O \rightleftharpoons ZnO_{(s)} + Mn_2O_{3(s)} \tag{8}$$

Zinc is the primary component of the negative electrode in an alkaline battery. It reacts with the electrolyte to produce *zinc oxide* and release electrons. The *Manganese dioxide* is the positive electrode component in the alkaline battery. It reacts with the electrolyte to produce *manganese oxide* and water, while also accepting electrons from the negative electrode. The concentration of the electrolyte, *potassium hydroxide*, remains, which means that it did not take part in terms of a loss in the chemical reaction, it rather fulfilled the role of conducting ions between the electrodes. [10].

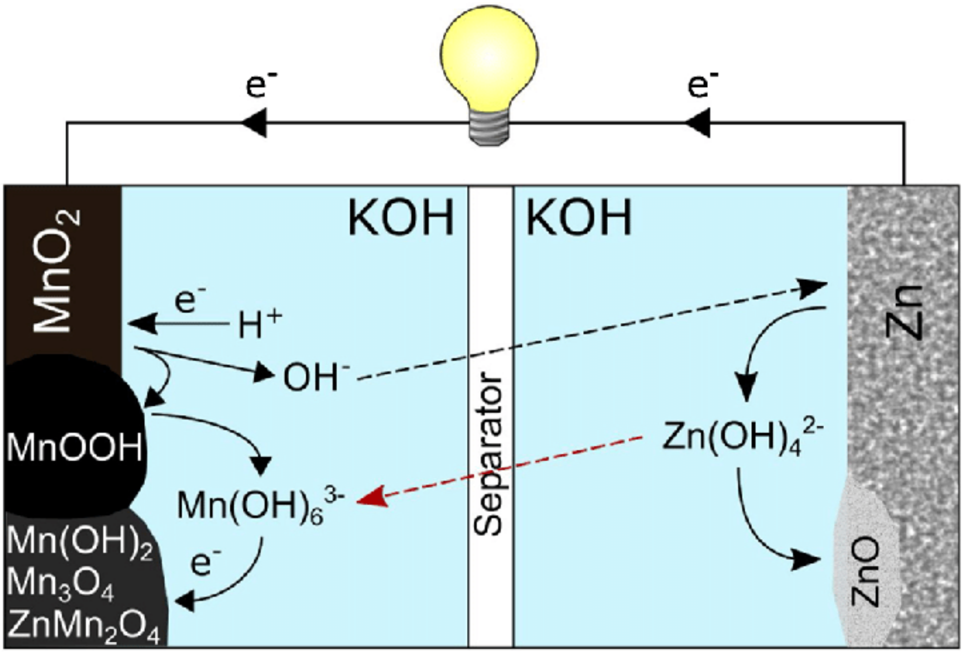

Figure 3: Reaction process of an alkaline battery

2.2.2 Manufacturing and Production

The production and manufacturing process of alkaline batteries involves several stages. Raw materials such as manganese dioxide and zinc powder are obtained and mixed with water and other chemicals to create a slurry. This slurry is then used to form the cathode and anode by applying it onto metal strips and allowing it to dry. The cathode and anode are then assembled with a separator, typically made of paper or plastic, and inserted into a cylindrical casing. The casing is then filled with an alkaline electrolyte, such as a potassium hydroxide solution, which enables the battery to generate electricity. The casing is sealed, and the battery undergoes a quality control inspection to ensure that it meets the required performance standards. Alkaline batteries are composed of several components, including a cathode made of manganese dioxide, an anode made of zinc powder, a separator made of paper or plastic, and an alkaline electrolyte that serves as a medium for the flow of ions between the cathode and anode [11].

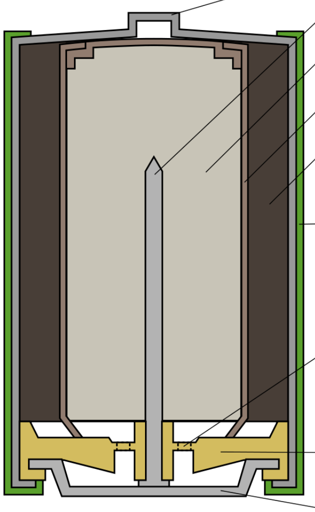

Figure 4: Components inside an alkaline battery

2.2.3 Inventory list

The main components of an alkaline AA battery typically include:

1.**Cathode**: The cathode of an alkaline AA battery is typically made of manganese dioxide (MnO2) and graphite. MnO2 makes up approximately 40-60

2..**Anode**: The anode of an alkaline AA battery is typically made of zinc (Zn) and potassium hydroxide (KOH) electrolyte. Zinc makes up approximately 50-70

3.**Separator**: The separator in an alkaline AA battery is typically made of a porous material, such as paper or plastic, that separates the cathode and anode while allowing the flow of ions between them.

4.**Electrolyte**: The electrolyte in an alkaline AA battery is typically a mixture of potassium hydroxide (KOH) and water. KOH makes up approximately 20-30

5.**Steel can**: The outer casing of an alkaline AA battery is typically made of steel, which provides protection and support for the internal components.

Component	Material	Amount (%)
Input		
Cathode	Electrolytic manganese dioxide	37
	Graphite	4
Anode	Powdered zinc	17
	Zinc oxide	1
	Gelling agent (starch)	1
Electrode separator	Cellulose	1.5
Electrolyte	Potassium hydroxide solution (35% wt)	11
Anode current collector	Brass	2.5
Can + plastic coat	Nickel-plated steel	22
	Polyvinyl chloride	1.5
Plastic cap	Nylon	1.5
Output		
Alkaline battery	The entire composition of the battery	100%

Table 3: Inventory for Alkaline AA battery

2.3 Assumptions

When performing an LCA analysis, it is crucial to establish certain assumptions concerning the inputs and calculations in SimaPro. These assumptions are not made arbitrarily, but rather grounded on thorough research. They are well-informed estimates, thoughtfully deliberated and chosen based on the most dependable available information.

In this report there will be assumptions regarding various parameters, such as the extraction of raw materials, energy consumption, transportation, production of battery-components, and assembly. The extraction of raw materials is a critical component of this process as it contributes significantly to the environmental impacts associated with the product. Therefore, assumptions are made about the location, type, and amount of raw materials required for the product's manufacture. Similarly, assumptions are made about the energy consumed during the manufacturing process, including the energy required in production, transportation and assembly.

Parameter	Country
Extraction of materials	Global avarage
Production of components	Global avarage
Assembly	Global avarage

Table 4: Assumptions on locations

3 Life cycle impact assessment

This chapter follows the ISO 14040 [5] and 14044 [6] standard methodology for life cycle impact assessment.

3.1 Methods & Impact categories

This report utilizes the *IPCC 2021 GWP100* [12] and *ReCiPe 2016* [13] methods, which are available in SimaPro software. The selection of the *ReCiPe 2016* method was based on a review of the impact categories included in the various methods, as illustrated in Figure 17 in the Appendix. For the specific impact category *Global Warming Potential*, the group has decided to use *IPCC 2021 GWP100*, as this is the most commonly used and known method for calculating the global warming potential for green house gases.

Method	Impact category	Unit
IPCC 2021 GWP100	Global warming potential	$kg\ CO_2 - eq$
ReCiPe 2016 midpoint	Stratospheric ozone depletion	$kg\ CFC - 11_{equivalents}$
	Ionizing radiation	kBq Co-60 eq
	Ozone formation, Human health	kg NOx eq
	Fine particulate matter formation	kg PM2.5 eq
	Ozone formation, Terrestrial ecosystems	kg NOx eq
	Terrestrial acidification	kg SO2 eq
	Freshwater eutrophication	kg P eq
	Marine eutrophication	kg N eq
	Terrestrial ecotoxicity	kg 1,4-DCB
	Freshwater ecotoxicity	kg 1,4-DCB
	Marine ecotoxicity	kg 1,4-DCB
	Human carcinogenic toxicity	kg 1,4-DCB
	Human non-carcinogenic toxicity	kg 1,4-DCB
	Land use	m2a crop eq
	Mineral resource scarcity	kg Cu eq
	Fossil resource scarcity	kg oil eq
	Water consumption	m3
ReCiPe 2016 endpoint	Damage to human health	$DALY$
	Damage to ecosystems	$Species.yr$
	Damage to resource availabillity	$USD2013$

Table 5: Methods and impact categories

3.1.1 Midpoints

Midpoint indicators focus on specific environmental impacts associated with a product or system, such as emissions of greenhouse gases. They are useful for identifying areas where improvements can be made to reduce the product's environmental impact and prioritize environmental issues based on their significance. Combining both midpoint and endpoint indicators provides a comprehensive understanding of the product's overall environmental impact and opportunities for improvement.

The midpoints that are calculated in this report is the ones listed in table 5.

3.1.2 Endpoints

While the midpoint indicators concentrate on individual environmental issues, such as global warming, the endpoint indicators depict environmental issues on more comprehensive aggregation levels, damage to human health, damage to ecosystems and damage to resource availability. This is illustrated in figure 5. Endpoints are useful for identifying areas where improvements can be made to decrease the overall environmental impact of a product/system.

Damage to Human Health The damage to human health reflects the potential risks and negative effects a product or system can have on human health throughout its life cycle. This is a crucial aspect of life cycle assessment (LCA). The damage to human health is evaluated in terms of disability-adjusted life years (DALYs). DALYs quantify the total number of years lost to illness or premature death attributed to a product or system. The potential health impacts of different products or systems can be compared to identify those that are more harmful, thus improvements can be made to minimize their negative impacts. [14]

Impairment of Ecosystems The impairment of ecosystems is another crucial aspect of Life Cycle Assessment. It accounts for potential negative effects a product or system can have on natural environments. This endpoint evaluates the damages that can be done to ecosystems and their services. This includes biodiversity loss, habitat destruction, water pollution and soil erosion. The impairment of ecosystems results are measured in ecotoxicity and ecopoints, where ecotoxicity measure the potential harm that a chemical or substance can cause to the environment, while ecopoints measure the potential damage to the ecosystem as a whole. [15]

Depletion of Resource Availability The depletion of resource availability takes in account the potential negative impacts a product or system can have on natural resources. That includes the exhaustion of non-renewable resources and depletion of renewable resources beyond their capacity of regeneration. The results of the depletion of resource availability vary, such as cumulative energy demand (CED), fossil fuel depletion potential (FFDP), and water depletion potential (WDP). They represent the depletion of resources caused by the product or system.[13]

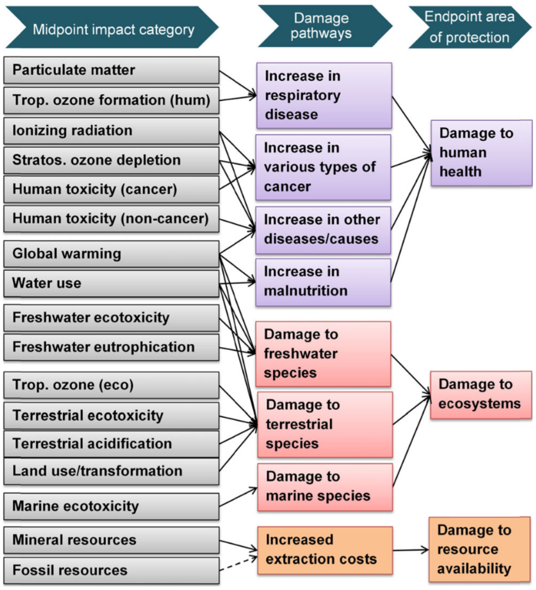

Figure 5: Overview of the impact categories that are covered in the ReCiPe 2016 [16]

3.2 Results

This chapter contains results from the two scenarios calculated in SimaPro. Firstly the results from each battery will be presented, thereafter a comparison. Both batteries are calculated with their weight required to deliver 1Wh of energy, which was calculated in chapter *1.2.2*.

3.2.1 Nickel-Metal hydride battery

3.2.1.1 IPCC 2021 GWP100 (NiMH)

Table 6 shows the greenhouse gas emissions from $11,88g$ NiMH battery, sorted into the materials contribution to the total emission. Table 13 in the appendix shows a more detailed version of each process used.

Process	Unit	Total
Total of all processes	kg CO2-eq	0,169774423
Nickel	kg CO2-eq	0,085731397
Lanthanum	kg CO2-eq	0,051045361
Cobalt	kg CO2-eq	0,024088538
Steel	kg CO2-eq	0,004570341
Polypropylene	kg CO2-eq	0,001548905
Manganese	kg CO2-eq	0,000925641
Potassium hydroxide	kg CO2-eq	0,000675186
Zinc	kg CO2-eq	0,00061306
Polyvinyl chloride	kg CO2-eq	0,000452602
Acrylic acid	kg CO2-eq	0,00012317
Deionized water	kg CO2-eq	2,22669E-07

Table 6: IPCC 2021 process contribution NiMH battery

Figure 6 gives an illustration of how much the different processes contribute to all three GWP100-categories. As seen in the pie-chart in figure 19, which shows if the GHG contributes to the *fossil*, *biogenic* or *land transformation* GWP100-categories, the GWP100-fossil will be the most relevant to look at in the interpretation.

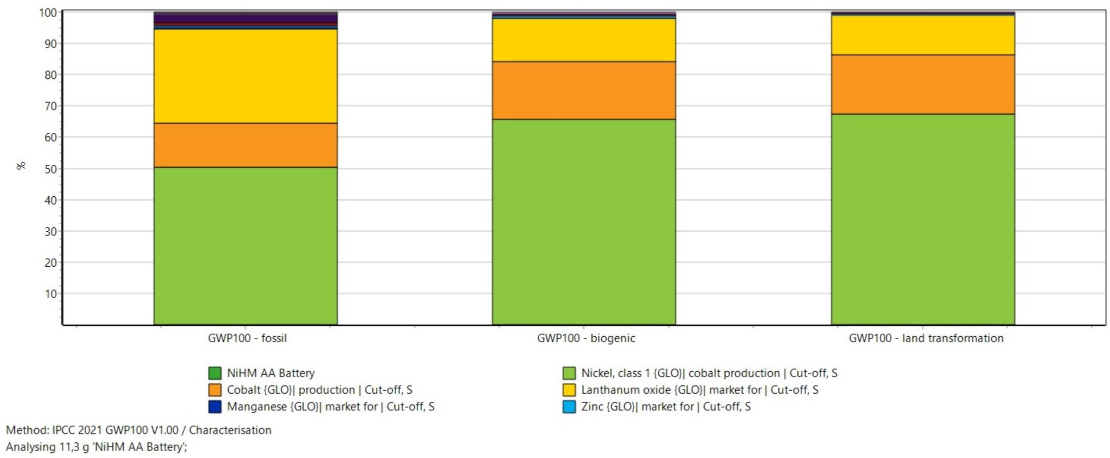

Figure 6: IPCC 2021 Characterisation of NiMH Battery

3.2.1.2 ReCiPe 2016 midpoint (NiMH)

Table 7 Shows the impact of NiMH battery from each impact category in the *ReCiPe 2016 midpoint* method.

Impact category	**Unit**	**Total**
Global warming	kg CO2 eq	0,181740613
Stratospheric ozone depletion	kg CFC11 eq	1,70627E-07
Ionizing radiation	kBq Co-60 eq	0,05175719
Ozone formation, Human health	kg NOx eq	0,00048764
Fine particulate matter formation	kg PM2.5 eq	0,0004917
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,000498031
Terrestrial acidification	kg SO2 eq	0,001327562
Freshwater eutrophication	kg P eq	0,000104301
Marine eutrophication	kg N eq	0,000694538
Terrestrial ecotoxicity	kg 1,4-DCB	7,176205856
Freshwater ecotoxicity	kg 1,4-DCB	0,037295189
Marine ecotoxicity	kg 1,4-DCB	0,050068039
Human carcinogenic toxicity	kg 1,4-DCB	0,041540069
Human non-carcinogenic toxicity	kg 1,4-DCB	1,062269301
Land use	m2a crop eq	0,020728212
Mineral resource scarcity	kg Cu eq	0,081658879
Fossil resource scarcity	kg oil eq	0,059246646
Water consumption	m3	0,032658695

Table 7: ReCiPe 2016 midpoint Impact categories NiMH Battery

Figure 7 shows the different processes contribution to each impact category in the *ReCiPe 2016 midpoint* method.

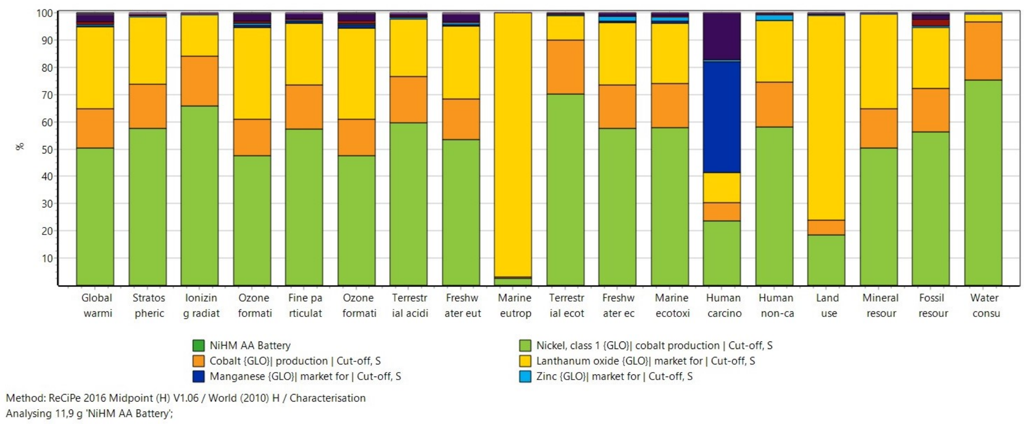

Figure 7: ReCiPe 2016 midpoint Characterisation NiMH Battery

3.2.2 Alkaline battery

3.2.2.1 IPCC 2021 GWP100 (Alkaline)

Table 8 shows the greenhouse gas emissions from $6,33g$ alkaline battery, sorted into the materials contribution to the total emission. Table 14 in the appendix shows a more detailed version of each process used.

Process	Unit	Total
Total of all processes	kg CO2-eq	0,015906056
Manganese dioxide	kg CO2-eq	0,006115945
Steel plate	kg CO2-eq	0,003171815
Zinc	kg CO2-eq	0,002911357
Brass	kg CO2-eq	0,000881107
Nylon	kg CO2-eq	0,000788711
Nickel sulfate	kg CO2-eq	0,000650738
Potassium hydroxide	kg CO2-eq	0,000640034
Graphite	kg CO2-eq	0,000387254
Polyvinylchloride	kg CO2-eq	0,000229293
Maize starch	kg CO2-eq	5,2487E-05
Zinc oxide	kg CO2-eq	4,81427E-05
Cellulose fibre	kg CO2-eq	2,8962E-05
Deionized water	kg CO2-eq	2,10235E-07

Table 8: IPCC 2021 process contribution Alkaline battery

Figure 8 gives an illustration of how much the different processes contribute to all three GWP100-categories. As seen in the pie-chart in figure 22, which shows if the GHG contributes to the *fossil*, *biogenic* or *land transformation* GWP100-categories, the GWP100-fossil will be the most relevant to look at in the interpretation.

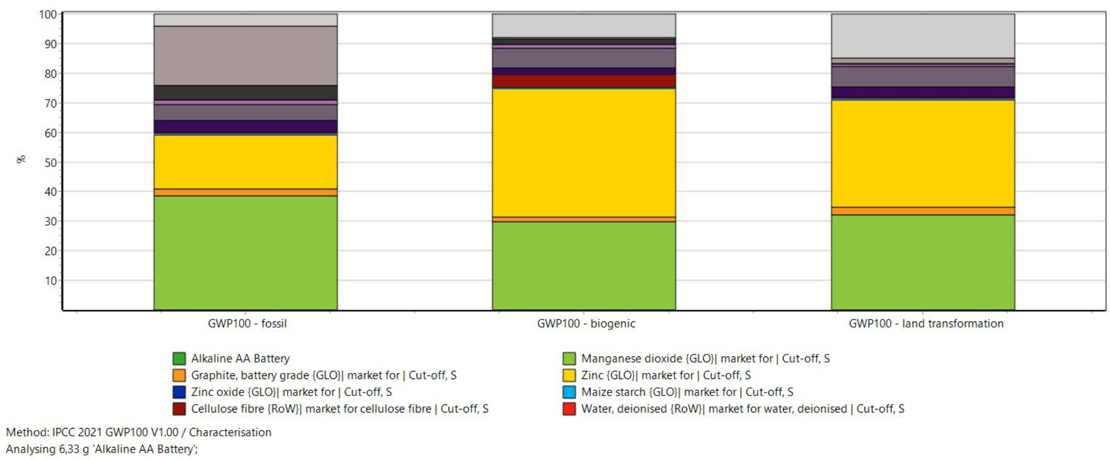

Figure 8: IPCC 2021 Characterisation of Alkaline Battery

3.2.2.2 ReCiPe 2016 midpoint (Alkaline)

Table 9 Shows the impact of NiMH battery from each impact category in the *ReCiPe 2016 midpoint* method.

Impact category	Unit	Total
Global warming	kg CO2 eq	0,0161483
Stratospheric ozone depletion	kg CFC11 eq	7,73573E-09
Ionizing radiation	kBq Co-60 eq	0,002248073
Ozone formation, Human health	kg NOx eq	5,05829E-05
Fine particulate matter formation	kg PM2.5 eq	4,28116E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	5,15453E-05
Terrestrial acidification	kg SO2 eq	0,000122778
Freshwater eutrophication	kg P eq	1,39346E-05
Marine eutrophication	kg N eq	1,10523E-06
Terrestrial ecotoxicity	kg 1,4-DCB	0,621983552
Freshwater ecotoxicity	kg 1,4-DCB	0,007725418
Marine ecotoxicity	kg 1,4-DCB	0,010231445
Human carcinogenic toxicity	kg 1,4-DCB	0,0023652
Human non-carcinogenic toxicity	kg 1,4-DCB	0,187955831
Land use	m2a crop eq	0,000694279
Mineral resource scarcity	kg Cu eq	0,001120954
Fossil resource scarcity	kg oil eq	0,004183952
Water consumption	m3	0,000487519

Table 9: ReCiPe 2016 midpoint Impact categories Alkaline battery

Figure 9 shows the different processes contribution to each impact category in the *ReCiPe 2016 midpoint* method.

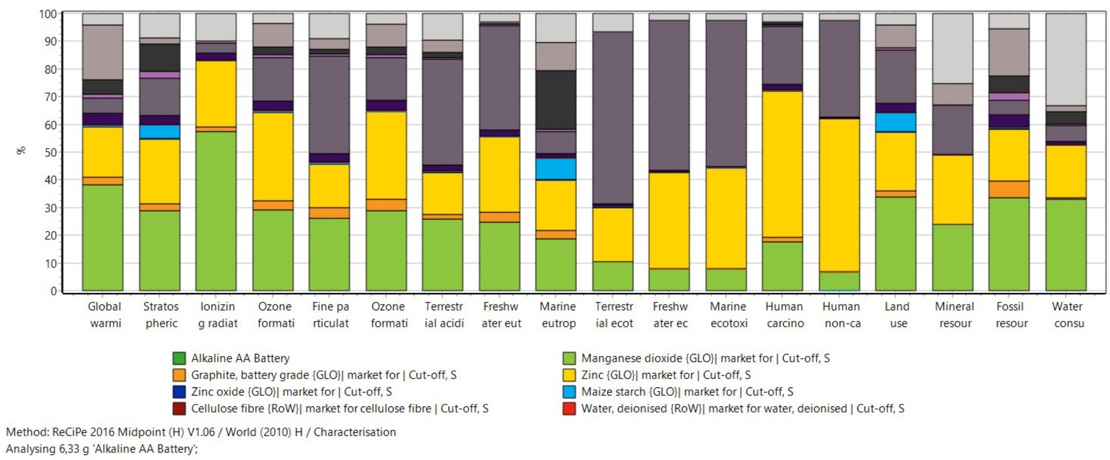

Figure 9: ReCiPe 2016 midpoint Characterisation Alkaline

3.2.3 Comparing batteries

3.2.3.1 IPCC 2021 GWP100

In order to evaluate the environmental impacts of Alkaline and NiMH batteries, Table 10 provides a comparison of their GWP100 values, as well as three specific damage categories: GWP100-fossil, GWP100-biogenic, and GWP100-land transformation.

Damage category	Unit	Alakalie	NiMH
GWP100	$kg\ CO_2 - eq$	0,0159	0,178
GWP100-fossil	$kg\ CO_2 - eq$	$0,0158$	$0,176$
GWP100-biogenic	$kg\ CO_2 - eq$	$4,66 \cdot 10^{-5}$	$8,4 \cdot 10^{-4}$
GWP100-land transformation	$kg\ CO_2 - eq$	$3,01 \cdot 10^{-5}$	$9,92 \cdot 10^{-4}$

Table 10: IPCC 2021 comparison

Figure 10 and 11 shows the characterization results of both batteries, with a comparison between the environmental impacts of the alkaline battery and the NiMH battery.

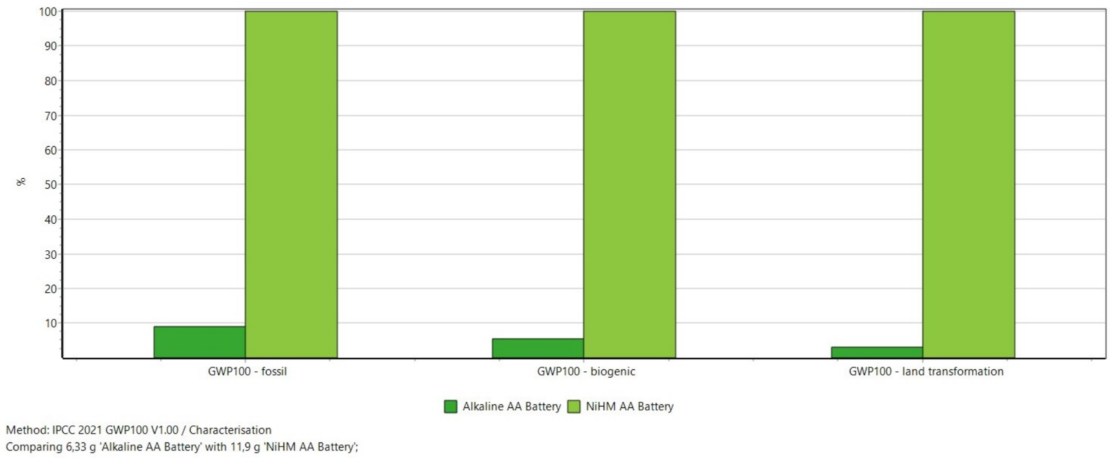

Figure 10: IPCC 2021 comparison characterization

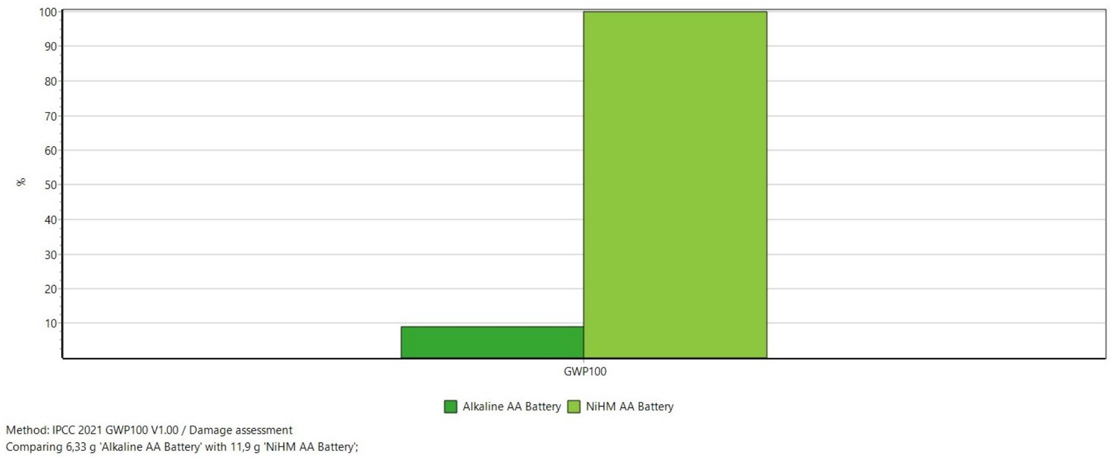

Figure 11: IPCC 2021 comparison Damage assessment

3.2.3.2 ReCiPe 2016 midpoint

Impact category	Unit	Alkaline	NiHM
Global warming	kg CO2 eq	0,0161483	0,181740613
Stratospheric ozone depletion	kg CFC11 eq	7,73573E-09	1,70627E-07
Ionizing radiation	kBq Co-60 eq	0,002248073	0,05175719
Ozone formation, Human health	kg NOx eq	5,05829E-05	0,00048764
Fine particulate matter formation	kg PM2.5 eq	4,28116E-05	0,0004917
Ozone formation, Terrestrial ecosystems	kg NOx eq	5,15453E-05	0,000498031
Terrestrial acidification	kg SO2 eq	0,000122778	0,001327562
Freshwater eutrophication	kg P eq	1,39346E-05	0,000104301
Marine eutrophication	kg N eq	1,10523E-06	0,000694538
Terrestrial ecotoxicity	kg 1,4-DCB	0,621983552	7,176205856
Freshwater ecotoxicity	kg 1,4-DCB	0,007725418	0,037295189
Marine ecotoxicity	kg 1,4-DCB	0,010231445	0,050068039
Human carcinogenic toxicity	kg 1,4-DCB	0,0023652	0,041540069
Human non-carcinogenic toxicity	kg 1,4-DCB	0,187955831	1,062269301
Land use	m2a crop eq	0,000694279	0,020728212
Mineral resource scarcity	kg Cu eq	0,001120954	0,081658879
Fossil resource scarcity	kg oil eq	0,004183952	0,059246646
Water consumption	m3	0,000487519	0,032658695

Table 11: ReCiPe 2016 midpoint table comparing Alkaline and NiMH

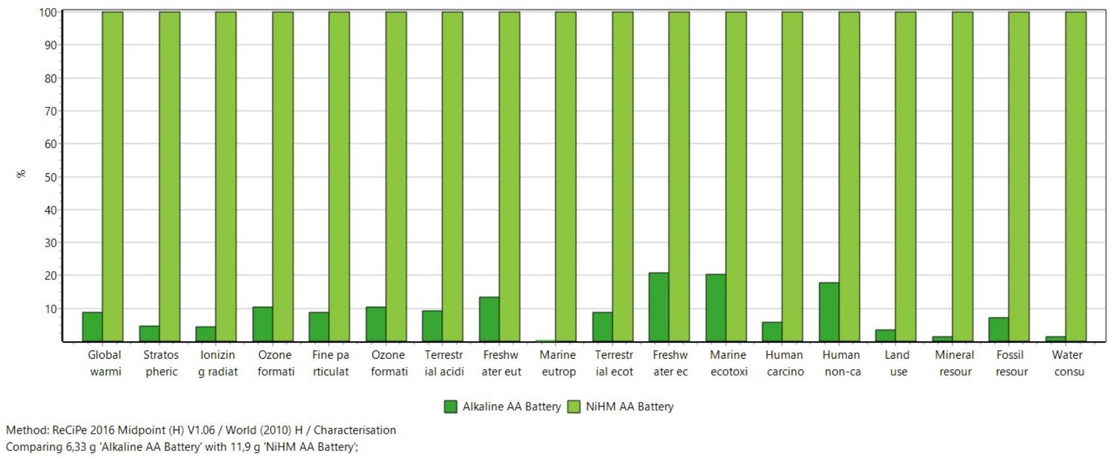

Figure 12: ReCiPe 2016 midpoint Characterisation comparing Alkaline and NiMH

3.2.3.3 ReCiPe 2016 endpoint

Damage category	Unit	Alkaline	NiHM
Human health	DALY	9,35682E-08	9,29369E-07
Ecosystems	species.yr	1,12491E-10	1,65507E-09
Resources	USD2013	0,00124084	0,038042786

Table 12: ReCiPe 2016 endpoint Damage assessment

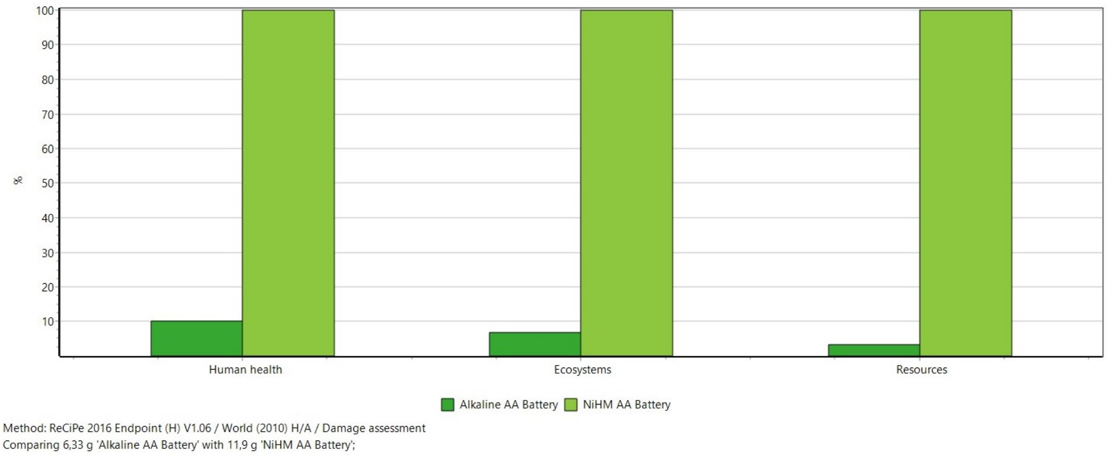

Figure 13: ReCiPe 2016 endpoint Damage assessment. Comparing 6,33g Alkaline with 11,88g NiMH battery.

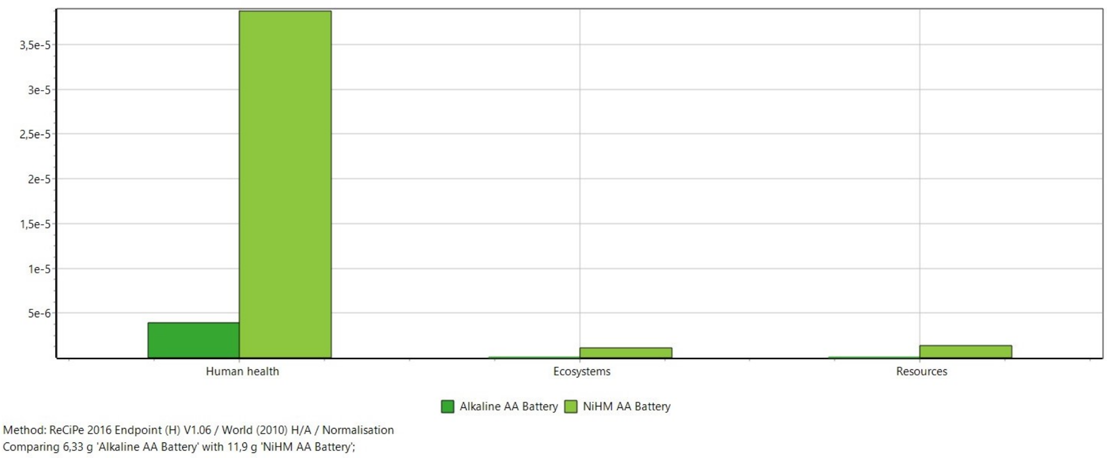

Figure 14: ReCiPe 2016 endpoint Normalisation. Comparing 6,33g Alkaline with 11,88g NiMH battery.

4 Interpretation

The life cycle interpretation is the fourth step in LCA (life cycle assessment) and it is explained in ISO 14040. In this stage, the information gathered from the previous three steps is examined, evaluated and discussed based on the analysis' objective and scope. Finally, the interpretation concludes with a summary of the LCA analysis.

4.1 Unlocking the Environmental Benefits of NiMH Batteries through Reuse

The calculations presented in this report are based on the assumption that a total of 6.33 grams of alkaline AA-battery and 11.88 grams of NiMH AA-battery are used. However, it should be noted that the calculations do not take into account the fact that the NiMH battery can be reused several times, resulting in a lower environmental impact compared to alkaline batteries depending on usage patterns. If a NiMH battery is used 50 times, its environmental impact can be compared to that of 50 alkaline batteries. It is important to note that this report only considers the cradle-to-gate phase and does not take into account the use phase. Collecting data on the use phase would be challenging and required extensive studies to map out the number of times a NiMH battery is used. Additionally, battery degradation can cause each cycle to differ in capacity, with the first use having a higher nominal capacity than next uses.

From researching the recharge capability of NiMH batteries, it shows that the batteries can be recharged between 500 - 1000 times. This however depends on how fast the batteries is charged. [17] This is one of many sources stating different amounts of charge cycles. Another important factor to consider is how many times the user will recharge the battery. There will be a possibility of users losing their chargers, throwing devices containing rechargeable battery, throwing batteries after 50 uses since it has degraded too much for their use etc. The variables are endless in this field, which leads to assumptions and simplifications.

For example, if we consider a rechargeable NiMH AA-battery that has been used 50 times before disposal, we can use Simapro to re-calculate the global warming potential of the battery, and we can expect to see a result that supports the NiMH battery as the better choice from a global warming perspective.

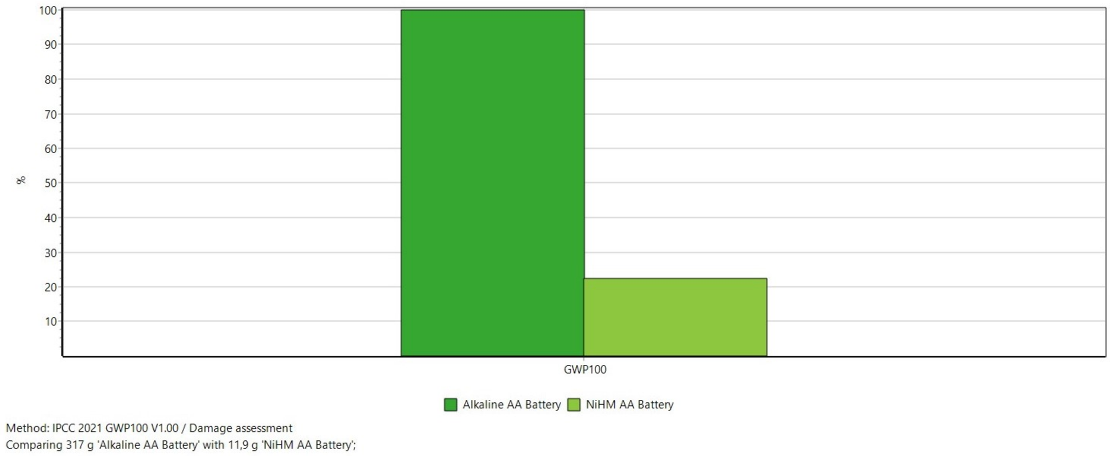

Figure 15: 50 Alakaline batteries VS 50 chargingcycles of NiMH battery

As seen in figure 15 the NiMH battery is a better choice when using it 50 times. This is however before waste management, external charges and electricity is taken into account. Those are not a part of this LCA-study, since the report focuses on cradle-to-gate.

4.2 How do the batteries compare?

In this section the two batteries will be compared in three different scenarios. The first being

Table 12, compares the ReCiPe 2016 midpoints for both alkaline and NiMH batteries. The results show that the NiMH battery has bigger environmental impacts on several impact categories. In particular, NiMH batteries have roughly ten times bigger impact on global warming and stratospheric ozone depletion than the alkaline batteries. Precisely, the NiMH battery emits an estimate of 0.18 kg CO2 eq, while the alkaline emits 0.016 kg CO2 eq. This could be explained by the NiMH battery requires more energy and resources to produce than the alkaline batteries. The NiMH battery contains more materials, including rare earth materials, such as lanthanum. This requires more energy-intense mining and processing.[18] The production of NiMH batteries generates more greenhouse gas emissions and other pollutants. [19] Using the IPCC 2021 method to find the GWP100, as seen in Table 10, the NiMH battery has higher impacts on GWP100, GWP100-fossil, GWP100-biogenic, and GWP100-land transformation.

Table 12, compares the ReCiPe 2016 endpoints for both alkaline and NiMH batteries. Again, we can see a significantly higher impact for each damage category from the NiMH battery. As before, this is because the production of NiMH batteries requires more energy, resources, and rare earth materials than alkaline batteries. Additionally, the process of recharging NiMH batteries can generate greenhouse gas emission and other pollutants, as well as how they are recycled. However, this is not looked at in this LCA and might require another one, or extending this one, to include use and end-of-life.

4.3 United Nations Sustainibility goals

The United Nations Sustainable Development Goals (SDGs) are a set of 17 goals adopted by the United Nations General Assembly in 2015. In terms of batteryproduction for NiMH and alakline batteries, the most relevant SDGs are 12, 13 and 15.

Figure 16: Sustainable Development Goals

SDG 12 Responsible consumption and Production:
The production of batteries, including NiMH and Alkaline batteries, can have a significant environmental impact due to the extraction and processing of raw materials, energy consumption, and waste generation. As seen in the results of this report.

SDG 13 Climate action The production of NiMH and Alkaline batteries contributes to the emissions of greenhouse gases. As seen in the results of this report.

SDG17 Life on land Extraction of raw materials for battery production has an ecological risk for agriculture in terms of heavy-metal pollution. [20]

4.4 Is a rechargeable battery always beneficial?

NiMH and alkaline batteries each have their own characteristics and are better suited for their own applications. A disposable alkaline battery could be better with devices that are used infrequently, as they have a longer self life than NiMH batteries and can last several years without losing their charge. Smoke detectors or fire alarms could be better suited for an alkaline battery per se. A NiMH battery could be better suited for frequently used devices, or if the device in question requires a lot of power and is used frequently. This could for example be in stage and TV productions, where wireless microphones often relies on AA, AAA, and 9V batteries. NiMH batteries can deliver more power over a longer period of time than alkaline batteries, if they are recharged. In short the NiMH battery is beneficial in most cases except for applications where the battery will sit unused for a long time. The initial manufacturing energy cost is greater for NiMH batteries, but if they are used multiple times, the disposable batteries become the lesser option. They help reduce the number of batteries that end up in landfills, making them more environmentally friendly. [21]

A report from *Kulturrom* from 2022[22] estimates that Norway uses around 1 million batteries in stage productions every year. Their report conducted a survey with 134 concert stages in Norway, where 80% stated that they still were using disposable batteries. This is an interesting report focusing on one specific industry.

5 Conclusion

In conclusion the LCA study of alkaline and NiMH batteries have revealed several environmental impacts related to their cradle-to-gate life. While the study has provided valuable insights into the environmental impacts of the products, there are some limitations to be acknowledged, including the reuse and charge cycles of the NiMH battery and assumptions made in weight and inventory lists.

Based on the results in this report, the production of NiMH batteries has a significantly greater environmental impact compared to the production of alkaline batteries. Therefore the reuse of the NiMH battery is crucial to make it a better alternative. However in some applications alkaline batteries would be a better option, for example in smoke detectors, stove guards and other applications where you would want the battery to hold its capacity over a long time.

This LCA study has demonstrated that by having a system boundary of only cradle-to-gate, the study can isolate one part of the life cycle and conclude that the remaining phase of the life cycle are crucial to make the NiMH battery a better choice. These findings can be used for stating the importance of recharging and reusing the NiMH batteries.

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Appendix

A Method

METHODS	Acidification	Climate change	Resource depletion	Ecotoxicity	Energy Use	Eutrophication	Human toxicity	Ionising Radiation	Land use	Odour	Ozone layer depletion	Particulate matter/ Respiratory inorganics	Photochemical oxidation
CML (baseline)	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	-	✓
CML (non baseline)	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	-	✓
Cumulative Energy Demand	-	-	-	-	✓	-	-	-	-	-	-	-	-
eco-indicator 99 (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
Eco-Scarcity 2006	-	-	✓	-	-	-	-	-	-	-	-	-	-
ILCD 2011, endpoint	✓	✓	-	-	-	✓	✓	✓	✓	-	✓	✓	✓
ILCD 2011, midpoint	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
TRACI 2.1	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	✓	✓
USEtox	-	-	-	✓	-	-	✓	-	-	-	-	-	-

Figure 17: Availability of impact categories per method.[23]

B IPCC

A NiMH

Process	Unit	Total
Total of all processes	kg CO2-eq	0,169774423
Nickel, class 1 {GLO}— cobalt production — Cut-off, S	kg CO2-eq	0,085731397
Lanthanum oxide {GLO}— market for — Cut-off, S	kg CO2-eq	0,051045361
Cobalt {GLO}— production — Cut-off, S	kg CO2-eq	0,024088538
Steel, low-alloyed {GLO}— market for — Cut-off, S	kg CO2-eq	0,004570341
Polypropylene, granulate {GLO}— market for — Cut-off, S	kg CO2-eq	0,001548905
Manganese {GLO}— market for — Cut-off, S	kg CO2-eq	0,000925641
Potassium hydroxide {GLO}— market for — Cut-off, S	kg CO2-eq	0,000675186
Zinc {GLO}— market for — Cut-off, S	kg CO2-eq	0,00061306
Polyvinyl chloride, from suspension process, S-PVC, at plant/RER	kg CO2-eq	0,000452602
Acrylic acid {GLO}— market for — Cut-off, S	kg CO2-eq	0,00012317
Water, deionised {RoW}— market for water, deionised — Cut-off, S	kg CO2-eq	2,22669E-07

Table 13: IPCC 2021 process contribution NiMH battery

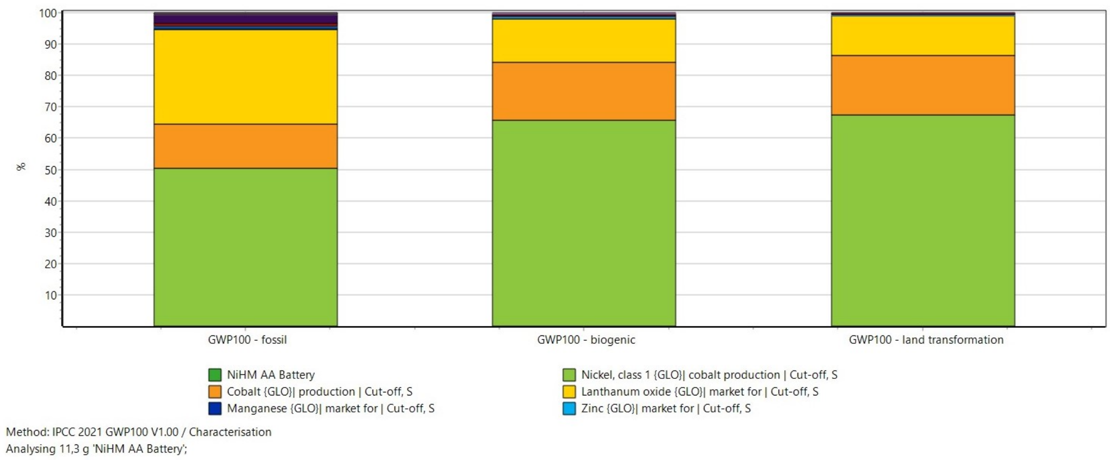

Figure 18: IPCC 2021 Characterisation of NiMH Battery

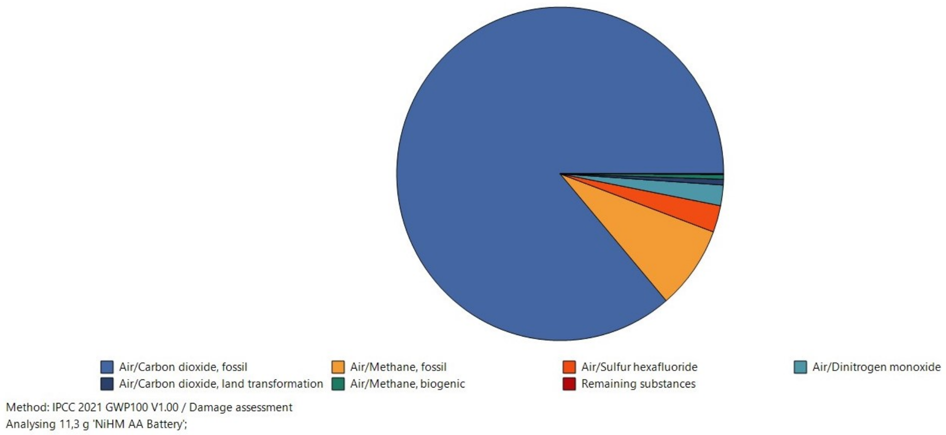

Figure 19: IPCC 2021 Damage assessment pie chart

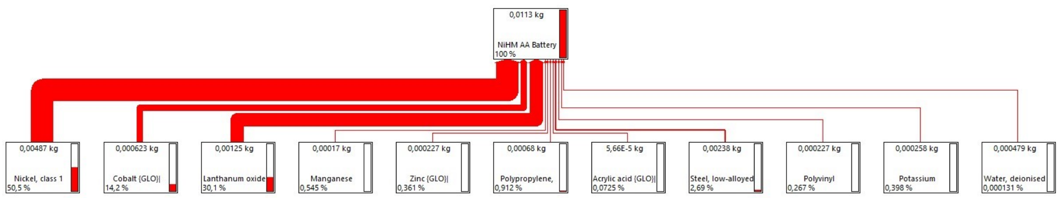

Figure 20: IPCC 2021 Damage assessment network

B Alkaline

Process	Unit	Total
Total of all processes	kg CO2-eq	0,015906056
Manganese dioxide {GLO}— market for — Cut-off, S	kg CO2-eq	0,006115945
Steel plate/GLO	kg CO2-eq	0,003171815
Zinc {GLO}— market for — Cut-off, S	kg CO2-eq	0,002911357
Brass {RoW}— market for brass — Cut-off, S	kg CO2-eq	0,000881107
Nylon 6-6 {RoW}— market for nylon 6-6 — Cut-off, S	kg CO2-eq	0,000788711
Nickel sulfate {GLO}— market for — Cut-off, S	kg CO2-eq	0,000650738
Potassium hydroxide {GLO}— market for — Cut-off, S	kg CO2-eq	0,000640034
Graphite, battery grade {GLO}— market for — Cut-off, S	kg CO2-eq	0,000387254
Polyvinylchloride, suspension polymerised {GLO}— market for — Cut-off, S	kg CO2-eq	0,000229293
Maize starch {GLO}— market for — Cut-off, S	kg CO2-eq	5,2487E-05
Zinc oxide {GLO}— market for — Cut-off, S	kg CO2-eq	4,81427E-05
Cellulose fibre {RoW}— market for cellulose fibre — Cut-off, S	kg CO2-eq	2,8962E-05
Water, deionised {RoW}— market for water, deionised — Cut-off, S	kg CO2-eq	2,10235E-07

Table 14: IPCC 2021 process contribution Alkaline battery

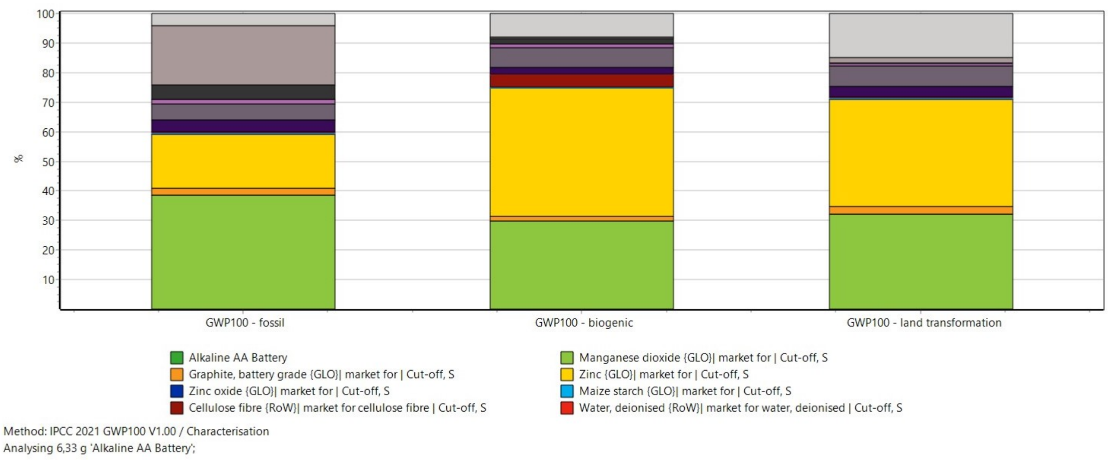

Figure 21: IPCC 2021 Characterisation of Alkaline Battery

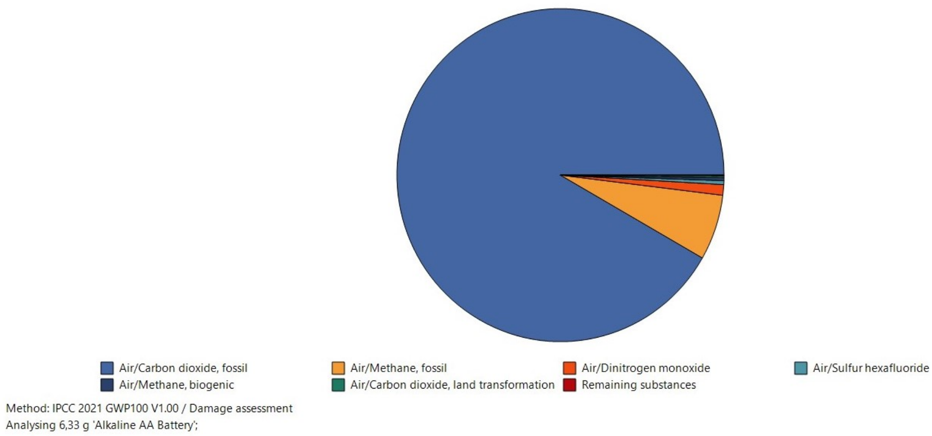

Figure 22: IPCC 2021 Damage assessment pie chart

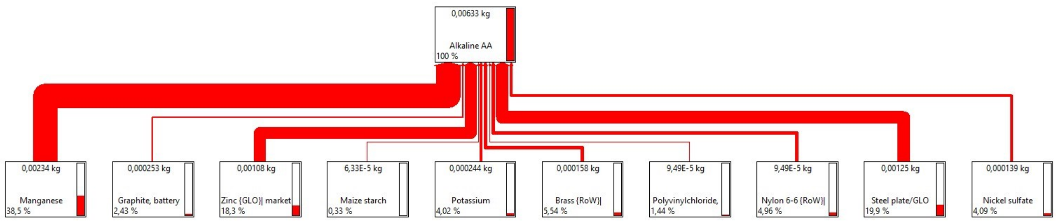

Figure 23: IPCC 2021 Damage assessment network

C ReCiPe 2016 midpoint

A NiMH

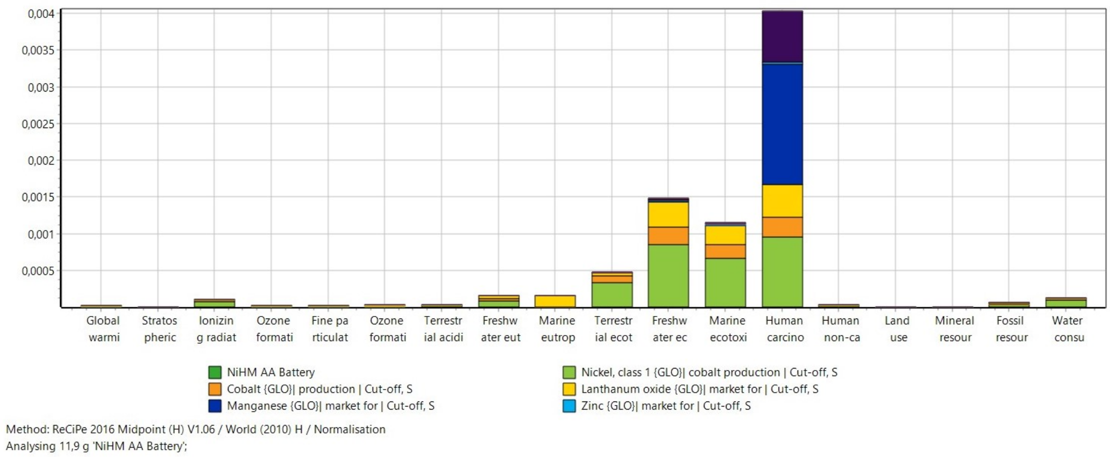

Figure 24: ReCiPe 2016 midpoint Normalisation NiMH Battery

B Alkaline

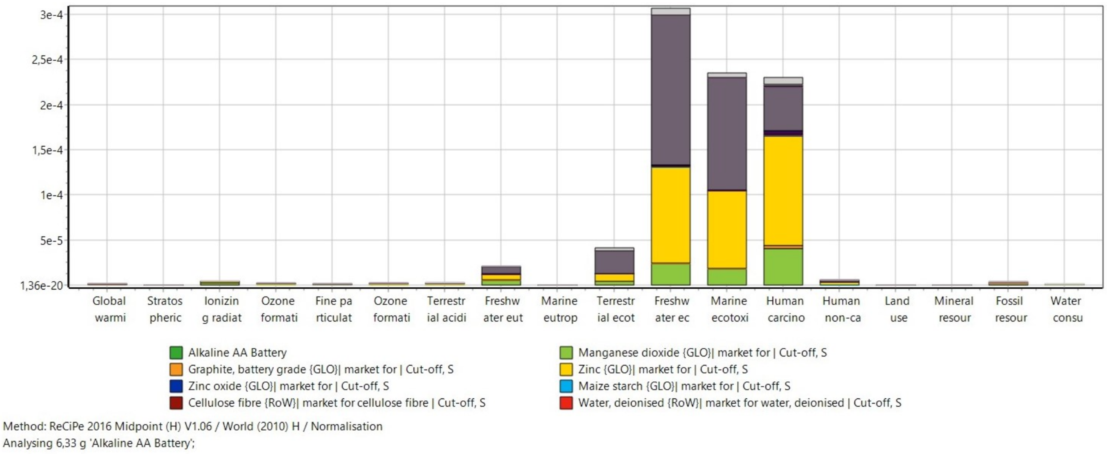

Figure 25: ReCiPe 2016 midpoint Normalisation Alkaline